KOMUNIKÁCIE
COMMUNICATIONS

OPERATION AND ECONOMICS

MECHANICAL ENGINEERING

ELECTRICAL ENGINEERING

CIVIL ENGINEERING

SAFETY AND SECURITY ENGINEERING

TRAVEL AND TOURISM STUDIES IN TRANSPORT DEVELOPMENT

Antonio Danesi - Davide Ongari - Cristian Poliziani - Federico Rupi

EVOLUTION OF THE ROAD AND RAIL TRANSPORT OF GOODS IN EUROPEAN COUNTRIES BEFORE AND AFTER THE FINANCIAL CRISES

The main goal of this paper is to analyse recent trends in freight transport volumes as well as their relation to socio-economic and infrastructural variables, in the case of the following major European countries: France, Germany, Italy, Poland, Spain and the United Kingdom. This analysis refers to the period 2005-2016, so that years affected by the global economic crisis, which shows its peak in 2009, are taken into account. This research demonstrated that not all the countries under study show a strong relation between freight traffic and GDP as it could have been expected based on well consolidated experiences and studies. Moreover, other relations are investigated, with mixed results, between the freight traffic volumes and the extension of the rail and road networks as well as oil price data.

Keywords: *freight transport, GDP, infrastructures, oil price, road and rail transport networks*

1 Introduction

Traditionally, the freight transport volumes are considered to depend on several socio-economic variables, as well as variables directly related to the transport system, such as the extension and features of transport network and oil price [1-2]. The main socio-economic variable, whose impact is typically considered to be the most relevant one on the freight traffic volumes, is the Gross Domestic Product (GDP) [3-7]; theoretically, more goods are produced and more will have to be transported within the country under consideration. Moschovou [8] illustrated this relation focusing on the recent period of crisis in Greece. Moreover, kilometres of the road and rail infrastructures in the country can affect the total freight transport [9-13]. In addition, oil price affects freight transport [14-15]: across the board, the higher the oil price is, the higher will be the amount of goods that will be transported by train rather than truck. In this paper, the above mentioned relations and factors are analysed under qualitative as well as quantitative perspectives, for six among the major European countries and with reference to the period 2005-2016.

2 The data set

Both socio-economic and transport system variables are taken into account, in the case of six European countries, with similar territorial surface and population, i.e. France, Germany, Italy, Poland, Spain and the United Kingdom.

All these countries are populated by between 40 and 80 million of inhabitants and show a surface of between 250 and 650 thousands square kilometers. For each country, data about the GDP, transport supply and freight transport volumes between year 2005 and 2016 are taken into consideration from different data sources [16-18], in order to investigate their statistical relations.

2.1 The Gross Domestic Product

Figure 1 shows the trends in the GDP values, collected from the Eurostat database for each European country belonging to the study sample, with reference to the period 2005-2016. All the GDP data are expressed in billion of euros, with reference to chain-linked values, taking 2010 as the base year. The economic crisis has shown its peak point after 2008, causing a turnaround in GDP trends for all the countries analysed, with the only exception of Poland. The UK, but especially Italy, show a significant decline: however, while the UK after 2008 has shown a strong recovery, the recovery for Italy has not been completed yet and Italian GDP in 2016 is the only one, which is still lower than that of 2005.

From 2005 to 2016, Poland shows a total growth in its GDP of 50.8%, proving to be much more dynamic compared to the other countries, that register a total growth between 8% and 18% only, for the whole period: 10% for France, 18% for Germany, 8% for Spain and 16% for the UK. Only Italy shows a negative growth rate equal to -3%. Poland seems not to have perceived the economic crisis at all, showing a constant growth along the study period.

Antonio Danesi[1], Davide Ongari[2], Cristian Poliziani[1,*], Federico Rupi[1]
[1]Department of Civil, Chemical, Economic and Environmental Engineering, University of Bologna, Italy
[2]Freelance transport analyst, Milan, Italy
*E-mail of corresponding author: cristian.poliziani2@unibo.it

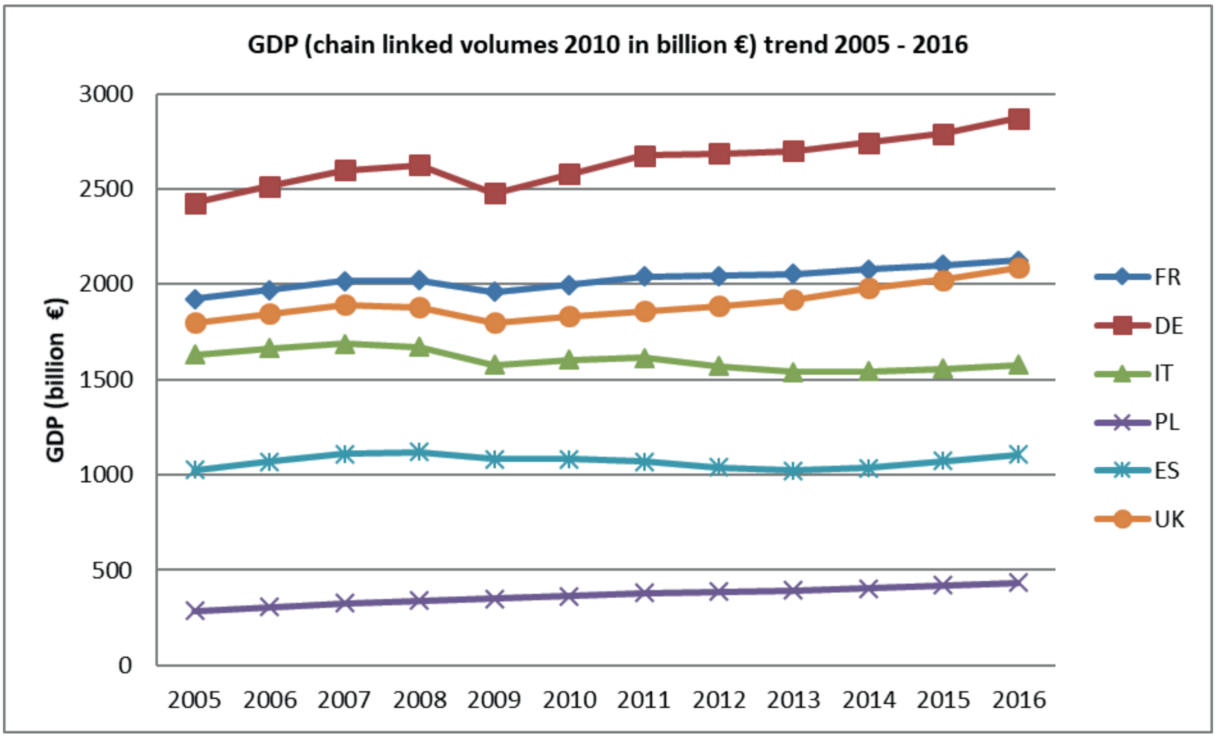


Figure 1 *2005-2016 GDP trends, in billions of euros, calculated in chain linked values (base year: 2010), for the countries under study*

Table 1 *Railway total length (km)*

Country	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Δ %	Δ
FR	29286	29463	29918	29901	29903	29871	30404	30581	29784	30905	28808	28364	-3.2	-922
DE	34221	34122	33890	33855	33714	33707	33576	33509	38703	38836	38828	38990	14.0	4769
IT	16545	16627	16667	16861	17004	17022	17045	17060	17070	17037	17041	17096	3.3	551
PL	19507	19429	19419	19627	19764	19702	19725	19617	18959	18942	18510	18429	-5.5	-1078
ES	15015	15212	15554	15550	15330	15837	15932	15922	15937	15901	16050	15922	6.0	907
UK	16208	16193	16212	16212	16151	16175	16408	16423	16423	16209	16209	16253	0.3	45

Table 2 *Motorway total length (km)*

Country	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Δ%	Δ
FR	10798	10848	10958	11042	11163	11392	11413	11413	11552	11560	11599	11612	7.5	814
DE	12363	12531	12594	12645	12813	12819	12845	12879	12917	12949	12993	12996	5.1	633
IT	6542	6554	6588	6629	6661	6668	6668	6726	6751	6844	6943	6943	6.1	401
PL	552	583	663	765	849	857	1070	1365	1482	1556	1559	1640	197.1	1088
ES	11432	12073	13013	13518	14021	14262	14554	14701	14981	15049	15336	15444	35.1	4012
UK	3665	3669	3673	3674	3672	3686	3733	3756	3760	3769	3768	3764	2.7	99

2.2 Extension of road and rail networks

Table 1 and Table 2 show the level of transport supply for rail and road transport systems, in terms of corresponding network extension. Table 1 shows, for each country, the total length of railways, the corresponding percentage growth in the study period (Δ %) and the absolute variations (Δ) in terms of kilometers added to the total infrastructure length. The most relevant growth in terms of extension of rail infrastructure has occurred in Germany, where the network has increased by more than 4,700 km (+14%). On the other hand, in Poland, the rail network has decreased by approximatively 1,000 km (-5.5%).

Table 2 shows the total length of motorways, the corresponding percentage growth in the study period (Δ%) and the absolute variations in terms of kilometers added to the road infrastructure (Δ): in the latter case, for all of the countries under study, an increase in network length has been registered, with particular regard to the

***Table 3** Crude Oil, Europe Spot Price FOB (dollars per barrel)*

2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Δ %
54.58	65.17	72.51	96.94	61.74	79.61	111.38	110.80	108.56	96.97	52.30	43.64	-20.0

***Table 4** National and international road and rail freight volumes (billion ton-km)*

Country	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Δ %
FR	246.0	252.6	261.8	246.7	205.7	212.2	219.9	204.9	203.7	197.8	187.9	188.4	-23.4 %
DE	405.5	437.0	458.0	457.2	403.3	420.4	437.1	417.1	418.3	422.7	428.7	431.4	+6.4 %
IT	234.6	211.3	204.7	204.3	185.4	194.4	162.6	144.2	146.2	138.0	137.6	135.3	-42.3 %
PL	161.8	181.9	205.2	216.9	224.2	251.0	261.5	271.2	298.5	301.0	311.3	341.4	+111.0 %
ES	244.8	253.3	270.1	254.0	2197	219.0	216.3	208.7	201.9	206.2	220.5	227.5	-7.1 %
UK	182.7	1874	192.3	181.4	158.7	165.3	174.5	179.9	169.6	165.3	180.9	172.1	-5.8 %

***Table 5** National and international rail freight volumes (billion ton-km)*

Country	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Δ %
FR	40.7	41.2	42.6	40.4	32.1	30.0	34.2	32.5	32.2	32.6	34.3	32.6	-19.9
DE	95.4	107.0	114.6	115.7	95.8	107.3	113.3	110.1	112.6	112.6	114.0	116.2	+21.8
IT	22.8	24.2	25.3	23.8	17.8	18.6	19.8	20.2	19.0	20.2	20.8	22.7	-0.3
PL	50.0	53.6	54.3	52.0	43.5	48.7	53.8	48.9	50.9	50.1	50.6	50.7	+1.5
ES	11.6	11.5	11.2	11.0	7.8	8.9	9.5	9.5	9.3	10.4	11.1	10.5	-9.4
UK	21.5	21.9	21.3	21.0	19.2	18.6	21.0	21.4	22.4	22.1	22.0	17.1	-20.2

case of Poland and Spain. Poland, in particular, shows a triplication in its total motorway length during the period under consideration. In absolute terms, the most relevant growth in the extension of motorway network has occurred in Spain, with an increase of more than 4,000 km from 2005 to 2016.

2.3 The oil price

In Table 3, oil price trend calculated in dollars per barrel of crude oil is reported, with reference to the period 2005-2016. Significant changes in oil prices have occurred in the period under study, with a decrease by 20%. Price of crude oil can be considered as a proxy of pump price values, which can vary very much between different pump stations and countries [19].

2.4 National and international freight transport by road and rail

This paragraph deals with the analysis of the national and international haulage, both by rail and road, from 2005 to 2016.

Table 4 shows the total national and international freight transport reported by carriers registered in the countries under analysis, with reference to both road and rail operations. The highest total traffic increase has been registered by Poland (+111.0%), while Italy has recorded the worst performance, with a decrease of total freight transport by 42.3%.

In the case of the rail freight (Table 5), data sets are based on the Regulation (EC) 91/2003 of the European Parliament and Council (2002) on rail transport statistics. Rail freight transport statistics show that, from 2008 to 2009, the decrease in transported goods is very significant. In 2009 the overall decrease in the goods transported by rail is equal to 18.1% with reference to the study sample. On the other hand, the total variation in rail freight transport from 2005 to 2016 is equal to +3.2%, i.e. equivalent to 7.9 billion ton-km, as far as the whole countries included in the study sample are concerned. Statistics about road haulage are presented in Table 6, based on the Council Regulation (EC) 1172/1998, so that reporting countries may exclude vehicles for road transport, whose load capacity is lower than 3.5 ton or maximum permissible laden weight is lower than 6 ton.

Table 6 shows the national and international road haulage expressed in billion ton-km, by vehicles registered in the reporting country, including cross-trade and cabotage. From 2008 to 2009, only Poland shows some traffic increases. All other countries seem to be affected by the global economic crisis, subsequently overcome by all countries, with the only exception of Italy, which shows a further significant reduction in road haulage between 2010 and 2016 (-6%). The total variation in road haulage, as far as all countries included in the study sample are concerned, is equal to +1.0 %, i.e. equivalent to 12.8 billion ton-km.

By comparing data reported in Tables 4-6, different trends emerge for the countries under study: France, Spain

Table 6 *National and international road freight volumes (billion ton-km)*

Country	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Δ %
FR	205.3	211.4	219.2	206.3	173.6	182.2	185.7	172.4	171.5	165.2	153.6	155.8	-24.1
DE	310.1	330	343.4	341.5	307.5	313.1	323.8	307	305.7	310.1	314.7	315.2	+1.6
IT	211.8	187.1	179.4	180.5	167.6	175.8	142.8	124	127.2	117.8	116.8	112.6	-46.8
PL	111.8	128.3	150.9	164.9	180.7	202.3	207.7	222.3	247.6	250.9	260.7	290.7	+160.0
ES	233.2	241.8	258.9	243	211.9	210.1	206.8	199.2	192.6	195.8	209.4	217	-7.0
UK	161.3	165.5	171	160.3	139.5	146.7	153.5	158.5	147.2	143.2	158.9	155	-3.9

Table 7 *National road haulage (billion ton-km)*

Country	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Δ %
FR	177.3	182.8	191.4	181.9	156.0	164.3	168.2	156.4	155.7	151.1	141.2	144.2	-18.7
DE	237.6	251.4	261.4	264.5	245.6	252.5	265.0	254.5	256.7	263.0	269.7	271.7	+14.3
IT	171.6	155.4	152.4	151.8	145.6	149.2	127.7	111.8	112.0	102.4	104.1	100.3	-41.6
PL	60.9	59.4	65.8	71.9	79.2	82.2	89.7	89.0	100.3	96.6	104.7	106.6	+75.0
ES	166.4	174.6	190.6	175.2	151.1	146.2	142.3	133.4	127.0	128.2	137.2	145.0	-12.9
UK	151.2	154.8	160.7	151.1	131.6	137.8	139.9	142.6	131.3	127.7	142.9	148.7	-1.7

Table 8 *Road transport performance adjusted for territoriality (billion ton-km)*

Country	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Δ %
FR	294.5	303.9	315.3	301.4	261.7	275.1	273.4	259.1	263.7	259.8	249.4	258.1	-12.4
DE	370.8	394.5	413.2	420.0	385.3	404.9	417.6	408.2	416.7	426.9	427.5	447.7	+20.7
IT	204.0	190.1	186.8	187.5	176.4	183.6	157.3	139.5	141.8	133.0	133.5	132.0	-35.3
PL	86.8	91.0	95.3	101.6	107.4	116.2	125.6	127.9	141.5	138.5	147.3	154.2	+77.7
ES	210.7	220.1	237.3	217.3	189.4	184.4	179.9	169.8	166.1	167.1	177.9	186.7	-11.4
UK	167.3	171.5	178.1	167.7	145.0	151.5	157.6	163.4	152.2	149.6	165.9	185.6	+10.9

and the United Kingdom show a decrease both in the road and rail freight volumes, between 2005 and 2016. In the same period, Italian carriers show a strong contraction of road freight, while rail haulage is almost constant. On the other hand, Germany shows a relevant growth in both road and rail transport and Poland shows a very high increase in road haulage, while rail haulage has registered only a very limited growth between 2005 and 2016. Table 7 reports data regarding national road freight transport by carriers registered in the corresponding country, while Table 8 reports data regarding national road freight transport adjusted for territoriality. The latter values account for haulage performed within the territory of each country by any vehicles, without considering the cross-trade and cabotage. The total variation of national haulage, by considering all the countries included in the study sample, is equal to -5.1%, i.e. equivalent to 7.9 billions of ton-km, for national road haulage, between 2005 and 2016. As far as the adjustment for territoriality is taken into consideration, an increase by +2.2%, i.e. equivalent to 30.2 billion of ton-km, for the national road transport performance has been registered. The latter observation seems to indicate that road transport market of the countries under study has seen a significant shift of freight traffic from local operators to operators registered in other countries.

Table 9 shows the signs of the total percentage variation of freight transport volumes in each country under study, for what concerns both rail and road haulage, between 2005 and 2016. Each country shows the same sign for the variation in rail and road haulage, as well as for total and national adjusted data, with the only exception of the United Kingdom. Indeed, the United Kingdom shows an increase only in the national adjusted road freight, while all other values show a negative sign. This is related to the fact that, in these years, carriers from different European countries have started working in the UK, replacing some local operators, probably to minimize service costs. Table 10 shows the adjusted road freight transport share controlled by carriers registered in the corresponding country (national road freight divided by the adjusted road freight). Only the United Kingdom, Italy and France show a high decrease in this value, due to the high increase in the adjusted road freight compared to the national one. In particular, the decreasing of this value for the United Kingdom is a consequence of the phenomenon highlighted in Table 9. France and Germany are the countries having recorded the highest percentage of freight traffic by foreign companies, in absolute terms.

***Table 9** Sign of total percentage variation of rail and road freight between 2005 and 2016*

Country	Rail freight	Nat. and int. road freight	Nat. road freight	Nat. adjusted road freight
FR	-	-	-	-
DE	+	+	+	+
IT	-	-	-	-
PL	+	+	+	+
ES	-	-	-	-
UK	-	-	-	+

***Table 10** National share of total freight transport - changes between 2005 and 2016*

Country	2005	2016	Δ
FR	60.2 %	55.9 %	-7.2 %
DE	64.1 %	60.7 %	-5.3 %
IT	84.1 %	76.0 %	-9.7 %
PL	70.2 %	69.1 %	-1.5 %
ES	79.0 %	77.7 %	-1.7 %
UK	90.4 %	80.1 %	-11.3 %

***Table 11** Elasticity and R-square values for relationships between the rail and road freight traffic from 2005 to 2016 and socio-economic and transport system variables (n.s. and f. are abbreviations for "not statistically significant" and "freight")*

E - R-square	FR		DE		IT		PL		ES	UK
GDP - Road f.	n.s.		0.71	0.79	4.90	0.64	1.58	0.96	n.s.	n.s.
GDP - Rail f.	n.s.		1.08	0.66	2.60	0.53	n.s.		n.s.	n.s.
Motorway - Road f.	n.s.		n.s.		n.s.		0.49	0.95	n.s.	n.s.
Railway - Rail f.	n.s.		n.s.		n.s.		n.s.		n.s.	n.s.
Motorway - Rail f.	-3.73	0.69	n.s.		n.s.		n.s.		n.s.	n.s.
Oil price - Road f.	n.s.		n.s.		n.s.		n.s.		n.s.	n.s.
Oil price - Rail f.	n.s.		n.s.		n.s.		n.s.		n.s.	n.s.
GDP in thousands €, Road f. and Rail f. in billion ton·km, Motorways and Railways in km										

3 Regression analysis

In this paragraph, relations between freight transport data and the values associated to the other independent variables, which are related both to the socio-economic sector, as well as the transport supply sub-system, are evaluated in terms of both linear and logarithmic regression analysis. In this framework, the elasticity of freight traffic, with respect to the independent variables, is estimated for all the countries included in the sample under study. Figure 2 shows for each country the comparison between the absolute values of national road haulage, national and international rail haulage and GDP, in the period 2005-2016. For Germany, Poland and Spain the freight transport trends appear to be strongly related to the GDP trends registered in the corresponding countries. Figure 3 shows the annual variations of the national and international rail and road haulage. Again, trends in the GDP are included in this charts and in the case of France, Germany and Poland, they seem to reproduce freight transport annual rates of increase well.

This analysis confirms that the economic crisis and the consequent austerity applied by the governments, which started in 2008, had the effect of producing a drastic decrease in terms of transported goods, both by road and rail. The rail freight traffic reduction was particularly strong. The country that lost the smallest amount of traffic is Poland, whose economy is growing in a fast way, like other East-European countries. The main results of the elasticity analysis performed in this research between the analysed variables are presented in Table 11.

More in detail, Table 11 reports the R-square and elasticity values for different pairs of attributes and for each country, with reference to the period 2005-2016. Statistical results leading either to the low R-square values or to counterintuitive signs of coefficients are omitted in Table 11. The existence of a link between GDP trends and road and rail haulage seems to be valid, at least for some countries of the sample under study, with special regard to Germany and Italy. High values of elasticity for Italy, compared to the expected ones based on the scientific literature, are possibly due to the huge loss in terms of freight transport in a period of the GDP stagnation. Relations between the freight traffic and infrastructural variables are not statistically significant, with the only

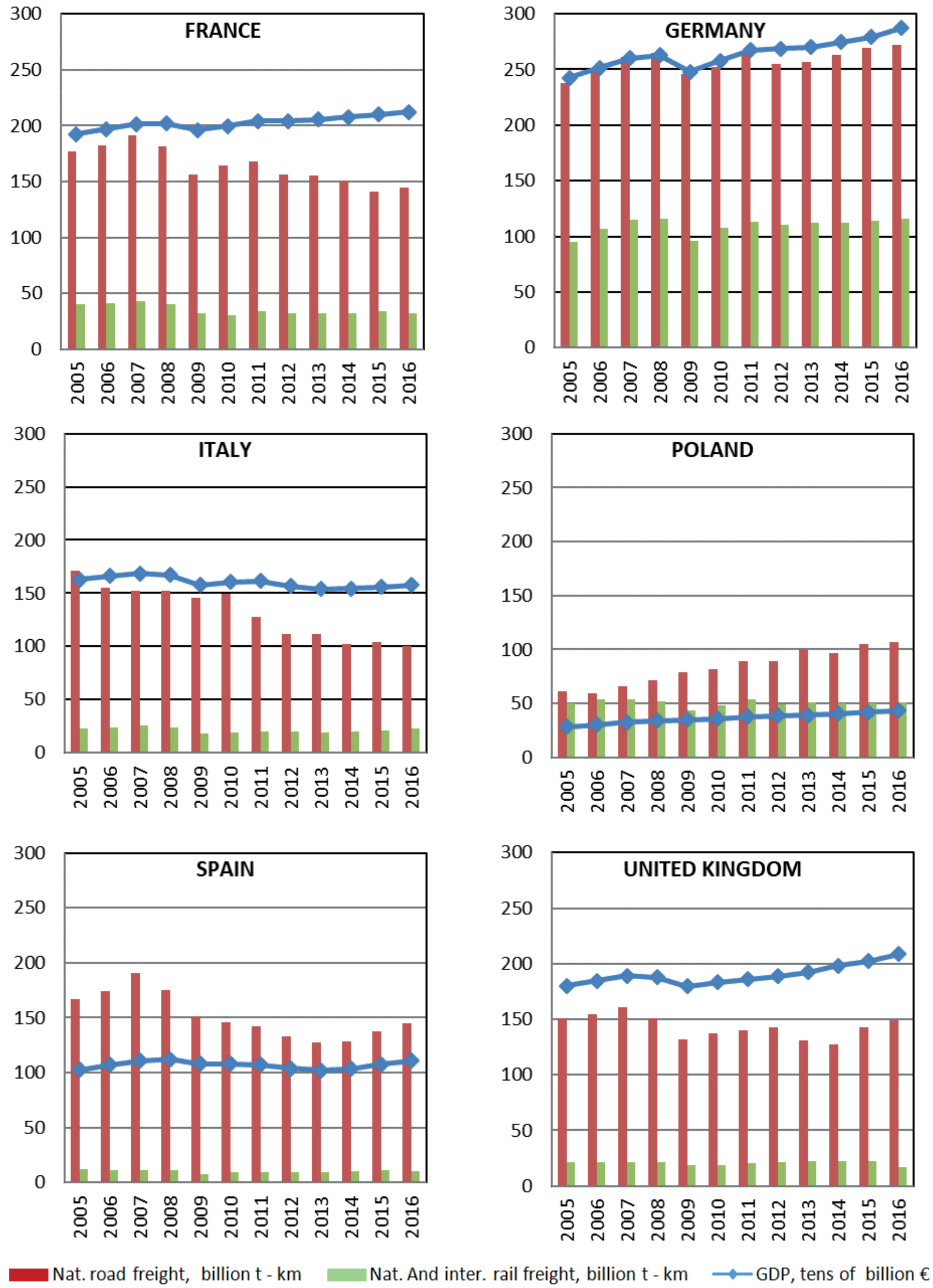


***Figure 2** Absolute values of national road haulage, national and international rail haulage and GDP, between 2005 and 2016*

exception of Poland, which has experienced a relevant variation on both the motorway length and the road freight, so that an elasticity of 0.49 with an R-square of 0.95 has been calculated. The cross-elasticity analysis between motorway length and rail freight has been performed: only the case of France confirms the statistical significance of this relation. All the statistically significant relations satisfy

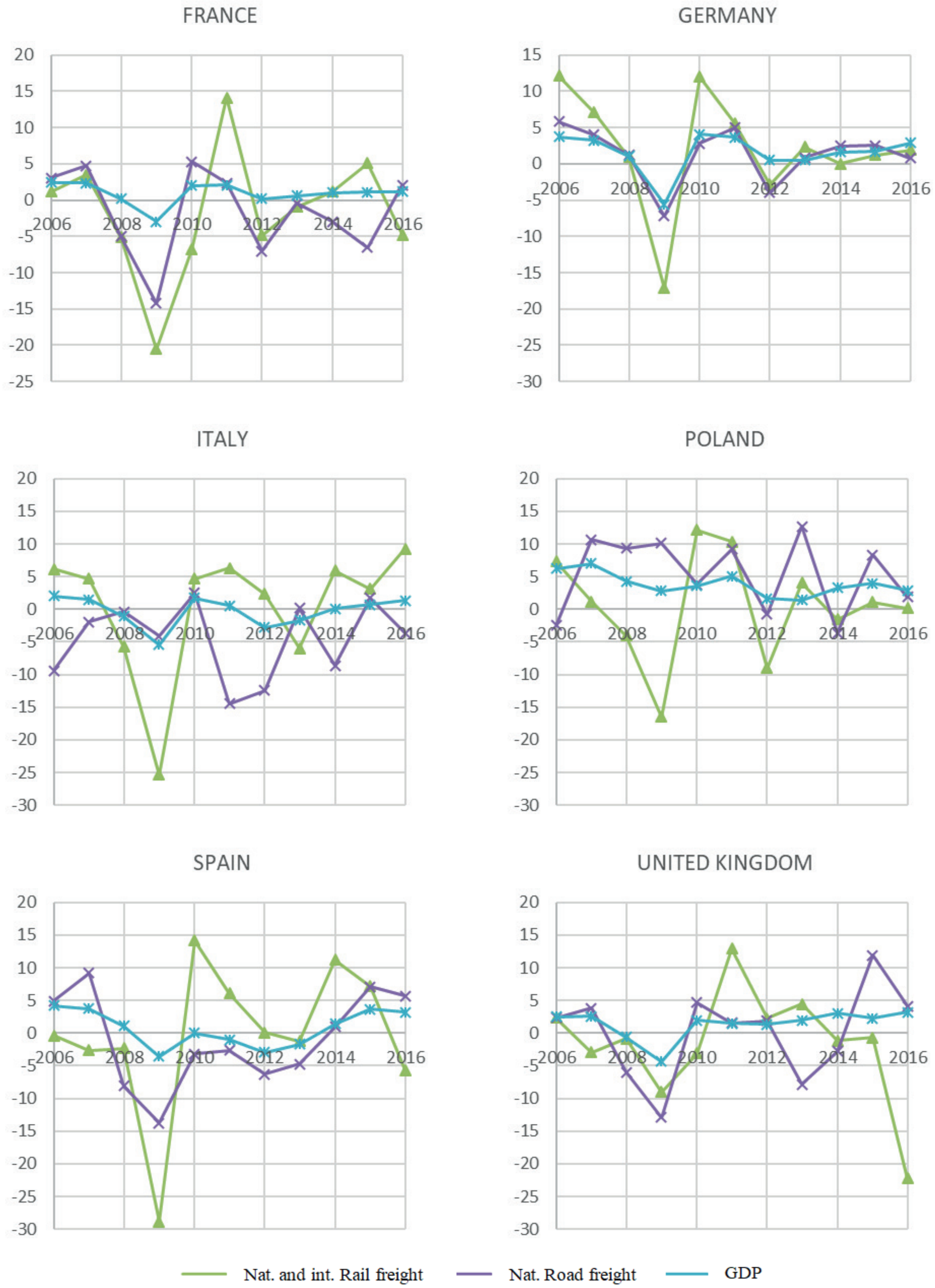


***Figure 3** Annual rate of increase of GDP, national road freight and national and international rail freight between 2005 and 2016*

the t-student test for their coefficient, showing t-values that range between 3 and 7.

A further relation has been analysed by taking into account the rail share of the freight transport in the European Union (Table 12) and the oil price registered

Table 12 European share of rail freight for the European Union - changes between the 2005 and 2016

2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Δ %
11.50 %	11.80 %	12.00 %	12.00 %	11.00 %	11.40 %	12.10 %	12.00 %	11.90 %	11.80 %	11.90 %	11.20 %	-2.6 %

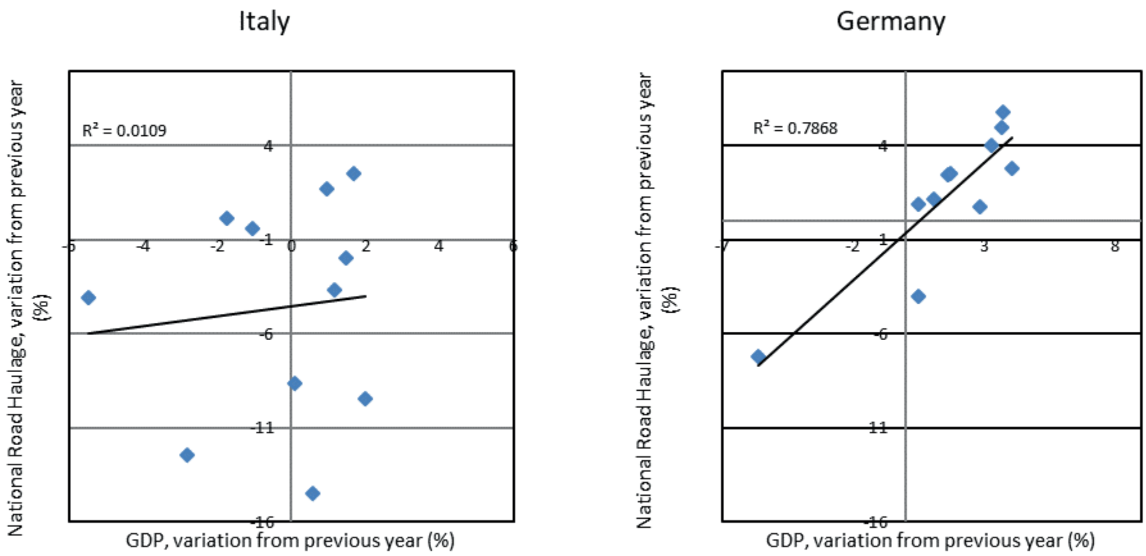


***Figure 4** Relation between the annual rate of increase of GDP and national road haulage, for Italy and Germany*

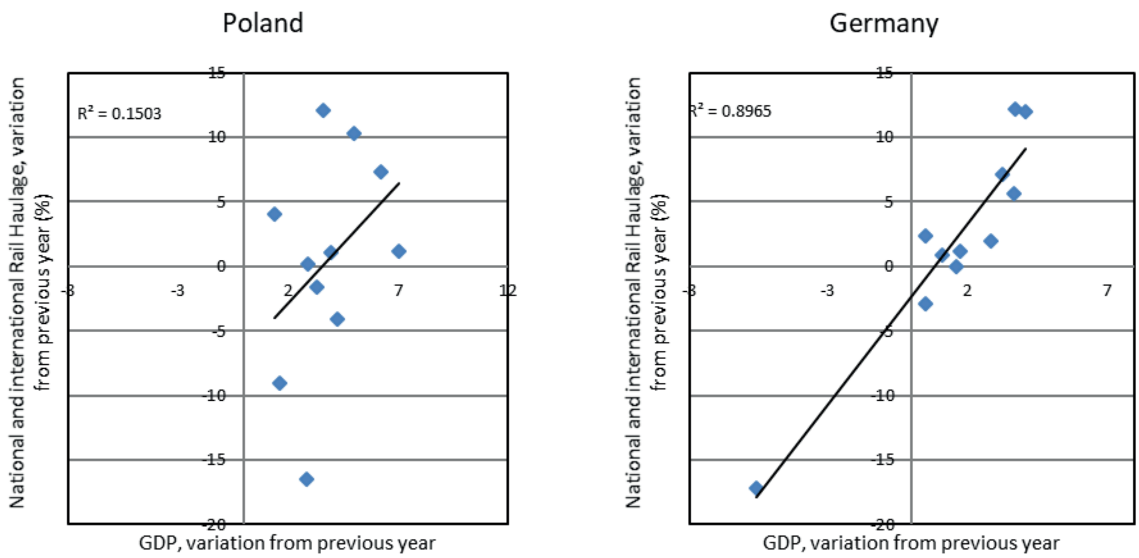


***Figure 5** Relation between the annual rate of increase of GDP and national and international rail haulage, for Poland and Germany*

in the same year. The relation between the percentage variation of these two variables has resulted to be quite low with an R-square equal to 0.48; moreover, by excluding values related to the exceptional cases of years 2008 and 2015 (outliers), the R-square regression value becomes equal to 0.94. As a consequence, increases in oil price seem to contribute effectively to the increase in the modal share controlled by the rail operations, compared to road operations, thus resulting in a significant decrease in CO_2 emissions, to a different extent in different countries.

Finally, Figures 4 and 5 present the results of the linear regressions estimated between the GDP annual rate of increase and annual rate of increase in national road freight as well as national and international rail freight traffic volumes. It can be noted that Germany shows a strong relationship between these variables, while for Italy and Poland no statistically significant relationship has been observed.

Moreover, Figure 6 presents the correlation existing between the railway length and rail haulage registered in

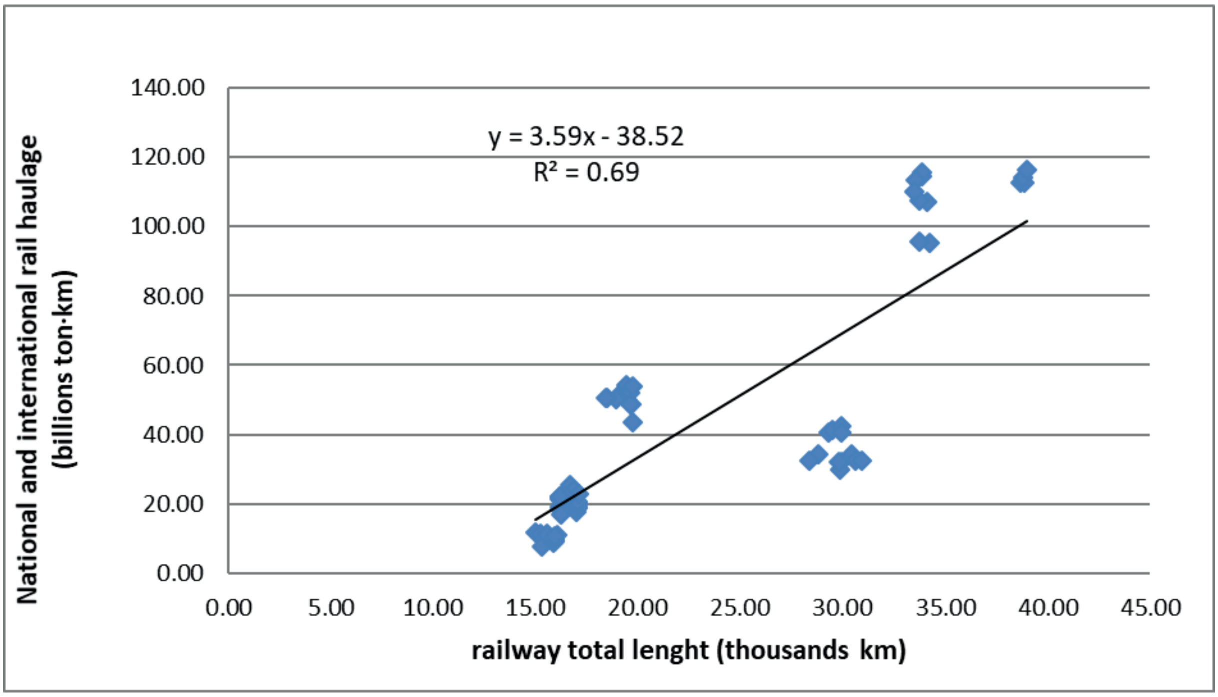


Figure 6 *Relation between the rail freight and railway length for all analysed countries*

the countries under analysis. This graph shows the positive correlation that seems to exist between these two variables.

4 Conclusions

In this paper, the socio-economic, infrastructural and road, as well the rail freight, traffic data have been analysed with reference to the following European countries: France, Germany, Italy, Poland, Spain and the United Kingdom. The analysis is focused on the trend of data registered in the period 2005-2016, when the negative reaction of GDP and land transport haulage can be clearly observed, following the economic crisis started in 2008. Indeed, this study confirms that the economic crisis and the consequent policy of austerity applied by many European governments, starting from year 2008, led, in many cases, to a drastic decrease in terms of freight traffic volumes, both by road and especially by rail. On the other hand, Poland has shown a continuous growth of both socio-economic and transport-related attributes in the period under consideration. In fact, Poland behaves very differently compared to other more mature economies and it emerges from other countries also by registering a total growth of motorway network length by 160%, between 2005 and 2016. A comparison between the annual variation of analysed attributes leads to observation of some relations among them, to a different extent in the various countries included in the study sample. Indeed, correlations between different pairs of attributes have been evaluated, by taking into account the freight traffic volumes as a dependent variable. Road haulage seems to be strongly related to GDP trend, at least as far as Germany, Italy and Poland are concerned. Moreover, it has been observed that a positive variation in the oil price involved, on average, a shift for freight from road to rail transport, with a significant decrease of the CO_2 emissions. Finally, Poland appears to be the best performing country in the period under study, for what concerns both economic parameters and the road and rail transport of goods.

References

[1] OTTEMOLLER, O., FRIEDRICH, H. Modelling change in supply-chain-structures and its effect on freight transport demand. *Transportation research part E: Logistic and Transportation Review* [online]. 2018, **121**(C), p. 23-42. ISSN 1366-5545. Available from: https://doi.org/10.1016/j.tre.2017.08.009

[2] TRLAKOVIC, J., DESPOTOVIC, D, RISTIC, L. Impact of technology-intensive exports on GDP of Western Balkan Countries. *Journal of Policy Modeling* [online]. 2018, **40**(5), p. 1038-1049. ISSN 0161-8938, eISSN 1873-8060. Available from: https://doi.org/10.1016/j.jpolmod.2018.01.006

[3] GAO, Y. ZHANGA, Y., LI, H., PENG, T., HAO, S. Study on the relationship between comprehensive transportation freight index and GDP in China. *Procedia Engineering* [online]. 2016, **137**, p. 571-580. eISSN 1877-7058. Available from: https://doi.org/10.1016/j.proeng.2016.01.294

[4] VARJAN, P., ROVNANIKOVA, D., GNAP, J. Examining changes in GDP on the demand for road freight transport. *Procedia Engineering* [online]. 2017, **192**, p. 911-916. eISSN 1877-7058. Available from: https://doi.org/10.1016/j.proeng.2017.06.157
[5] ALISES, A., VASSALLO, J. Comparison of road freight transport trends in Europe. Coupling and decoupling factors from an Input-Output structural decomposition analysis. *Trasportation Research part A: Policy and Practice* [online]. 2015, **82**, p. 141-157. ISSN 0965-8564, eISSN 1879-2375. Available from: https://doi.org/10.1016/j.tra.2015.09.013
[6] LUPI, M., MANTECCHINI, L., RUPI, F. Econometric models for the Italian railway transportation demand. *Ingegneria Ferroviaria*. 2004, **3**(3), p. 237-24. ISSN 0020-0956. Available from: http://hdl.handle.net/11568/187961
[7] FERRARI, P. Some necessary conditions for the success of innovations in rail freight transport. *Transportation Research Part A: Policy and Practice* [online]. 2018, **118**, p. 747-758. ISSN 0965-8564, eISSN 1879-2375. Available from: https://doi.org/10.1016/j.tra.2018.10.020
[8] MOSCHOVOU, T. Freight transport impacts from the economic crisis in Greece. *Transport policy* [online]. 2017, **57**, p. 51-58. ISSN 0967-070X, eISSN 1879-310X. Available from: https://doi.org/10.1016/j.tranpol.2017.04.001
[9] ENGSTROM, R. The Roads' Role in the freight Transport System. *Transportation Research Procedia* [online]. 2016, **14**, p. 1443-1452. ISSN 2352-1465. Available from: https://doi.org/10.1016/j.trpro.2016.05.217
[10] HOLGUIN-VERAS, J., LEA, J. A., SANCHEZ-DIAZ, I., BROWNE, M., WOJTOWICZ, J. State of the art and practice of urban freight management: Part I: Infrastructure, vehicle-related, and traffic operations. *Transportation Research Part A: Policy and Practice* [online]. 2018. ISSN 0965-8564, eISSN 1879-2375. Available from: https://doi.org/10.1016/j.tra.2018.10.037
[11] KELLNER, F., OTTO, A., BRABANDER, C., Bringing infrastructure into pricing in road freight transportation - a measuring concept based on navigation service data. *Transportation Research Procedia* [online]. 2017, **25**, p. 794-805. ISSN 2352-1465. Available from: https://doi.org/10.1016/j.trpro.2017.05.458
[12] KHALED, A. A., MINGZHOU, J., CLARKE, D. B., HOQUE, M. A. Train design and routing optimization for evaluating criticality of freight railroad infrastructures. *Transportation Research Part B: Methodological* [online]. 2015, **71**, p. 71-84. ISSN 0191-2615. Available from: https://doi.org/10.1016/j.trb.2014.10.002
[13] WIEGMANS, B., CHAMPAGNE-GELINAS, A., DUCHESNE, S., SLACK, B., WITTE, P. Rail and road freight transport network efficiency of Canada, member states of the EU, and the USA. *Research in Transportation Business & Management* [online]. 2018, 28, p. 54-65. Available from: https://doi.org/10.1016/j.rtbm.2018.10.004
[14] GAVRIILIDIS, K., KAMBOUROUDIS, D. S., TSAKOU, K., TSOUKNIDIS, D. A. Volatility forecasting across tanker freight rates: the role of oil price shocks. *Transportation Research Part E: Logistics and Transportation Review* [online]. 2018, **118**, p. 376-391. ISSN 1366-5545. Available from: https://doi.org/10.1016/j.tre.2018.08.012
[15] LI T., XUE, L., CHEN, Y., CHEN, F., MIAO, Y., SHAO, X., ZHANGE, CH. Insights from multifractality analysis of tanker freight market volatility with common external factor of crude oil price. *Physica A: Statistical Mechanics and its Applications* [online]. 2018, **505**, p. 374-384. ISSN 0378-4371. Available from: https://doi.org/10.1016/j.physa.2018.02.107
[16] Statistical Pocketbook from 2005 to 2016 - European commission [online]. Available from: https://ec.europa.eu/transport/
[17] Keystat from 2005 to 2016 - ITF [online]. Available from: https://www.itf-oecd.org/key-transport-statistics
[18] Oil price data - U. S. Energy Information Administration [online]. Available from: https://www.eia.gov/
[19] KANG, W., PEREZ DE GRACIA, F., RATTI, R., The asymmetric response of gasoline price to oil price shocks and policy uncertainty. *Energy Economics* [online]. 2018, **77**, p. 66-79. ISSN 0140-9883, eISSN 1873-6181. Available from: https://doi.org/10.1016/j.eneco.2018.09.007

Grzegorz Dydkowski - Jozef Gnap

PREMISES AND LIMITATIONS OF FREE PUBLIC TRANSPORT IMPLEMENTATION

For many years issues of the free provision of transport services, including urban public transport, were outside the main trends of transport economics considerations. However, nowadays, the discussion is ongoing related to usefulness and limitations of the free urban public transport implementation. Protection of the city environment, reduction of personal cars traffic, and increased accessibility and mobility in cities are given as premises for such solution introduction. However, assessments of introduced solutions may not necessarily confirm the assumptions made. Financial problems and those in provision of services - characteristic of goods and services provided for free - add to that. The paper has undertaken the issue related to premises and limitations related to introduction of the fare free urban public transport in regard to the pursuit of effectiveness in the public management.

Keywords: *public transport, free provision, public funds, effectiveness, mobility, policy*

1 Introduction

In the media, and in professional publications as well, a discussion has been carried out for a few years related to the usefulness and limitations of the free collective public transport implementation. Examples are provided, usually of small cities, which introduced such solutions and benefits, which they plan to achieve due to that. Services of urban collective public transport are free already for many years for selected social groups, these are primarily children (frequently up to 4 years of age), disabled and elderly persons (at the age of more than 70 years). In addition, e.g. councillors, members of parliament, volunteer blood donors, and job seekers are entitled to free rides. A part of entitlements is established by cities, hence the solutions are not uniform. Discussions are related to what extent it would be favourable and justified to give entitlements to all Also residents using the urban public transport in a specific city.

When making a decision on that it is necessary to consider that implementation of a free collective public transport system means reduction of funds inflowing to the urban public transport system. Albeit the ticket revenues cover only a part of costs, for example for five urbanised centres of Poland the ticket revenue consisted in 2017 only 33.7% of total expenditure and 36.4% of transport expenditure - based on example of five chosen urbanised centres in Poland, i.e. Warsaw, cities of the central part of Silesian Voivodeship, Poznan, Gdansk, and Szczecin [1], but in nominal terms the obtained funds are not small. At the same time it is difficult to withdraw from such decision, introduction of the free transport is most often a solution for many years.

Obviously the introduction of the free travelling has many supporters, they refer to protection of the city environment, reduction of personal cars traffic in favour of urban public transport; also most generally free availability of goods and services is by nature acceptable, because people do not notice that such services are at a cost, but they do not pay for them directly and that becomes most important for many of them. Because one assigns an entirely different weight to spending own funds - in a thrifty way, but much less to spending the public money. Although such funds originate from taxes, but at the moment of collection they lose their specific owner - obviously this is the public sector - but, as it is shown by many real life examples, the public sector manages resources in a less effective way than the private sector [2-3]. It is also possible to compare economies with state/public ownership of means of production with market economies.

So far, the free urban transport services were not the subject of consideration within the public sector economics [4]. The issues of free provision of transport services for many years were not included in the main area of economic transport problems considerations in Poland - hence there are not many results of studies here. In recent years the issues of urban collective public transport tariffs, in the context of free travelling, are more and more extensively undertaken in the literature on the transport economics. The situation abroad was similar - now it is possible to mention a few dozen valuable papers from the field of „free fare public transport" within recent more than ten years

Grzegorz Dydkowski[1,*], Jozef Gnap[2,*]
[1]Department of Transport, University of Economics in Katowice, Poland and Metropolitan Transport Authority in Katowice (ZTM in Katowice), Poland
[2]Department of Road and Urban Transport, Faculty of Operation and Economics of Transport and Communications, University of Zilina, Slovakia
*E-mail of corresponding author: grzegorz.dydkowski@ue.katowice.pl, jozef.gnap@fpedas.uniza.sk

(See Google Scholar having entered the „free fare public transport" phrase).

This paper raises the issue related to premises and limitations related to introduction of a free urban public transport system; this is a view from the economy point of view and from the perspective of searching for effectiveness in the public management and in public funds spending.

2 Premises for public financing of urban collective transport

Most generally, the beginning of gainful urban and regional passenger transport was at the end of the 19th and at the beginning of the 20th century. The urban transport in majority of cities was developing then as a private venture, services were financed by fares paid by passengers. At that time the service prices were regulated by the supply and demand and - as it is the case in such situations and acc. to assumptions - that was ensuring the optimum utilisation of resources. Users of urban public transport were paying fares, which were to cover the costs of used resources and to ensure funds necessary for development. The transport services were provided by private entities, based on general rules, or after obtaining relevant concessions from city authorities [5].

With the passage of time the importance of urban transport for efficient functioning of cities, activation of new districts and hence their development and the city areas growth became to be noticed. So public authorities started to interfere in the urban collective transport services. As a result, the taking over by cities of the ownership (via buying out shares or concessions) of urban collective transport entities was observed, implementation of investment projects by cities, in particular in the field of transport infrastructure, as well as gradual participation in financing the public transport activities.

Development of individual motorisation was a significant factor resulting in the necessity to support urban collective public transport. An increasing number of cars, in particular from mid-20th century in Western European countries, for the urban public transport meant a decline in the passengers number and this next resulted in decreased ticket revenues, which over time could not cover the costs of service provision. Hence the necessity to support urban public transport to maintain the volume of transport by public means of transport. Prices of urban public transport services systematically were becoming one of basic instruments to carry out the transport policy in a given area. Over time, the prices of urban public transport became also instruments to pursue the social policy, to promote employment and to protect health.

Processes similar to those in Western Europe states in the 1950s and 1960s were proceeding later on in countries of the former Eastern bloc. In Poland by the end of 1960s the revenues from tickets were still generally covering the cost of public transport services provision. However, the growth of individual motorisation, which started in the 1970s, was systematically causing a growing share of travelling by cars and decreasing movements by the public transport. The necessity to increase the public transport competitiveness against movements by personal cars becomes significant, too [6-7].

In the situation of public financing there is redistribution of funds between users themselves (travelling based on short- and long-term tickets), between various social groups in the municipality, between municipalities (cross-financing between municipalities in a common public transport system). In this context questions are raised with respect to the level of public financing; the subsidy may be small, e.g. of a dozen or so percent, but it can reach as much as 70-80% of a specific service, like it is now the case in many cities. The higher the public financing, the greater the funds redistribution and the higher burden on public budgets. Moreover, for the entity providing a transport service in practice also the employer changes. In the situation of very high public financing it is the public entity that is, so to speak, the employer and it determines the expectations; in an opposite situation, where the small public financing is assumed, passengers using the services and via fares financing those services provision are the employer.

3 Is the introduction of free urban public transport justified?

The discussion and consideration on the free public transport is not something new, only the motives or conditions change, under which this solution implementation is possible. In the past, in socialist states, the free access to many goods or services was perceived as a high stage of the then society development, but this solution was never implemented on a massive scale. Now, attention is drawn to availability of the public transport and its substitution with respect to individual motorisation.

At e introduction of the free public transport benefits are sought in the growing number of rides by the public transport, parallel to giving up individual motorisation. A premise for such statement is the assumption that if some good is provided for free, then the consumption can substantially grow, because people do not need to pay for it. The analysis to what extent introduction of the free public transport results in a change of transport behaviour was carried out by R. Tomanek [8, based on: 9-14]. Declarations related to giving up a personal car at the introduction of free public transport are rather cautious, but also dependent on a number of factors, including the final ticket prices, relationship of the car usage costs, the existing division of transport tasks. It is possible to assume that in Polish cities the number of actual new users will not exceed a level of 13% [8], where also in this case the caution should be exercised, considering a car-oriented culture of mobility in Poland. Hence under conditions of widespread motorisation, availability and comfort of cars use, no increase of a dozen or a few dozen percent in

Table 1 *Hierarchy of transport postulates among passengers of the Upper-Silesian Industrial Region. Source: [17]*

Parameter	Total number of points	Parameter	Total number of points
Punctuality	8.24	Travel time	7.60
Security	8.24	Convenience of traveling	7.44
Directness of connection	8.12	External marking of vehicles	7.21
Reliability	7.74	Passenger information	6.81
Availability of the bus network	7.73	Ticket price	6.57
Frequency of running	7.66	Functionality and aesthetics of stops	6.26
Cleanliness of vehicles	7.61	Efficiency of an e-ticket validator	5.87

Table 2 *Attractiveness of free public transport in everyday trip to work. Source: [11]*

Willingnes to switch	Overall (%)	Company car (%)	Private car (%)
Yes, certainly	9	7	10
Maybe	39	30	42
No, certainly not	52	63	48

travelling by the public transport will occur as a result of prices lowering.

Implementation of the fare free urban public transport is to result significantly in a reduced use of cars in the city. That is the objective set by politicians in local governments of cities. However, local politicians in the councillors, office administration and organiser system do not acknowledge the fact that cars are purchased for the purpose that household members would have a better comfort of moving within the city area than that offered by the substitutive urban public transport. The effectiveness of expected benefits from a free urban public transport is low - the car traffic went down by approx. 5%. Local politicians and their households are the best example in cities with free urban public transport. They still travel by cars, like employees of operators, having free tickets [15].

As the most surveys of transport preferences of big city residents show that the most important transport postulates formulated by them apply to the transport offer, namely direct connections, punctuality, frequency, and accessibility. The expectation of a low cost is for respondents most often a postulate of medium or low importance (Table 1). The results of questionnaire surveys, carried out within the area of Municipal Transport Union of the Upper-Silesian Industrial Region, for the needs of formulating the assumptions of Plan of Sustainable Public Transport Development and results of cyclically performed surveys of Gdynia residents transport preferences and behaviour could be considered an example [16-18].

In addition, the available results of transport preference surveys carried out in cities outside Poland show that the price is not the main factor affecting the choice of means of transport. The results of questionnaire survey of commuters to Brussels, carried out in 2005 by the staff of Vrije Universiteit Brussel can be used as an example. The survey was carried out on a sample of 1 276 respondents (526 car users, 740 railway passengers). The carried out survey shows that only 10% of surveyed persons commuting by an own car declared the willingness to use a free of charge public transport. Instead, 42% were respondents, who could not clearly declare such willingness and as many as 48% of surveyed persons were the people, who would certainly not change the means of transport (Table 2). The lack of appropriate connections and an insufficient travel speed were mentioned among the main barriers discouraging the surveyed persons to use the public transport in daily commuting [11, 16].

Another argument, presented in favour of the free public transport introduction, is elimination of the mobility exclusion. The free access to services means higher access for persons with low income, which is indisputable and difficult to challenge. However, one should consider whether introduction of the free transport would not limit development of this service sector due to reduction of funds by those originating so far from tickets (in big cities approx. 1/3 of funds). Obviously, the assumption is that funds assigned to the urban public transport should not be decreased, they should be supplemented with a subsidy and benefits obtained in other places, e.g. reduced expenditure on road repairs due to smaller car traffic, but the reality is frequently different from the assumptions made. The deficit in public budgets funds maintaining for years, the necessity to use aid funds and loans for investment projects cause that it is not possible to count on stable and high financing from public funds. Sooner or later, the free of charge public transport will result in an increase in taxes or in giving up other public tasks.

Attention should be also drawn to the fact that in systems of free services, i.e. services not financed directly by the users, but financed from funds available to public entities, hence in general originating from taxes and various charges, there are no mechanisms of flexible adaptation to expectations and - e.g. in the case of growing service volume, so for instance in the urban public transport - starting additional connections. This is widely experienced in the case of health care services, where there is a demand for specific types of medical services, but there are no possibilities to provide them, because there are no additional public funds that could be allocated to such services. At the same time there is no problem with such services if the user pays. Thus, it is possible to assume that a free urban public transport will result in just such behaviour, i.e. unprofitability or unwillingness to start additional connections, as it is the case of free goods, already mentioned medical services and health protection, but also care services, education or schools.

A low assessment of free goods is also a problem. Providers of goods or of free services know that they are provided free of charge and this decreases their motivation in general to raise and maintain a high quality of services and to develop. Because it is free, actually everybody should be happy that it is. In a similar way the users, at the moment of spending their funds, expect a service consistent with their preferences - also in terms of quality. They do not necessarily express such expectations in the case of free services, frequently a free service is like a social one, of poor quality, addressed just to those, who do not have funds to pay for it. Hence a problem originates, to what extent a fare free urban public transport will make it a poorer quality service and a service perceived as such.

Services of urban public transport are not basic needs, directly related to satisfying hunger, shelter, medical assistance in the case of accidents or illness. In the case of small distances a possibility to walk or to ride a bicycle is a substitute, which does not imply significant expenditure. Obviously, a possibility of changing the place, accessibility to various venues of activity or broadly understood mobility is important and affects the quality of life, however, the usage of urban public transport prices to implement various policies becomes widespread, not only those related to ensuring an efficient transport system.

In modern societies the issues of health protection (concessions for volunteer blood donors), promotion of employment (transport for unemployed), air protection (free transport on smog days), welfare and social functions (pensioners, persons 70+, disabled, children and youth, opposition activists, MPs and senators) are obviously important, but can all that be implemented by means of public transport prices? Is it just? Are the worst-off financed by reducing the prices? Each investment project, improving the living standard of residents, like a stadium, sports arena, swimming pool, kindergarten etc. also requires a capital expenditure, and the users of those investments pay e.g. for an entrance ticket. However, it is very weird that travelling to those services in certain cities is to be for free. There is no such attitude in very wealthy cities worldwide [15]. Free certain municipal services, such as urban public transport, water or electricity consumption, or the use of apartments, are provided in Cuba, Belarus, Venezuela, Turkmenistan, and Tajikistan. Each municipal service for free or paid by a lump sum in those states results in devastation of municipal assets, and - what is the worst - the lack of respect for reasonable consumption of those goods-services [15].

Another motive, raised and supposed to support implementation of free travelling by the urban public transport, is elimination of the transaction costs (cost of sales). However, attention should be drawn to the fact that the ticket sales and inspection systems do not create such a significant cost to decide about introducing a free of charge transport. In general, the tickets inspection itself and financial recovery is financed from the obtained revenue resulting from the imposed additional charges for travelling without a valid ticket. An argument for introduction of the fare free urban public transport, popping up among politicians, is - what can be surprising - an excessive amount of subsidies from the local government budget as against the revenues obtained from tickets sold. The justification is 'very simple' - if subsidies are approx. 80% of total revenues and the funds from tickets sale only 20%, it is better to give up the tickets distribution (very costly tickets distribution systems have been constructed on a scale not existing in Europe), the tickets inspection and shift to the fare free urban public transport. After all, it is possible to keep the city budget expenditure on public transport on the hitherto level and perhaps even reduce it, through the reduction of expenditures of the entities providing the transport services [15].

Taking into account the quoted results of research, it should be stated that the price is not a basic factor, which will ensure a change of method of movement and hence giving up a car in favour of using the public transport services. Changes in the transport tasks division may be evaluated as a few or a dozen or so percent, but it is necessary to consider the necessity of resolving the problems of financing the current activity and development, as well as the problems accompanying the situation, where goods and services are provided for free.

4 Practical dimension of free travelling

In theory, but also in practice, a problem originates to what extent, via public transport prices, functions other than an efficient public transport should be fulfilled. In the price management on a current basis it is possible to encounter applications of various social groups to grant appropriate entitlements to free and concessionary travelling by the public transport and hence to widen the catalogue of hitherto entitlements [19]. Each such application has its social dimension - for the applicants it means appreciation by the public authority of carried out in the past or now activity important for the society, recognition and respect and at the same time some aid having a financial dimension, after all, in the form of reduced expenditure on the public transport. At the same time for public authorities and public transport managers the widening of groups entitled to free or concessionary travelling means a necessity to assign higher funds from the municipality budget on transport financing or to cut costs of urban public transport operations e.g. by reduction of the transport offer. Already now in the urban public transport, for example organised in the central part of the Silesian Voivodeship, more than a half of travellers enjoy entitlements to free or concessionary travelling, in addition the prices of season tickets are calculated much below the price, which would result from the number of rides carried out in a given period. As a result, an average payment for one ride is significantly - even three times lower - than the price of a single-travel ticket. Granting entitlements to free or concessionary travelling for the next social groups, at already a significant share of persons holding such entitlements, results frequently in inflating prices of normal tickets, including single-travel tickets. This results in deterioration of price competitiveness of the public transport and ultimately may be one of reasons to give up services of passenger public transport by passengers, who are not entitled to concessionary travels and who use such services occasionally. This additionally increases the deficit of urban public transport services - calculated as the ticket revenue minus costs of services provision.

Prices of urban public transport services are set by municipal local governments. In addition, they are authorised, as it has been previously stated, to determine groups of persons entitled to free and concessionary rides, or to introduce special prices or free rides, for example in relation to the carried out mobility policy or to reduction of the negative effects of transport in the city. The location of powers in the field of local public transport tariff/prices on municipal local government level caused that both prices, and to some extent, groups of persons entitled to concessionary rides, differ between cities. If, for example, the entitlement to concessionary (50%) rides for children, youth, and pensioners, or free travelling for persons 70+ does not raise observations and exists widely in Poland, then there are groups, with respect to which various opinions exist, whether they should also be entitled to concessionary or free rides by the urban public transport. In general, this is related to the question, to what extent prices of urban public transport should be used to accomplish policy goals of e.g. health care, unemployment prevention, pro-family policy support, or promotion of education. What is the effectiveness in this case and whether other instruments should be used, for instance providing direct support to persons, who need it.

When considering the system of the fare free transport it is necessary to take into account that the service by the public transport is carried out by municipal public transport systems - first of all bus and tram transport systems (in certain cities also trolleybuses, water trams, and metro in Warsaw) and also by railway carriers. Such systems in big cities and in conurbations operate within a common area, but in Poland there are separate systems of price setting and groups of persons entitled to concessionary and free rides. In addition, the sources and rules of public financing differ - municipality budgets or Voivodeship budgets and the state budget in the case of railway transport. That means that the policy of ticket prices as well as of solutions implementation in the field of concessionary and free rides are not always consistent. Urban systems feature a wider range of persons entitled to concessionary and free rides. The introduction of fare free transport in cities or for specific groups of persons, e.g. children and youth, is related primarily to urban systems. As a result, the modal shifts occur - passengers can use fare free public transport except for rail transport, hence in relations, which are served by both rail and bus/tram transport, it is more favourable to use buses and trams in general. This is not good, because shifts in the transport work occur inconsistently with objectives formulated in transport policies. So disproportions in concessions existing in urban public transport systems and in urban and regional railway transport should be eliminated by the introduction of a consistent and uniform system of concessions and free rides in the urban transport and in the railway transport [20-21].

5 Summary

A fare free urban public transport seems as an attractive solution - its introduction allows to obtain a positive assessment and to win passengers favour, it integrates with a general policy of sustainable development of urban transport systems, with increased availability of urban services and actions aimed at residents; mobility improvement. However, the analysis of carried out surveys of residents' transport preferences and behaviour, as well as assessments made in cities, which implemented the fare free public transport services, result in a less positive assessment of this solution. Shifts in the transport work division from individual transport to the public transport are not big and the lack of revenue from sales means that the funds feeding the transport entities will be reduced or the public expenditure will grow. The next issues seem to be postponed in time, will be related to difficulties with ensuring a bigger transport offer and development and introduction of new innovative solutions in this sector. For example, switching to vehicles with lower emission, including electric buses, will be related to significant expenditure on the vehicles and infrastructure, as well as costs will originate related to lower usage of those vehicles - due to the time necessary to charge batteries. Irrespective of that also effects characteristic of goods and services provided for free are likely.

The depriving of revenue on the sales of services may be also related to difficulties in the current financing of urban public transport services. Transport features high energy consumption, materials consumption and a significant share of human factor related costs in the total cost. It is difficult to achieve a growth of productivity, just opposite, the congestion of cities and regulations applicable to drivers working time result in its decrease. Also the labour costs increase as well as burdens incurred in relation to that. In the future it is difficult to assume a decline in fuel or electricity prices, their significant increase should be rather expected. As a result, the growing costs of transport services should be considered and this in turn will require ensuring appropriate financing. A component of media, solutions, widespread approval for solutions implementation is visible in the urban public transport, resulting in lowered charges or introduction of free services, unfortunately these are not necessarily solutions, which ensure city effectiveness, competitiveness and development in a longer time horizon.

References

[1] Urban transport in figures. Data for 12 months of 2017 (in Polish) [online]. Warszawa, 2018. Avaliable from: https://www.igkm.pl/

[2] FREEDMAN, M. I R. Free to choose (in Polish). Sosnowiec: Wydawnictwo Aspekt, 2009. ISBN 978-83-922697-6-2.

[3] SAVAS, E. S. *Privatisation. Key for better management* (in Polish). Warszawa: Polskie Wydawnictwo Ekonomiczne, 1992.

[4] KAMERSCHEN, D. R, MCKENZIE, R. B., NARDINELLI, C.: *Economy* (in Polish). Gdansk: Fundacja Gospodarcza NSZZ Solidarnosc, 1999.

[5] DYDKOWSKI, G. *Urban transport integration* (in Polish). Katowice: Wydawnictwo Uniwersytetu Ekonomicznego w Katowicach, 2009. ISBN 978-83-7246-452-1.

[6] TOMANEK, R. *Competitiveness of urban transport* (in Polish). Katowice: Wydawnictwo Akademii Ekonomicznej, 2002.

[7] URBANEK, A. Car-oriented mobility culture from the point of view of Polish households' expenditures. In: SUCHANEK, M. (ed) *New research trends in transport sustainability and innovation*. *TranSopot 2017 Conference* [online]. Springer International Publishing, 2018. eISBN 978-3-319-74461-2. Avaliable from: https://doi.org/10.1007/978-3-319-74461-2

[8] TOMANEK, R. Effectiveness of free of charge public transport in cities (in Polish). *Komunikacja publiczna / Public Transport*. 2017, **69**(4), p. 18-25. ISSN 1429-5788, eISSN 2543-6570.

[9] BOUSSAUW, K., VANOUTRIVE, T. Transport policy in Belgium: translating sustainability discourses into unsustainable out - comes. *Transport Policy* [online]. 2017, **53**, p. 11-19. ISSN 0967-070X, eISSN 1879-310X. Avaliable from: https://doi.org/10.1016/j.tranpol.2016.08.009

[10] VOLINSKI, J. *Implementation and outcomes of fare - free transit systems. A synthesis of transit practice* [online]. Washington, D. C.: Transportation Research Board, 2012. ISSN 1073-4880, ISBN 978-0-309-22361-4. Avaliable from: https://doi.org/10.17226/22753

[11] WITTE, A., MACHARIS, C., MAIRESSE, O. How persuasive is 'free' public transport? A survey among commuters in the Brussels Capital Region. *Transport Policy* [online]. 2008, **15**(4), p. 216-224. ISSN 0967-070X, eISSN 1879-310X. Avaliable from: https://doi.org/10.1016/j.tranpol.2008.05.004

[12] MOSES, L. N., WILLIAMSON JR, H. F. Value of time, choice of mode, and the subsidy issue in urban transportation. *Journal of Political Economy* [online]. 1963, **71**(3), p. 247-264. ISSN 0022-3808, eISSN 1537-534X. Available from: https://doi.org/10.1086/258769

[13] CANTERS, R. Hasselt cancels free public transport after 16 years (Belgium) - Eltis [online]. 2014. [Viewed 2017-07-10]. Avaliable from: http://www.eltis.org/di-scover/news/hasselt-cancels-free-public-transport-after-16-years-belgium-0

[14] CATS, O., SUSILO, Y. O., REMAIL, T. The prospects of fare-free public transport: evidence from Tallinn. *Transportation* [online]. 2017, **44**(5), p. 1083-1104. ISSN 0049-4488, eISSN 1572-9435. Avaliable from: https://doi.org/10.1007/s11116-016-9695-5

[15] BAKOWSKI, W. Passive attitude of local politicians in the economic approach to the regulation of residents´ movements within an urban area (in Polish). *Komunikacja publiczna / Public Transport*. 2018, **71**(2), p. 34-37. ISSN 1429-5788, eISSN 2543-6570.

[16] URBANEK, A. Will a free of charge urban transport convince passengers to give up personal cars? (in Polish). *Komunikacja publiczna / Public Transport*. 2017, **69**(2), p. 30-35. ISSN 1429-5788, eISSN 2543-6570.

[17] Analysis of results of questionnaire survey carried out within the KZK GOP area (in Polish). Referat Badan i Rozwoju KZK GOP. Katowice, 2012.

[18] Report on 2015 marketing survey (in Polish). Zarzad Komunikacji Miejskiej w Gdyni. Gdynia, 2016.

[19] DYDKOWSKI, G., TOMANEK, R., URBANEK, A. *Tariffs and fare collection systems in the urban public transport* (in Polish). Katowice: Wydawnictwo Uniwersytetu Ekonomicznego w Katowicach, 2018. ISBN 978-83-7875-441-1.

[20] GNAP, J., KONECNY, V., POLIAK, M.: Demand elasticity of public. *Ekonomicky casopis / Journal of Economics*. 2006, **54**(7), p. 668-684. ISSN 0013-3035.

[21] POLIAK, M., MRNIKOVA, M., JASKIEWICZ, M., JURECKU, R., KACIAKOVA, B. Public transport integration. *Communications - Scientific Letters of the University of Zilina* [online]. 2017, **19**(2), p. 127- 132. ISSN 1335-4205, eISSN 2585-7878. Avaliable from: http://komunikacie.uniza.sk/index.php/communications/article/view/196

Kamil Krasuski - Artur Gos

THE NUMERICAL SIMULATION OF THE ATMOSPHERE DELAYS IMPACT ON RADAR MEASUREMENT IN AVIATION

The article presents numerical simulations with regard to determining the impact of the ionospheric and tropospheric delays on a radar-aircraft slant distance measurement. During the first experimental test, numerical calculations were made, showing the relationship between the ionosphere correction and the zenith angle in order to determine the measurement error of a radar-aircraft slant distance. During the second experimental test, numerical calculations were made demonstrating a relationship between the tropospheric correction and zenith angle in order to determine a measurement error of a radar-aircraft slant distance. The experimental test was conducted for the primary surveillance radar AVIA-W located on the grounds of the military aerodrome EPDE in Deblin. Based on the conducted research tests, it was found that the impact of the ionosphere delay can cause an error in a radar measurement above 4 m. Moreover, influence of the troposphere delay can cause an error of a radar measurement by approximately 0.2 m. The numerical simulation made in this research study may be used in the radiolocation of moving objects, as well as the GNSS satellite navigation in aviation.

Keywords: *radar, troposphere delay, ionosphere delay, aircraft*

1 Introduction

Radar as an air traffic control system is one of the most important navigation devices. It provides a safe, orderly and expeditious flow of air traffic. For this purpose, two types of radars are used: primary surveillance radar (PSR) and secondary surveillance radar (SSR). The primary surveillance radar provides a graphic representation of the aircraft location, displaying the azimuth and distance of the aircraft in relation to the radar antenna to be used by the air traffic controller. Additionally, through use of the secondary surveillance radar, the following information can be displayed: flight altitude, identification, speed of the aircraft, and many other data. The primary surveillance radar can operate as the Air Traffic Control (ATC) Radar or as the en-route radar. The Air Traffic Control Radar is designed as a short range radar (operating within 120 km), working in the vicinity of one or more aerodromes. It is used to provide an efficient performance of air traffic services in the terminal manoeuvring area (TMA). The en-route radar can also aid an instrumental approach to landing (ILS, NDB, TACAN, VOR). In the case of exploiting an en-route radar to control an area, the radar‘s range must be much larger (above 200 km). The en-route radar provides information about the position of the aircraft and the progress of its flight from a large area. An increase in the size of surveillance is at the cost of impaired accuracy [1].

The main role of a radar operation is to determine the position of an aircraft as a function of a slant distance and azimuth. The measurement of slant distance to the aircraft is heavily affected by the atmosphere factor in the form of the ionospheric and tropospheric delay. Ionosphere is a dispersive medium [2], which translates into the relationship between the speed of a carrier wave and a radar frequency operation. For this reason, the ionospheric delay shortens the radar-aircraft slant distance [3]. Moreover, the ionosphere delay exerts a direct impact on determination of the aircraft coordinates in the horizontal plane. On the other hand, troposphere is a neutral medium [4], so the speed of a carrier wave does not depend upon the frequency of the radar operation. The parameter of the tropospheric delay causes scaling (also reducing) [5] of a radar-aircraft slant distance. An atmospheric disturbance is therefore an extremely important aspect in radar measurements.

The aim of this article is to present a relationship, as well as conducting simulation tests, with regard to impact of the atmospheric delays for designation of a radar-aircraft slant distance. The paper proposes a numerical solution to determine the effect of the atmosphere upon a radar measurement, taking into account the ionosphere and troposphere corrections. The proposed algorithms for the conducted computer simulations facilitate a better understanding of impact of the atmosphere upon the operation of the primary surveillance radar within the microwave band. The article is divided into five parts. At the end, it is supplemented with a list of scientific references.

2 Mathematical model

The study uses two basic models determining the relationship between the atmospheric delay and the

Kamil Krasuski*, Artur Gos
Department of Air Navigation, Faculty of Aviation and Aeronautics, Polish Air Force University, Deblin, Poland
*E-mail of corresponding author: k.krasuski@law.mil.pl

Figure 1 *Location of the AVIA-W radar at Deblin aerodrome [8]*

accuracy of the designation of a radar measurement. In the first place, the relationship between the ionospheric delay and the radar-aircraft slant distance is shown. The mathematical relationship has been presented in Equation (1), as below [6]:

$$\frac{dl}{L} = \frac{Cx}{2} \cdot \frac{VTEC}{R \cdot \cos z} \cdot \frac{1}{f^2}, \tag{1}$$

where:

dl - absolute error of a slant distance radar-aircraft for ionosphere delay,

L - slant distance radar-aircraft,

$$\frac{Cx}{2} = 40.3 \cdot 10^{16} \ \frac{m}{TECU \cdot s^2},$$

VTEC - Vertical TEC,

R - Earth radius, $R = 6371\ km$,

z - maximum of zenith angle,

f - frequency of radar microwave,

f = 1300-1400 *MHz*.

Influence of the ionospheric delay to designate the radar aircraft slant distance is determined as a function of VTEC ionospheric delay, Earth radius, zenith angle, and the radar frequency carrier wave.

In the second place, the authors designated the effect of the tropospheric delay to determine the radar aircraft slant distance. The mathematical relationship is presented in Equation (2), as below [6]:

$$\frac{db}{L} = \frac{dTrop}{R} \cdot \frac{1}{\cos z}, \tag{2}$$

where:

db - absolute error of slant distance radar-aircraft for the troposphere delay,

dTrop - absolute error of the troposphere delay.

Influence of the tropospheric delay to designate the radar aircraft slant distance is determined as a function of *dTrop* absolute error of troposphere delay, Earth radius, and zenith angle.

Equations (1) and (2) are used in computer simulations and calculations to estimate the impact of the atmospheric delay on the determination of the radar-aircraft slant distance.

3 Research test

In the framework of the experimental test, a number of computer simulations were made with regard to impact of atmospheric delays on radar measurements. The numerical calculations were performed for the localization of the primary surveillance radar AVIA-W [7], mounted on the grounds of the military aerodrome EPDE in Deblin (see Figure 1) [8]. The basic technical specifications of the AVIA-W radar, localized at the military aerodrome EPDE in Deblin, are presented below [7, 9]:

- Radar maximum range 100 km,
- Maximum height range capability: 10 km,
- Accuracy of distance measurement: does not exceed 350 m,
- Accuracy of azimuth measurement: does not exceed 1°,
- Coverage for elevation angle: not more than 45°,
- Azimuth bandwidth: 1.3°,

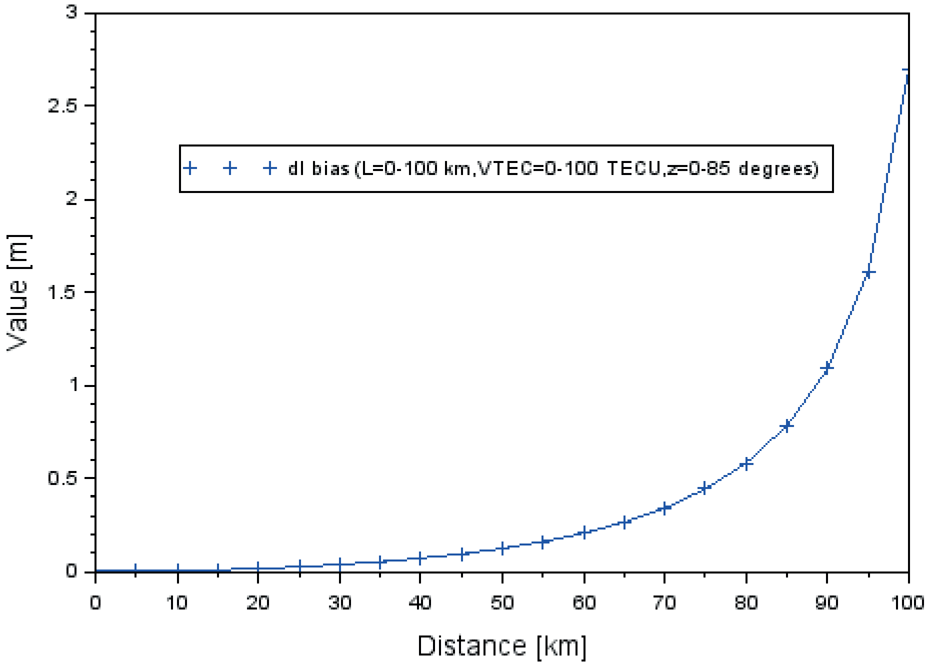


Figure 2 *Impact of the ionospheric delay in a radar measurement (case 1: L=0÷100km, VTEC=0÷100 TECU, z=0÷85⁰)*

- Radar's operating frequency band: L,
- Operating frequency of primary surveillance radar receivers: 1310 ± 5 MHz (channel A), 1347 ± 5 MHz (channel B),
- Wavelength: 23 cm,
- Average repetition rate: 939 pps,
- Number of pulses per one revolution of antenna: 6,432 pulses/revolution,
- UWB high peak power pulse: 0.45 MW (channel A), 0.5 MW (channel B),
- UWB pulse width: 1.25 µs (channel A), 1.35 µs (channel B),
- Coefficient of noises of main waveguide system: 5.5 dB,
- Coefficient of noises of auxiliary waveguide system: 8 dB,
- Correct system operation at wind speeds of up to 30 m/s,
- Strength of antenna system at wind speeds of up to 50 m/s,
- Dimensions of antenna reflector: 12 x 4 m,
- Antenna rotation speed: 10 or 15 rev/min ± 10% (depending on the operating mode),
- Power consumption: 65 kW.

The AVIA-W in Deblin is equipped with the two transmit-receive channels, ensuring a high degree of reliability, contrary to one channel operation. It is also possible to use a frequency-diversity receiver. The system also has the adjustable polarity, thus it is capable of suppressing harmful reflections from the storm clouds and clear air turbulence (referred to as angels). Moreover, AVIA-W facilitates a remote control of the equipment, thus the transmit-receive part of its operation is possible without the necessity to keep a constant watch at the place of its installation. The radar is equipped by a digital compensation system of passive interference (constant echo suppression). In the past, the signals originally developed by the station were displayed on analogue indicators. Currently, the AVIA-W in Deblin was equipped by a device TU-20L of imaging and data processing, which made the imaging displayed on digital indicators [7, 9].

The basic technical parameters of AVIA-W radar were applied in numerical simulation in research test. In addition, the value of parameter such as a radar maximum range, operating frequency of primary surveillance radar receivers and maximum height range capability were included in computations. Based on this, the numerical simulation was executed in a specialist software. The numerical simulation was done in the software Scilab v6.0.0 [10], being part of Windows 64. In the course of the conducted numerical tests for the determination of the impact of the ionospheric delay in radar measurements, the following initial values of the parameters from equation (1) were adopted:

- the value L changes from 0 km to 100 km,
- the value $VTEC$ changes from 0 TECU to 100 TECU,
- Earth radius is equal to $R = 6371\ km$,
- the frequency f equals 1310 MHz,
- the maximum zenith angle changes from 0^0 to 85^0,
- zenith angle is calculated as follow [11]:

$$z = 90^\circ - el\,, \tag{3}$$

where:
el - elevation angle, $el = \arctan\left(\frac{h}{L}\right)$,
h - radar height range, h=10 km.

In the course of the conducted numerical tests for determination of the impact of the tropospheric delay

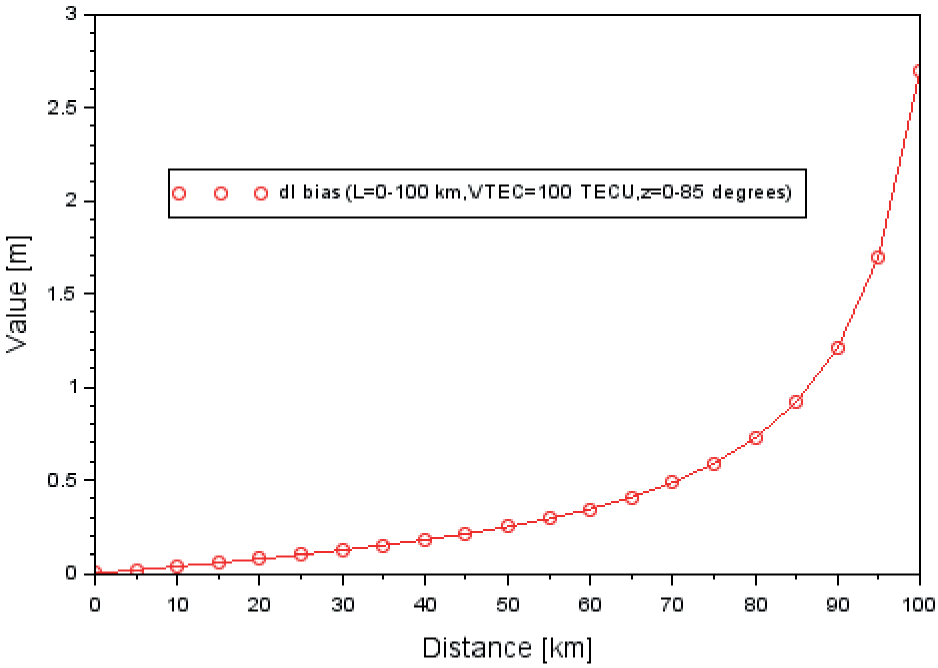


Figure 3 *Impact of the ionospheric delay in a radar measurement (case 2: L=0÷100 km, VTEC=100 TECU, z=0÷85^0)*

in radar measurements, the following initial values of parameters from equation (2) were adopted:

- the value *L* changes from 0 km to 100 km,
- the value *dTrop* changes from 0 m to 1 m,
- Earth radius is equal to *R* = 6371 *km*,
- the maximum zenith angle changes from 0^0 to 85^0.

4 Results and discussion

Within the conducted research, a number of computer simulations on the impact of atmospheric delays were made. The simulations were related to determining the radar-aircraft slant distance. Regarding the impact of the ionospheric delay in radar measurements, three numerical simulations were made, assuming the following initial conditions:

- Case 1: all parameters (*L*,*VTEC*,*z*) change,
- Case 2: the parameters (*L*,*z*) change, parameter *VTEC* is constant,
- Case 3: the parameters (*L*,*VTEC*) change, parameter *z* is constant.
- Regarding the impact of the troposphere delay in radar measurements, three numerical simulations were made, assuming the following initial conditions:
- Case 1: all parameters (*L*,*dTrop*,*z*) change,
- Case 2: the parameters (*L*,*z*) change, parameter *dTrop* is constant,
- Case 3: the parameters (*L*,*dTrop*) change, parameter *z* is constant.

Figure 2 shows a simulation of impact of the ionospheric delay, of the measured radar-aircraft slant distance, using different values of initial parameters. In accordance with Equation (1) in calculations was assumed that:

- the value *L* changes from 0 km to 100 km,
- the value *VTEC* changes from 0 TECU to 100 TECU.
- the maximum zenith angle changes from 0^0 to 85^0.

In the analyzed case, the radar-aircraft slant distance measurement varies from 0 m to 2.69 m. Values of the parameter *dl* are respectively equal to: under 0.02 m at a distance between an aircraft and an aerodrome of up to 20 km, under 0.04 m at a distance an aircraft and an aerodrome of up to 30 km, above 0.07 m at a distance between an aircraft and an aerodrome of up to 40 km, above 0.12 m at a distance between an aircraft and an aerodrome of up to 50 km, above 0.20 m at a distance between an aircraft and an aerodrome of up to 60 km, above 0.34 m at a distance between an aircraft and an aerodrome of up to 70 km, above 0.57 m at a distance between an aircraft and an aerodrome of up to 80 km, above 1.08 m at a distance between an aircraft and an aerodrome of up to 90 km, approximately 2.69 m at a distance between an aircraft and an aerodrome of up to 100 km. Therefore, it can be observed that impact of the ionospheric delay is quite significant in radar measurements at a distance between an aircraft and an aerodrome of above 90 km.

Figure 3 shows another simulation of impact of the ionosphere delay on the measured radar-aircraft slant distance, assuming that the ionosphere correction is constant in the calculations. In accordance with Equation (1) in calculations was assumed that

- the value *L* changes from 0 km to 100 km,
- the value *VTEC* equals 100 TECU.
- the maximum zenith angle changes from 0^0 to 85^0.

In this specific case, the measurement error of the radar-aircraft slant distance varies from 0 m to 2.69 m, respectively. Values of parameter *dl* are under 0.08 m at a distance between an aircraft and an aerodrome of up to 20 km, above 0.12 m at a distance between an aircraft and an aerodrome of up to 30 km, under 0.18 m at a distance

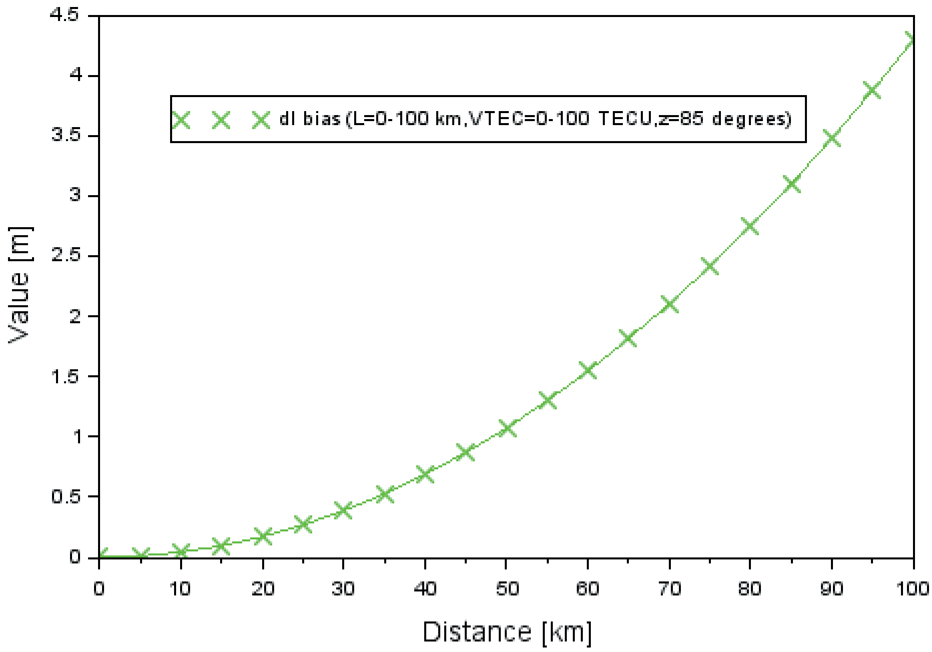


Figure 4 *Impact of the ionospheric delay in a radar measurement (case 3: L=0÷100km, VTEC=0÷100 TECU, z=85⁰)*

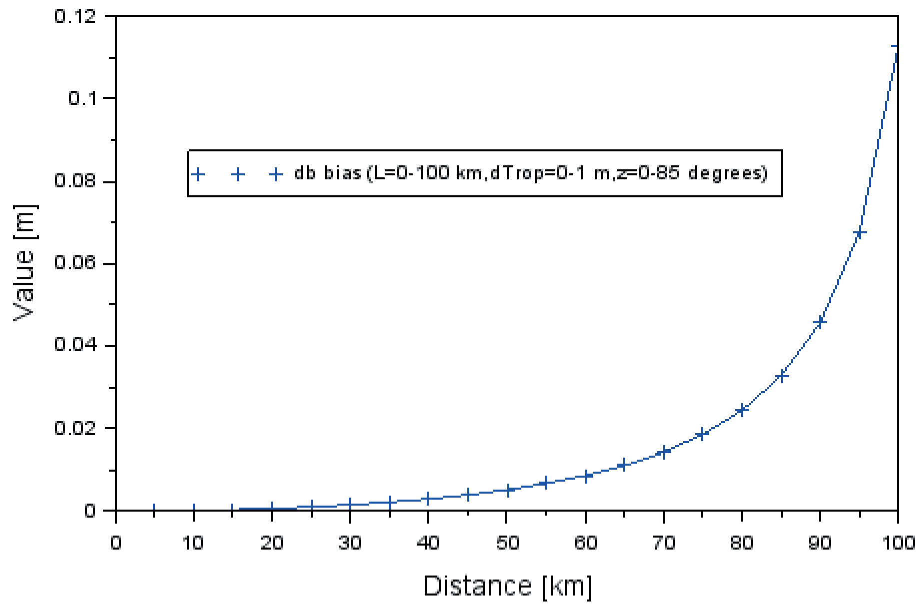


Figure 5 *Impact of the tropospheric delay in a radar measurement (case 1: L=0÷100km, dTrop=0÷1m, z=0÷85⁰)*

between an aircraft and an aerodrome of up to 40 km, below 0.25 m at a distance between an aircraft and an aerodrome of up to 50 km, above 0.34 m at a distance between an aircraft and an aerodrome of up to 60 km, above 0.48 m at a distance between an aircraft and an aerodrome of up to 70 km, above 0.72 m at a distance between an aircraft and an aerodrome of up to 80 km, above 1.20 m at a distance between an aircraft and an aerodrome of up to 90 km, approximately 2.69 m at a distance between an aircraft and an aerodrome of up to 100 km. Therefore, it can be observed that impact of the ionospheric delay is quite significant in radar measurements at a distance between an aircraft and an aerodrome of above 90 km.

Figure 4 shows another simulation illustrating impact of the ionospheric delay upon the measured radar-aircraft slant distance, assuming that the zenith angle is constant in the calculation. In accordance with Equation (1) in the calculations, it was assumed that

- the value L changes from 0 km to 100 km,
- the value $VTEC$ changes from 0 to 100 TECU.
- the maximum zenith angle equals 85^0.

In the analyzed case, the radar-aircraft slant distance measurement changes from 0 m to 4.29 m. Values of the parameter dl are as follows: over 0.04 m at a distance between an aircraft and an aerodrome of up to 10 km, above 0.17 m at a distance between an aircraft and aerodrome of up to 20 km, above 0.38 m at a distance between an aircraft

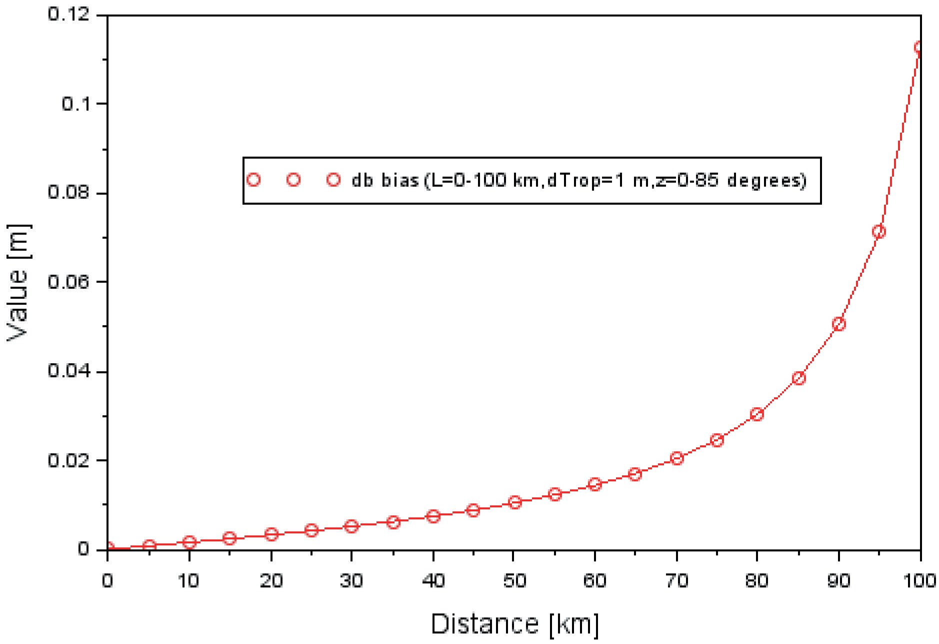


Figure 6 *Impact of tropospheric delay in a radar measurement (case 2: L=0÷100km, dTrop=1m, z=0÷85⁰)*

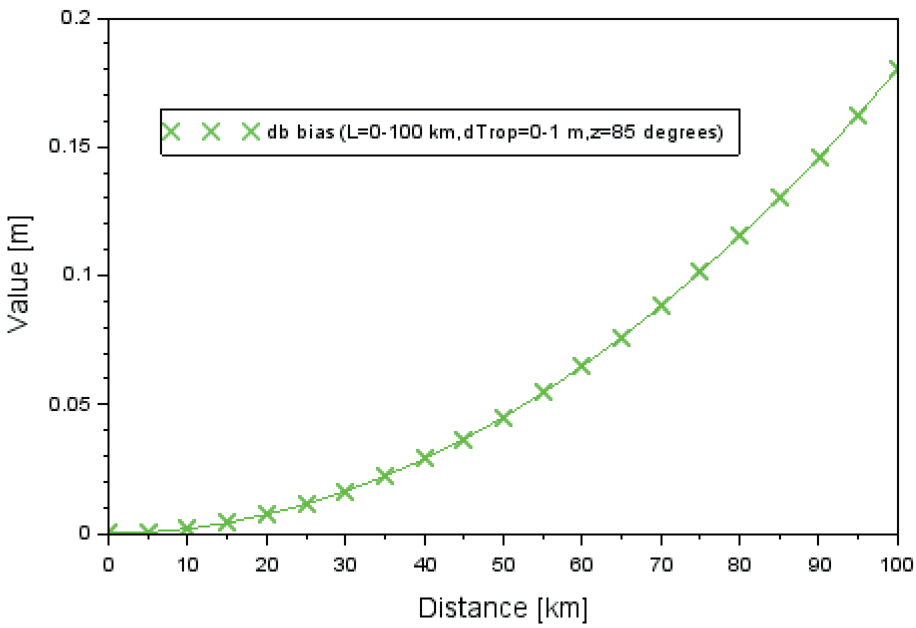


Figure 7 *Impact of the tropospheric delay in a radar measurement (case 3: L=0÷100km, dTrop=0÷1m, z=85⁰)*

and an aerodrome of up to 30 km, above 0.68 m at a distance between an aircraft and an aerodrome of up to 40 km, over 1.07 m at a distance between an aircraft and an aerodrome of up to 50 km, more than 1.54 m at a distance between an aircraft and an aerodrome of up to 60 km, more than 2.10 m at a distance between an aircraft and an aerodrome of up to 70 km, above 2.74 m at a distance between an aircraft and an aerodrome of up to 80 km, above 3.47 m at a distance between an aircraft and an aerodrome of up to 90 km, approximately 4.29 m at a distance between an aircraft and an aerodrome of up to 100 km. Based on the conducted simulations, it was found that the impact of the ionospheric delay is already quite significant from 50 km in a radar measurement, assuming that the zenith angle is constant.

Figure 5 shows a simulation of impact of the tropospheric delay of the measured radar-aircraft slant distance, using different values of the initial parameters. In accordance with Equation (2) in the calculations, it was assumed that

- the value L changes from 0 km to 100 km,
- the value $dTrop$ changes from 0 m to 1 m,
- the maximum zenith angle changes from 0^0 to 85^0.

In the analyzed case, the radar-aircraft slant distance measurement changes from 0 m to approximately 0.12 m. Values of the parameter db are less than 0.01 m at a distance between an aircraft and an aerodrome of up to 60 km, above 0.01 m at a distance between an aircraft and an aerodrome of up to 70 km, above 0.02 m at a distance between an aircraft and an aerodrome up to 80 km, less than 0.05 m at a distance between an aircraft and an aerodrome of up to 90 km, approximately 0.12 m at a distance between an aircraft and aerodrome of up to 100 km. Thus, it can be observed that impact of the tropospheric delay is quite small in radar measurements at a distance between an aircraft and an aerodrome ranging from 0 km to 100 km.

Figure 6 shows another simulation of impact of the troposphere delay on the measured radar-aircraft slant distance, assuming that the tropospheric correction is constant in the calculations. In accordance with Equation (2) in the calculations, it was assumed that

- the value L changes from 0 km to 100 km,
- the value $dTrop$ equals 1 m,
- the maximum zenith angle changes from 0^0 to 85^0.

In the analyzed case, the error of radar-aircraft slant distance measurement changes from the value 0 m to 0.11 m. Values of the parameter db are as follows: over 0.01 m at a distance between an aircraft and an aerodrome of up to 60 km, above 0.02 m at a distance between an aircraft and an aerodrome of up to 70 km, above 0.03 m at a distance of an aircraft and an aerodrome of up to 80 km, above 0.05 m at a distance between an aircraft and an aerodrome of up to 90 km, approximately 0.11 m at a distance between an aircraft and an aerodrome of up to 100 km. Thus, it can be observed that in the analyzed example, impact of the tropospheric delay is also quite small in radar measurements at a distance between an aircraft and an aerodrome ranging from 0 km to 100 km.

Figure 7 shows another simulation of impact of the troposphere delay upon the measured radar-aircraft slant distance, assuming that the zenith angle is constant in the calculations. In accordance with Equation (2) in calculations was assumed that:

- the value L changes from 0 km to 100 km,
- the value $dTrop$ changes from 0 m to 1 m,
- the maximum zenith angle is equal to 85^0.

In the analyzed case, the error of radar-aircraft slant distance measurement changes from the value 0 m to 0.18 m. Values of the parameter db are as follows: over 0.01 m at a distance between an aircraft and an aerodrome of up to 30 km, below 0.03 m at a distance between an aircraft and an aerodrome of up to 40 km, below 0.05 m at a distance between an aircraft and an aerodrome of up to 50 km, above 0.06 m at a distance between an aircraft and aerodrome of up 60 km, under 0.09 m at a distance between an aircraft and an aerodrome of up to 70 km, more than 0.11 m at a distance between an aircraft and an aerodrome of up to 80 km, below 0.15 m at a distance between an aircraft and an aerodrome of up to 90 km, 0.18 m at a distance of an aircraft and an aerodrome of up to 100 km. Based on this, it can be observed that in the considered example, the impact of the troposphere delay to determine radar-aircraft slant distance is the largest. However, this effect seems to be small in comparison to impact of the ionospheric delay in radar measurements.

5 Conclusions

The paper presents numerical simulations, which determine the effect of atmospheric delays in radar measurements in aviation. An experimental test was conducted for the primary surveillance radar AVIA-W located on the grounds of the military aerodrome EPDE in Deblin. All the computer simulations were performed for the basic radio-navigation parameters of the AVIA-W radar, taking into account the frequency of the carrier wave and the maximum radar range. The article presents findings of the numerical calculations of impact of the ionospheric and tropospheric delays upon the radar-aircraft slant distance measurement. In the case of the effect of the ionospheric delay upon radar-aircraft slant distance, the following were found:

- the impact of the ionopheric delay in radar measurements is clearly visible at a distance between an aircraft and an aerodrome of above 90 km,
- the ionospheric disturbance equal to 100 TECU is noticeable in radar measurements at a distance between an aircraft and an aerodrome exceeding 90 km,
- the influence of the zenith angle equal to 85^0 causes an error in a radar measurement of even more than 4 m.
- In the case of the tropospheric delay effect upon the slant distance radar aircraft, the following were found:
- the impact of the tropospheric delay in radar measurements is small, exceeding 0.10 m at a distance between an aircraft an aerodrome equal to 100 km,
- the impact of the tropospheric delay of 1 m is small in radar measurements, exceeding 0.10 m,
- the impact of the zenith angle equal to 85^0 causes a radar measurement error under 0.20 m.

Among many parameters applying in numerical simulation, the zenith angle is a crucial factor in computations. The zenith angle can be expressed as a function of a radar range distance and radar altitude range. If the radar altitude range will be changed then influence of atmosphere delay will be different. The theoretical research with radar altitude range can be carried out for AVIA-W radar only to elevation angle equaling to 45 degrees, e.g. for maximum altitude of 100 km. It should be noticed that altitude of 100 km is a lower layer of ionosphere zone in atmosphere. Moreover, if the ionosphere state of 100 km layer will be disturbed, then it will be visible in radar measurements, as well.

The obtained findings of computer simulations for the AVIA-W radar are crucial in planning an air operation and during its execution. The ionospheric disturbance results in shortening a radar-aircraft slant measurement, which in turn leads to a decrease in the accuracy of determining the aircraft's horizontal coordinates. Besides that, a tropospheric disturbance also causes a decrease in the accuracy of determining the aircraft horizontal position. The results are extremely important in radar measurements and can be used in the GNSS satellite technology, within the GBAS augmentation system in aviation. Therefore, in the future the authors plan to perform numerical simulations on the impact of atmospheric delays also with regard to application of the GNSS satellite technology in aviation.

Acknowledgements

This paper was supported by Polish Air Force University for 2019 year.

References

[1] ICAO. *DOC 9426-AN/924 air taffic services planning manual*. 1st (provisional) ed. International Civil Aviation Organization: Montreal, Canada, 1984.
[2] ALIZADEH, M. M., WIJAYA, D. D., HOBIGER, T., WEBER, R., SCHUH, H. Ionospheric effects on microwave signals. In: *Atmospheric effects in space geodesy* [online]. BOHM, J., SCHUH, H. (eds.). Berlin Heidelberg: Springer-Verlag, Springer Atmospheric Sciences, 2013, p. 35-71. ISBN 978-3-642-36931-5, eISBN 978-3-642-36932-2. Available from: https://doi.org/10.1007/978-3-642-36932-2_2
[3] SCHAER, S. *Mapping and predicting the Earth's ionosphere using the Global Positioning System*. PhD thesis. Switzerland: Bern University, 1999. ISBN 3-908440-01-7.
[4] LEANDRO, R., SANTOS M., LANGLEY, R. UNB neutral atmosphere models: development and performance. National Technical Meeting of the Institute of Navigation ION NTM 2006 : proceedings. Institute of Navigation, 2006, p. 564-573.
[5] DACH R., HUGENTOBLER, U., FRIDEZ, P., MEINDL, M. *Bernese GPS software version 5.0*. University of Bern, Astronomical Institute, 2007.
[6] BEUTLER, G., BAUERSIMA, I., GURTNER, W., ROTHACHER, M., SCHILDKNECHTT, T., GEINGER, A. *Atmospheric refraction and other important biases in GPS carrier phase observations*, *in atmospheric effects on geodetic space measurements*. Monograph 12. Kensington, Australia, 1987, p. 15-43.
[7] CZEKALA Z. *Parade of radars* (in Polish). Warszawa: Wydawnictwo Dom Wydawniczy Bellona, 1999. ISBN 83-11-08806-3.
[8] Map - Google [online]. [Viewed 2019-04-17]. Avaliable from: https://www.google.pl/maps/search/d%C4%99blin+lotnisko/@51.5560658,21.9006601,887m/data=!3m1!1e3
[9] MIL AIP Poland [online]. [Viewed 2019-04-17]. Avaliable from: http://www.ais.pansa.pl/mil/aip.html
[10] SciLab [online]. [Viewed 2019-04-17]. Avaliable from: https://www.scilab.org
[11] Radar basics - Radartutorial.eu [online]. [Viewed 2019-04-17]. http://www.radartutorial.eu/01.basics/Calculation%20of%20height.en.html

Annex

Abbreviation	Full name
Radar	Radio Detection and Ranging
PSR	Primary Surveillance Radar
SSR	Secondary Surveillance Radar
ATC	Air Traffic Control
TMA	Terminal Manoeuvring Area
ILS	Instrument Landing System
NDB	Non-Directional Beacon
TACAN	Tactical Air Navigation
VOR	VHF Omni-directional Range
VTEC	Vertical TEC
UWB	Ultra Wide-Band
TECU	Total Electron Content Unit
GBAS	Ground Based Augmentation System
GNSS	Global Navigation Satellite System

Kamil Krasuski - Ewelina Kobialka - Marek Grzegorzewski

RESEARCH OF ACCURACY OF THE AIRCRAFT POSITION USING THE GPS AND EGNOS SYSTEMS IN AIR TRANSPORT

The article presents and describes results of research in determination of the aircraft positioning accuracy with use of the GPS and EGNOS satellite systems in the air navigation. The article, in particular, makes a comparison of the designated aircraft coordinates in the GPS and EGNOS systems in relation to the reference position, determined from the precision differential RTK-OTF technique. The experimental test was conducted in Slovakia, in the vicinity of Kosice airport. In the test, a trial flight by Cessna aircraft was executed over the village of Bidovce (LZBD) in Slovakia, in East-Central Europe. Within the conducted investigations, the GPS and EGNOS positioning accuracies were determined in real time during an in-flight experimental test. Based on the conducted investigations, it was found that the accuracy of the GPS positioning in the air navigation equals ±10 m throughout the most part of the air test. In the same period the EGNOS positioning accuracy in air navigation is equal to ± 5 m.

Keywords: *EGNOS, GPS, ICAO, aviation test, accuracy*

1 Introduction

The ICAO has introduced global systems of the GNSS satellite navigation to be used in civil aviation, during the execution of air operations. Amongst the GNSS navigation systems, it is possible to distinguish the NAVSTAR GPS and GLONASS satellite systems. Furthermore, in order to improve the performance of the GNSS satellite systems in aviation, it is possible to exploit ABAS, SBAS and GBAS augmentation systems. The GPS satellite system allows determining the accuracy of the determined aircraft position in air navigation, as follows [1-2]:

- an average accuracy equals 9 m in the horizontal plane,
- an average accuracy equals 15 m in the vertical plane,
- the worst accuracy equals 17 m in the horizontal plane,
- the worst accuracy equals 37 m in the vertical plane.

In addition, the accuracy of the GPS system in accordance with the PBN recommendation in the air transport is determined for each stage of the flight path, as below [2-3]:

- en-route operation: 3.7 m in the horizontal plane, in the vertical plane there are no recommendations or technical standards,
- terminal operation: 0.74 km in the horizontal plane, in the vertical plane there are no recommendations or technical standards,
- initial approach: 220 m in the horizontal plane, in the vertical plane no recommendations or technical standards,
- indirect approach: 220 m in the horizontal plane, in the vertical plane no recommendations or technical standards,
- Non-Precision Approach (NPA): 220 m in the horizontal plane, in the vertical plane there are no recommendations or technical standards,
- airport departure: 220 m in the horizontal plane, in the vertical plane there are no recommendations or technical standards.

Moreover, the accuracy of the EGNOS system in accordance with the PBN recommendation in air transport is determined for each stage of the flight path, as below [2-3]:

- approach and landing operations with vertical guidance APV-I: 16 m in the horizontal plane, 20 m in the vertical plane,
- approach and landing operations with vertical guidance APV-II: 16 m in the horizontal plane, 8 m in the vertical plane,
- LPV200 approach: 16 m in the horizontal plane, 4 m in the vertical plane.

The aim of this study is to verify and determine the positioning accuracy of the aircraft, using the GPS system and the EGNOS system in air navigation. The research work is universal for conducting air navigation in the area of Slovakia. The obtained results are practical for the execution of the air operations in Slovakia, in East-Central Europe. Therefore, the GPS and EGNOS positioning accuracy, obtained in this paper, appear to be innovative for pilots and navigators in this part of Europe.

2 Mathematical model

The basic observation equation of the GPS positioning method in air navigation can be expressed as [4]:

Kamil Krasuski*, Ewelina Kobialka, Marek Grzegorzewski
Department of Air Navigation, Faculty of Aviation and Aeronautics, Polish Air Force University, Deblin, Poland
*E-mail of corresponding author: k.krasuski@law.mil.pl

$$l = d + c \cdot (dtr - dts) + Ion + Trop + \mathrm{Re}l + TGD\,, \quad (1)$$

where:

l - pseudorange (code measurement) at the frequency of L1 in the GPS system,

d - geometrical distance between the satellite and the receiver, it takes into account the correction of the Sagnac effect,

$$d = \sqrt{(X - X_{GPS})^2 + (Y - Y_{GPS})^2 + (Z - Z_{GPS})^2}\,, \quad (2)$$

(X,Y,Z) - the aircraft coordinates, the parameters determined in the process of developing the GPS code observations,
$(X_{GPS}, Y_{GPS}, Z_{GPS})$ - coordinates of the GPS satellites in the geocentric XYZ frame are determined based on the model of a Kepler orbit,
c - speed of light,
dtr - correction of the receiver clock, parameter determined based on the aircraft coordinates,
dts - correction of the satellite clock bias, measured based on the polynomial 2nd degree from a GPS navigation message,
Ion - ionospheric correction, in the SPP method, determined based on the Klobuchar model,
$Trop$ - tropospheric correction, determined based on the deterministic model of a tropospheric delay,
$\mathrm{Re}l$ - relativistic effect, determined based on the navigation message data,
TGD - a group delay in sending a code measurement for GPS satellites based on the navigation message data.

The basic observation equation of the EGNOS positioning method in air navigation can be expressed, as [5]:

$$\begin{aligned} l = d^* + c \cdot (dtr - dts^*) + Ion^* + Trop^* + \\ + \mathrm{Re}l + TGD + PRC \end{aligned}\,, \quad (3)$$

where:
l - pseudorange (code measurement) at the frequency L1 in the GPS system,
d^*- geometrical distance between the satellite and the receiver, it takes into account the correction of the Sagnac effect as well as the fast-term and long-term corrections in the EGNOS system,

$$d^* = \sqrt{(X - X^*_{GPS})^2 + (Y - Y^*_{GPS})^2 + (Z - Z^*_{GPS})^2}\,, \quad (4)$$

(X, Y, Z)- coordinates of the aircraft, the parameters determined by using the EGNOS corrections,
$(X^*_{GPS}, Y^*_{GPS}, Z^*_{GPS})$ - coordinates of the GPS satellites in the geocentric XYZ frame are determined based on the model of a Kepler orbit, and also by using fast-term and long-term corrections in the EGNOS system,
c- speed of light,
dtr- correction of the receiver clock, parameter determined based on the aircraft coordinates,
dts^*- correction of satellite clock bias, measured based on the polynomial 2nd degree from a GPS navigation message, using the fast-term and long-term corrections in the EGNOS system,
Ion^* - ionospheric correction, determined from the regular grid model GRID, using polynomial interpolation parameter VTEC,
$Trop^*$ - tropospheric correction, determined from the model of the troposphere RTCA-MOPS,
$\mathrm{Re}l$ - relativistic effect, determined based on the navigation message data,
TGD - a group delay in sending a code measurement for GPS satellites based on the navigation message data,
PRC - fast-term corrections in the EGNOS system.

The unknown aircraft coordinates from Equations (1) and (2) in the XYZ geocentric frame are determined, as instructed by the ICAO, with the least squares method in the stochastic process. The stochastic process does take into account the weight of code measurements, typically in the function of the angle of elevation. The process of determining the aircraft coordinates is conducted for all the registered measuring epochs. In the case of conducting the air navigation, the aircraft coordinates should be expressed in the ellipsoidal BLh frame, as [6]:

$$\begin{bmatrix} B \\ L \\ h \end{bmatrix} = \begin{bmatrix} arc\tan\left(\dfrac{Z/\rho}{1-e^2}\right) \\ arc\tan\left(\dfrac{Y}{X}\right) \\ \dfrac{\rho}{\cos B} - R \end{bmatrix}, \quad (5)$$

where:
(a,b) - semi-major and semi-minor axes of the BLh ellipsoidal frame,

e - eccentricity, $e = \sqrt{\dfrac{a^2 - b^2}{a^2}}$,

R - radius of the curvature of the prime vertical, $R = \dfrac{a}{\sqrt{1 - e^2 \cdot \sin^2 B}}$,

$\rho = \sqrt{X^2 + Y^2}$,
(B,L,h)- geodetic coordinates of aircraft's position in the BLh ellipsoidal frame,
B - Latitude,
L - Longitude,
h - ellipsoidal height.

The determined aircraft coordinates in the ellipsoidal BLh frame will form the foundation for further deliberations in this article. It should be stressed that based on Equation (3), it was possible to determine the position of the aircraft, separately for the GPS solution - see Equation (1), and independently for the EGNOS solution - Equation (2).

3 The research test

For the purposes of this publication, an air experiment, which involved the Cessna, was conducted in Bidovce (LZBD), Slovakia, in East-Central Europe [7]. The research experiment was performed jointly by the Faculty of

Figure 1 *The onboard receivers in the Cessna plane [photo by: Marek Grzegorzewski]*

Table 1 *Results of the standard deviation of the Cessna reference trajectory*

Parameter	Standard deviation for Latitude [m]	Standard deviation for Longitude [m]	Standard deviation for ellipsoidal height [m]
Minimum value	0.02	0.01	0.01
Maximum value	0.50	0.20	0.68
Mean value	0.04	0.01	0.10

Aeronautics of Deblin Air Force University and the Faculty of Aeronautics of Košice Technical University. A dual-frequency satellite receiver Septentrio AsteRx2 (see Figure 1) was mounted on board the Cessna. The GNSS navigation receivers recorded the GPS/EGNOS satellite observations in real time. The test flight took place in the vicinity of Kosice airport. En-route of the Cessna, there was one physical reference station CORS. Moreover, for the sake of the computations in the post-processing mode, two virtual reference stations in the ASG-EUPOS in the POZGEO-D service were generated. In this way, it was possible to recover the precise reference trajectory for the flight of the Cessna in the RTK mode for three independent computations in the OTF mode. Next, the Cessna reference position was averaged, as [8]:

$$B_{ref} = \frac{\sum_{i=1}^{n} B_{RTK-OTF,i}}{n}; L_{ref} = \frac{\sum_{i=1}^{n} L_{RTK-OTF,i}}{n}; \quad h_{ref} = \frac{\sum_{i=1}^{n} h_{RTK-OTF,i}}{n}, \tag{6}$$

where:
$n = 3$,
$i = 1,2,3$,
$B_{RTK\text{-}OTF,i}$ - estimated Latitude from the RTK technique from a single OTF solution,
$L_{RTK\text{-}OTF,i}$ - estimated Longitude from the RTK technique from a single OTF solution,
$h_{RTK\text{-}OTF,i}$ - estimated ellipsoidal height from the RTK technique from a single OTF solution,
B_{ref} - estimated reference trajectory for Latitude,
L_{ref} - estimated reference trajectory for Longitude
h_{ref} - estimated reference trajectory for ellipsoidal height.

For the reference position, the positioning accuracies were determined, as well in the form of standard deviations of coordinates (B_{ref}, L_{ref}, h_{ref}). The values of standard deviations of reference coordinates (B_{ref}, L_{ref}, h_{ref}) were determined based on the relationship [9]:

$$mB_{ref} = \frac{(B_{RTK-OTF,i} - B_{ref})}{n-1}; \quad mL_{ref} = \frac{(L_{RTK-OTF,i} - L_{ref})}{n-1}; \quad , mh_{ref} = \frac{(h_{RTK-OTF,i} - h_{ref})}{n-1}, \tag{7}$$

where:
mB_{ref} - standard deviation of the reference trajectory for Latitude,
mL_{ref} - standard deviation of the reference trajectory for Longitude,
mh_{ref} - standard deviation of the reference trajectory for ellipsoidal height.

Table 1 shows the values of standard deviations for the designated precision trajectory of the Cessna flight reference. The average value of the standard deviation is 0.04 m for coordinate B, 0.01 m for coordinate L, and 0.10 m for coordinate h. In turn, the lowest values of standard deviations equal respectively: 0.02m for coordinate B, 0.01 m for coordinate L and 0.01 m for coordinate h. The highest values of standard deviations are 0.50 m for the coordinate B, 0.20 m for the coordinate L and 0.68 m for the coordinate h, respectively.

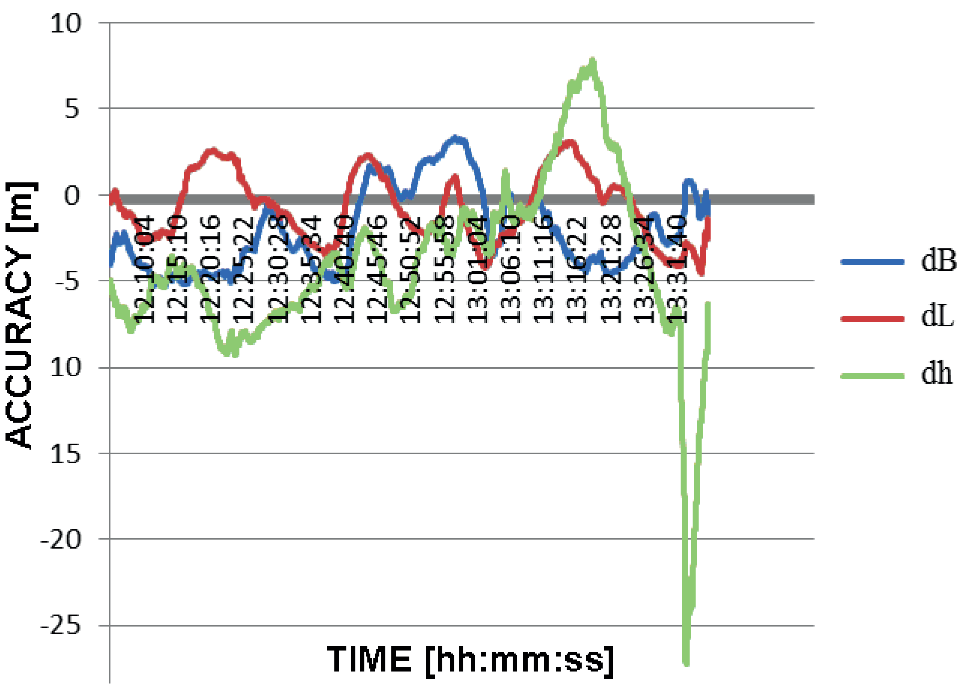


Figure 2 *Accuracy of the Cessna plane position based on the GPS solution*

Table 2 *Comparison of the GPS accuracy to the ICAO technical standards*

Parameter	GPS solution	ICAO technical standards	Conclusion
Accuracy of Latitude	± 5 m	17 m	did not exceed the accuracy limit of GPS system in aviation
Accuracy of Longitude	± 5 m	17 m	did not exceed the accuracy limit of GPS system in aviation
Accuracy of ellipsoidal height	± 27 m	37 m	did not exceed the accuracy limit of GPS system in aviation

4 Results and discussion

In the framework of the research into the air experiment, first and foremost, it was possible to determine the accuracy of the GPS positioning in the air navigation. For this purpose, a comparison was made between the ellipsoidal BLh coordinates determined from Equations (1) and (5), and precise trajectory coordinates of the Cessna flight reference from Equation (6), as [8, 10-11]:

$$\begin{cases} dB = B_{GPS} - B_{ref} \\ dL = L_{GPS} - L_{ref} \\ dh = h_{GPS} - h_{ref} \end{cases}, \quad (8)$$

where:

B_{GPS} - estimated Latitude from the GPS solution, based on Equation (1) and (3),

L_{GPS} - estimated Longitude from the GPS solution, based on Equation (1) and (3),

h_{GPS} - estimated ellipsoidal height from the GPS solution, based on Equations (1) and (5),

dB - accuracy of aircraft position for the Latitude axis in the GPS system,

dL - accuracy of aircraft position for the Longitude axis in the GPS system,

dh - accuracy of aircraft position for the ellipsoidal height axis in the GPS system.

Figure 2 shows values of the GPS satellite positioning accuracy in the air navigation in the research test. The accuracy of the horizontal coordinate B changes from -5 m to +3.5 m. Besides that, the accuracy of the horizontal coordinate L changes from -5 m to +3 m. In addition, the accuracy of the vertical coordinate h changes from -27 m to +7.5 m. However, for the major part of the duration of the flight, the accuracy of the vertical h ranges from -9 m to +7.5 m.

Table 2 shows results of the GPS positioning accuracy in aviation in relation to the limit error values of the aircraft

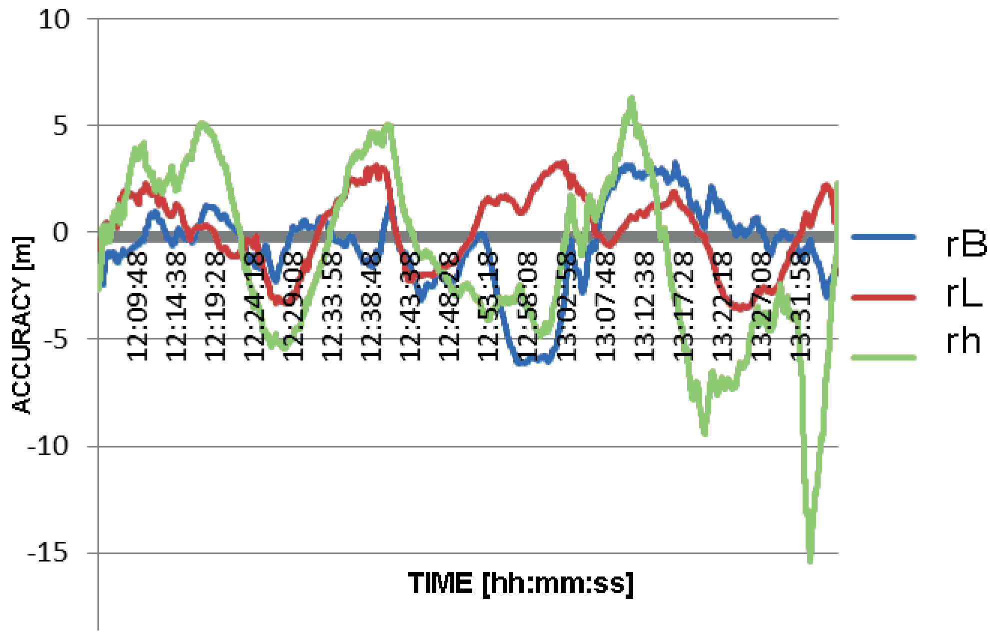


Figure 3 *Accuracy of the Cessna plane position based on the EGNOS solution*

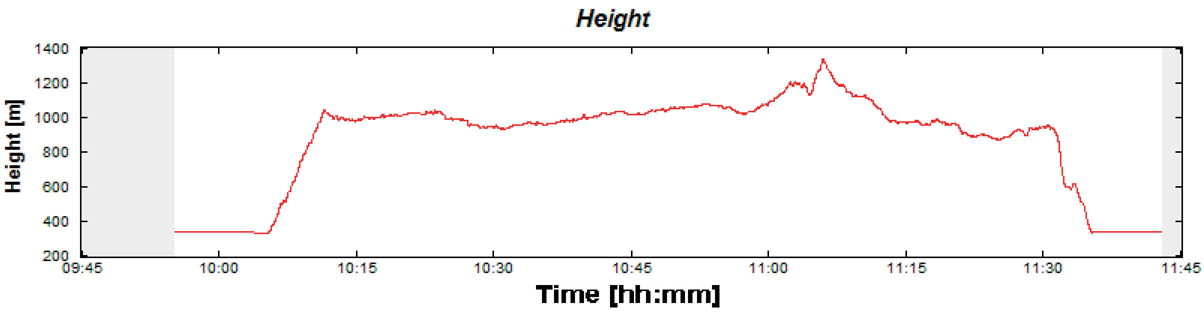


Figure 4 *The vertical profile of the Cessna plane at a flight test*

position in accordance with the ICAO recommendations. Based on the comparison, it can be seen that:

- the lowest accuracy of the horizontal coordinate B in the air test equalled ± 5 m and it did not exceed the limit value of 17 m for navigating in the horizontal plane LNAV,
- the lowest accuracy of the horizontal coordinate L in the air test equalled ± 5 m and it did not exceed the limit value of 17 m for navigating in the horizontal plane LNAV,
- the lowest accuracy of the vertical coordinate h in the air test equalled ± 27 m and it did not exceed the limit value of 37 m for navigating in the horizontal plane LNAV.

Therefore, the obtained results, with regard to the GPS positioning accuracy, meet the ICAO recommendations for using this sensor in aviation to conduct the LNAV horizontal and VNAV vertical navigation [12].

In the second stage of the research, the accuracy of the EGNOS positioning in the air navigation was determined. For this purpose, a comparison was made between the ellipsoidal BLh coordinates determined from Equations (3) and (5), and precise trajectory coordinates of the Cessna flight from Equation (6), as [8, 10-11]:

$$\begin{cases} rB = B_{EGNOS} - B_{ref} \\ rL = L_{EGNOS} - L_{ref} \, , \\ rh = h_{EGNOS} - h_{ref} \end{cases} \tag{9}$$

where:

B_{EGNOS} - estimated Latitude from the EGNOS solution, based on Equation (3) and (5),
L_{EGNOS} - estimated Longitude from the EGNOS solution, based on Equation (3) and (5),
h_{EGNOS} - estimated ellipsoidal height from the EGNOS solution, based on Equation (3) and (5),
rB - accuracy of aircraft position for the Latitude axis, based on the EGNOS solution,
rL - accuracy of aircraft position for the Longitude axis, based on the EGNOS solution,
rh - accuracy of aircraft position for the ellipsoidal height axis, based on the EGNOS solution.

***Table 3** Comparison of the GPS accuracy at phase of landing to the ICAO technical standards of NPA procedure*

Parameter	GPS solution	ICAO technical standards	Conclusion
Accuracy of Latitude	± 3 m	220 m	did not exceed the accuracy limit of GPS system in NPA procedure
Accuracy of Longitude	± 5 m	220 m	did not exceed the accuracy limit of GPS system in NPA procedure
Accuracy of ellipsoidal height	±27 m	Not active	No comparison

***Table 4** Comparison of the EGNOS accuracy at phase of landing to the ICAO technical standards of APV-I procedure*

Parameter	EGNOS solution	ICAO technical standards	Conclusion
Accuracy of Latitude	±3 m	16	did not exceed the accuracy limit of EGNOS system in APV-I procedure
Accuracy of Longitude	±3 m	16	did not exceed the accuracy limit of EGNOS system in APV-I procedure
Accuracy of ellipsoidal height	±15 m	20	did not exceed the accuracy limit of EGNOS system in APV-I procedure

Figure 3 shows values of the positioning accuracy of the EGNOS satellite navigation in the experimental test. The accuracy of the horizontal coordinate B changes from -6 m to +3.5 m. Besides that, the accuracy of the horizontal coordinate L changes from -3 m to +3.5 m. In addition, the accuracy of the vertical coordinate h changes from -15 m to +6.5 m. However, for the major part of the duration of the flight, the accuracy of the vertical coordinate h ranges from -9 m to +6.5 m.

Figure 4 shows a vertical flight trajectory during the air test. The approach to landing of the Cessna started at 11:30:00 hours in accordance with the GPST. At the same time, the GPS positioning accuracy was as follows: ± 3 m for the component B, ± 5 m for the component L, ± 27 m for the component h. It can be observed that in the case of the h coordinate, there was a dramatic degradation of the GPS accuracy of positioning in aviation. This phenomenon proves very dangerous for the execution of the approach to landing procedure by an aircraft. In the EGNOS solution, the positioning accuracy during the approach to landing was as follows: ± 3 m for the component B, ± 3 m for the component L, ± 15 m for the component h. Similarly to the GPS solution, in the EGNOS solution there was also a degradation in the positioning accuracy of the vertical coordinate h.

Table 3 presents results of the GPS positioning accuracy in the NPA procedure in relation to the ICAO recommendations. Based on the comparison, it can be observed that:

- the lowest accuracy of the horizontal coordinate B in the approach to landing procedure equalled ± 3 m and it did not exceed the limit value of 220 m for navigating in the horizontal plane LNAV,
- the lowest accuracy of the horizontal coordinate L in the approach to landing procedure equalled ± 5 m and it did not exceed the limit value of 220 m for navigating in the horizontal plane LNAV,
- the lowest accuracy of the horizontal coordinate h in the approach to landing procedure equalled ± 27 m; however the ICAO technical standards do not define the limit of accuracy in the vertical plane, therefore the comparison is not possible in this case.

Therefore, the obtained results in the GPS positioning accuracy with regard to the APV-I procedure meet the ICAO recommendations for navigating in the horizontal plane. The comparison was not possible in the vertical plane due to the lack of the ICAO recommendations [3].

Table 4 presents results of the EGNOS positioning accuracy in the approach to landing procedure with the APV-I vertical guidance in relation to the ICAO recommendations. Based on the comparison, it can be observed that:

- the lowest accuracy of the horizontal coordinate B in the approach to landing procedure equalled ± 3 m and it did not exceed the limit value of 16 m for navigating in the horizontal plane LNAV,
- the lowest accuracy of the horizontal coordinate L in the approach to landing procedure equalled ± 3 m and it did not exceed the limit value of 16 m for navigating in the horizontal plane LNAV,
- the lowest accuracy of the horizontal coordinate h in the approach to landing procedure equalled ± 15 m and it did not exceed the limit value of 20 m for navigating in the vertical plane LNAV.

Therefore, the obtained results in the EGNOS positioning accuracy with regard to the APV-I procedure meet the ICAO recommendations for navigating in the horizontal and vertical planes. It can be concluded that the findings are satisfactory and confirm the ICAO accuracy requirements in the air transport [3].

5 Conclusions

The paper discusses and presents the results of research which focused on determining the GPS and EGNOSS positioning accuracy in air navigation. The paper presents accuracy findings obtained during the operation of the GNSS receiver in an air experiment. The results of the accuracies were determined for the readings of aircraft positions on the receiver Septentrio AsteRx2e. The navigation receiver Septentrio AsteRx2 was fixed in a Cessna aircraft during a flight test carried out in Slovakia, in the village of Bidovce (LZBD). The determined coordinates were referenced to a precise reference position, designated in the differential RTK-OTF technique. The precise aircraft trajectory from the RTK-OTF technique was estimated with standard deviation better than 0.10 m. Based on the conducted investigations, it was found that the accuracy of the GPS positioning in aviation equals ±10 m and of the EGNOS system, it is ±5 m. The obtained results of accuracy of the GPS system does not exceed the limit values of the aircraft positioning according to the ICAO recommendations of. 17 m for lateral navigation and 37 m for vertical navigation. In addition, the paper compares the accuracy findings of the GPS positioning and EGNOS positioning with the ICAO technical requirements with regard to limit values in the NPA procedure and an approach with the AVP-I vertical guidance. The worst accuracy of the GPS positioning in the horizontal plane equals to 3-5 m and it is higher than the ICAO recommendations of 220 m. Moreover, the worst accuracy of the GPS positioning in the vertical plane equals to 27 m. The worst accuracy of the EGNOS positioning in the horizontal plane in the APV-I procedure equals to 3 m and it is higher than the ICAO recommendations of 16 m. In addition, the EGNOS accuracy positioning in the vertical plane in APV-I procedure does not exceed the limit value of the aircraft positioning according to the ICAO recommendations of 20 m. The obtained results of the aircraft positioning show that the GPS system and EGNOS system can be applied in the air navigation.

Acknowledgements

This paper was supported by Polish Air Force University for 2019 year.

References

[1] KRASUSKI, K. Application the GPS observations in SPP method for aircraft positioning in flight experiment in Deblin, Poland (01.06.2010). *Journal of Automation, Mobile Robotics and Intelligent Systems* [online]. 2017, **11**(1), p. 42-47. ISSN 1897-8649, eISSN 2080-2145. Available from: https://doi.org/10.14313/JAMRIS_1-2017/5.

[2] ICAO standards and recommended practices (SARPS), annex 10 volume I (radio navigation aids), 2006 - International Civil Aviation Organization [online]. [Viewed 2018-10-15]. Available from: www.ulc.gov.pl/pl/prawo/prawo-mi%C4%99dzynarodowe/206-konwencje

[3] CIECKO, A., GRUNWALD, G. Examination of autonomous GPS and GPS/EGNOS integrity and accuracy for aeronautical applications. *Periodica Polytechnica Civil Engineering* [online]. 2017, **61**(4), p. 920-928. ISSN 0553-6626, eISSN 1587-3773. Available from: https://doi.org/10.3311/PPci.10022

[4] SANZ SUBIRANA, J., JUAN ZORNOZA, J. M., HERNANDEZ-PAJARES, M. *GNSS Data Processing. Volume I: Fundamentals and Algorithms*. ESTEC, Noordwijk, Netherlands: ESA Communications, 2013. ISBN 978-92-9221-886-7.

[5] LI, L., JIA, C., ZHAO, L., CHENG, J., LIU, J., DING J. Real-time single frequency precise point positioning using SBAS corrections. *Sensors* [online]. 2016, **16**(8), p. 1-13. ISSN 1424-8220. Available from: https://doi.org/10.3390/s16081261

[6] OSADA, E. *Geodesy* (in Polish). Wroclaw: Oficyna Wydawnicza Politechniki Wroclawskiej, 2001, p. 237-241. ISBN 83-7085-663-2.

[7] CIECKO, A., GRZEGORZEWSKI, M., OSZCZAK, S., CWIKLAK, J., GRUNWALD, G., BALINT, J., SZABO, S. Examination of EGNOS safety-of-live service in Eastern Slovakia. *Annual of Navigation* [online]. 2015, **22**(1), p. 65-78. eISSN 2300-6633. Available from: https://doi.org/10.1515/aon-2015-0021

[8] GRZEGORZEWSKI, M. Navigating an aircraft by means of a position potential in three dimensional space. *Annual of Navigation*. 2005, **9**, p. 1-111. eISSN 2300-6633.

[9] GRZEGORZEWSKI, M., JARUSZEWSKI, W., FELLNER, A., OSZCZAK, S., WASILEWSKI, A., RZEPECKA, Z., KAPCIA, J., POPLAWSKI, T. Preliminary results of DGPS/DGLONASS aircraft positioning in flight approaches and landings. *Annual of Navigation*. 1999, **1**, p. 41-53. eISSN 2300-6633.

[10] GRZEGORZEWSKI, M., CIECKO, A., OSZCZAK, S., POPIELARCZYK, D. Autonomous and EGNOS positioning accuracy determination of Cessna aircraft on the edge of EGNOS coverage. *2008 National Technical Meeting of The Institute of Navigation : proceedings*. 2008, p. 407-410.

[11] SWIATEK, A., JAWORSKI, L., TOMASIK, L. EGNOS monitoring prepared in space research centre P.A.S. for SPMS project. *Artificial Satellites* [online]. 2017, **52**(4), p. 109-120. eISSN 2083-6104. Available from: https://doi.org/10.1515/arsa-2017-0010

[12] JAFERNIK, H., FELLNER, A., MROZIK, M., KRASUSKI, K. Results of aircraft positioning tests in post-processing using the GNSS. *Scientific Journal of Silesian University of Technology. Series Transport* [online]. 2017, **95**, p. 67-74. ISSN 0209-3324, eISSN 2450-1549. Available from: https://doi.org/10.20858/sjsutst.2017.95.7

Annex

Abbreviation	Full name
GPS	Global Positioning System
EGNOS	European Geostationary Navigation Overlay Service
RTK-OTF	Real Time Kinemtic - On The Fly
ICAO	International Civil Aviation Organization
GLONASS	Global Navigation Satellite System
PBN	Performance-Based Navigation
NPA	Non-Precision Approach
APV	Approach with Vertical Guidance
CORS	Continuously Operating Reference Stations
LNAV	Lateral Navigation
VNAV	Vertical Navigation
SBAS	Satellite Based Augmentation System
ABAS	Aircraft Based Augmentation System
GBAS	Ground Based Augmentation System
GNSS	Global Navigation Satellite System
GPST	GPS Time
VTEC	Vertical TEC
ASG-EUPOS	Aktywna Siec Geodezyjna EUPOS
RTCA-MOPS	Radio Technical Commission for Aeronautics-Minimum Operational Performance Standards

Tomas Kucera

APPLICATION OF THE ACTIVITY-BASED COSTING TO THE LOGISTICS COST CALCULATION FOR WAREHOUSING IN THE AUTOMOTIVE INDUSTRY

Activity-based costing is one of the procedures that proved to be very suitable for the financial management of warehouse activities in the automotive industry. Accurate and up-to-date data enables managers to properly plan and manage all the warehousing related activities in the automotive industry. In the activity-based costing approach, overheads costs are allocated in relation to specific logistics activities of the company. The aim of the article is the application of activity-based costing to the logistics cost calculation for warehousing in the automotive industry. The article focuses on the practical application of activity-based costing to the logistics cost calculation for warehousing in the automotive industry to a particular logistics service provider. It highlights the positive and negative use of this method in the practical case study, which is one of the major qualitative scientific methods. The resulting effect of using the activity-based costing method should be to refine the information that is used for the decision-making problems of the top management of the logistics service provider.

Keywords: *activity-based costing, logistics cost calculation for warehousing, automotive industry, logistics costs*

1 Introduction

Logistics is today an area that has an irreplaceable role in the business. The chain of logistics activities ensures the smooth running of the production process and logistics costs are associated with each logistic activity. Those costs are not negligible items that affect to a large extent the overall profit or loss of a company. The need to monitor costs in terms of logistics activities is a prerequisite for identifying rationalization measures in logistics activities and optimizing the logistics costs of a company.

Logistic costs constitute an important percentage of the total costs in automotive industry [1]. Logistics activities take place in every supply channel, including customer service, warehousing, transportation, inventory management, information flow, and order processing [2]. Supply chain operations and logistics are vital tools for businesses to remain competitive in today's major economic activities [3-4]. Rutner and Langlev [5], Lambert and Burduroglo [6] and Lynch, Keller and Ozment [7] draw attention to the fact that logistics have been under pressure for a long time to reduce the costs of the company. As a result, the areas of logistics are explored, where the cost optimization options are focused on individual logistics activities and processes. Kucera [8] argues that logistics managers are usually interested in providing the high quality services to their customers at minimum costs. Logistics services have gradually become the only way for the third-party logistics companies to improve logistics capabilities and integrate logistics resources [9-10]. Bokor [11-12] notes that requirements for the quality of logistics services are getting higher and higher. At the same time, however, the financial resources available to companies are rather limited. In such a business environment, according to Bokor [13], logistics service providers have to pay special attention to the optimal allocation of resources in various decision-making tasks. It is a basic step in monitoring and evaluating logistics costs to support the decision-making tasks [14-15]. Logistics costs are a substantial part of an operation in a supply chain [16]. Logistics costs arise in different types of logistics activities in the automotive industry and affect material flow and accompanying financial and information flows; thanks to this fact, information support and evaluation are important tasks for the company [17]. Automotive companies have started to optimize logistics costs by implementing logistics cost management systems [18]. Warehousing costs and management has become a very important element in the supply chain in recent years because it is not just a centralized warehouse for goods and value-added services [19-20].

Currently, all the companies are striving for different techniques to create better supply chain management for their competitive advantage. Activity-based costing is one method that is typically used to improve the business performance, identify the high-cost activities, and measure logistics management performance [21-22].

Tomas Kucera*
Department of Transport Technology and Control, Faculty of Transport Engineering, University of Pardubice, Czech Republic
*E-mail of corresponding author: tomas.kucera@upce.cz

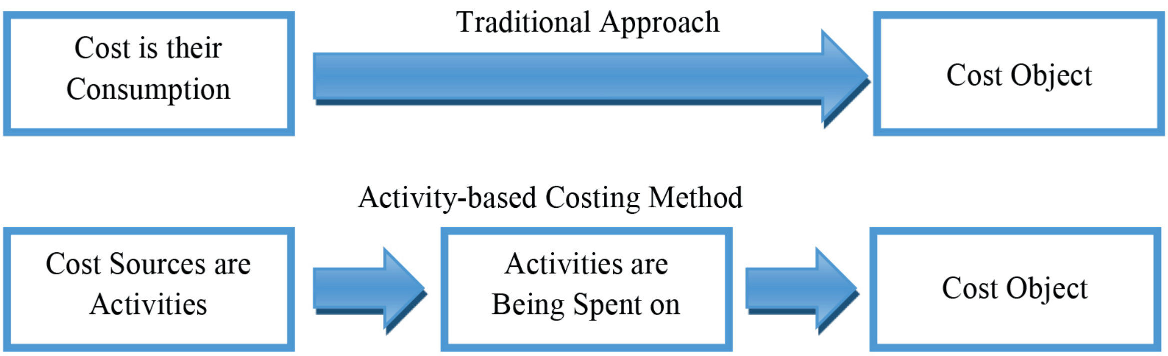


Figure 1 *Comparison of traditional calculation methods and activity-based costing; based on [48] and [49]*

The aim of this article is a practical application of activity-based costing to the logistics cost calculation for warehousing in the automotive industry to a particular logistics service provider. Article highlights the positive and negative use of this method in the practical case study, which is one of the major qualitative scientific methods. The real case study is the method of the qualitative research based on the study of one or a small number of situations for application of the findings for the similar cases according to Nielsen, Mitchell and Nørreklit [23].

2 Theoretical background and methodology

Logistics costs can be defined with respect to the basic concepts of logistics [24]. Logistics costs are created in different business areas and are classified by most studies as a percentage of goods sales. There are at least six individual cost components, namely transport, warehousing, inventory management, administration of logistics, packaging and indirect logistics costs [25-29]. The percentage of logistics costs is approximately 10 % of the gross domestic product [30-32], so managing and optimizing logistics costs is crucial to society [33]. Jonsson [34] defines the costs that can be attributed to logistics. There are large differences in logistics costs between companies in various industries; several scientific studies [35-38] report that their share of the company's revenue is at least 6 percent. This percentage varies considerably between 6 % and 25 %, but they all agree that the share of logistics costs is the lowest in automotive companies.

Feng at al. [39] and Tu and Wang [40] find that finding efficient methods in the process of calculating logistics costs is very difficult nowadays, but it is a topical issue in the area of logistics cost management.

Yin [41] and Yuqin [42] present that through the cost management process, costs can be effectively reduced and resources efficiently allocated. The goal of logistics cost management is to reduce costs and increase the competitiveness of logistics service providers. Yin [41] and Lijun [43] argue that logistics costs are divided into many industries and this makes it difficult to obtain relevant information from managerial accounting.

A significant part of the logistics tasks are implemented by logistics service providers, these companies play a key role in the more efficient and efficient operation of selected industries. Therefore, their operation must be effective enough, which means that logistics service providers must be aware of the main operational factors of logistics processes. These processes should be monitored and evaluated through management information systems.

Bokor [12] emphasizes that the costing of logistics costs has become a challenge in logistics and supply-chain management. Bokor and Markovits-Somogyi [44] state that it is necessary to obtain reliable and accurate information about the structure of the calculations to achieve efficient allocation of resources within the logistics service provider. Traditional approaches to calculations may not be sufficient to achieve this goal in the case of complex and heterogeneous logistics services.

Bokor and Markovits-Somogyi [44] and Bokor [45] claim that traditional costing methods are not always able to provide the information necessary to support decision-making in the required quality. They may even disrupt the cost calculations of logistics services, so it is necessary to implement appropriate costing methods that improve the accuracy and reliability of the data obtained. According to [44], one of the applicable methods is activity-based costing.

Griful-Miquela [46] considers improving the allocation of overheads costs as the most important difference between conventional costing methods and activity-based costing. The use of overriding methods was appropriate in the past when work was a major component of costs. In the activity-based costing approach, overheads costs are allocated in relation to specific logistics activities of the company.

Stevenson and Cabell [47] Gros and Grosova [48] and Gros, Barancik and Cujan [49] draw attention to the fact that while traditional costing directly allocates resources to cost objects, the activity-based costing method advances in two stages. First, the resources are assigned to the individual activities and in the next

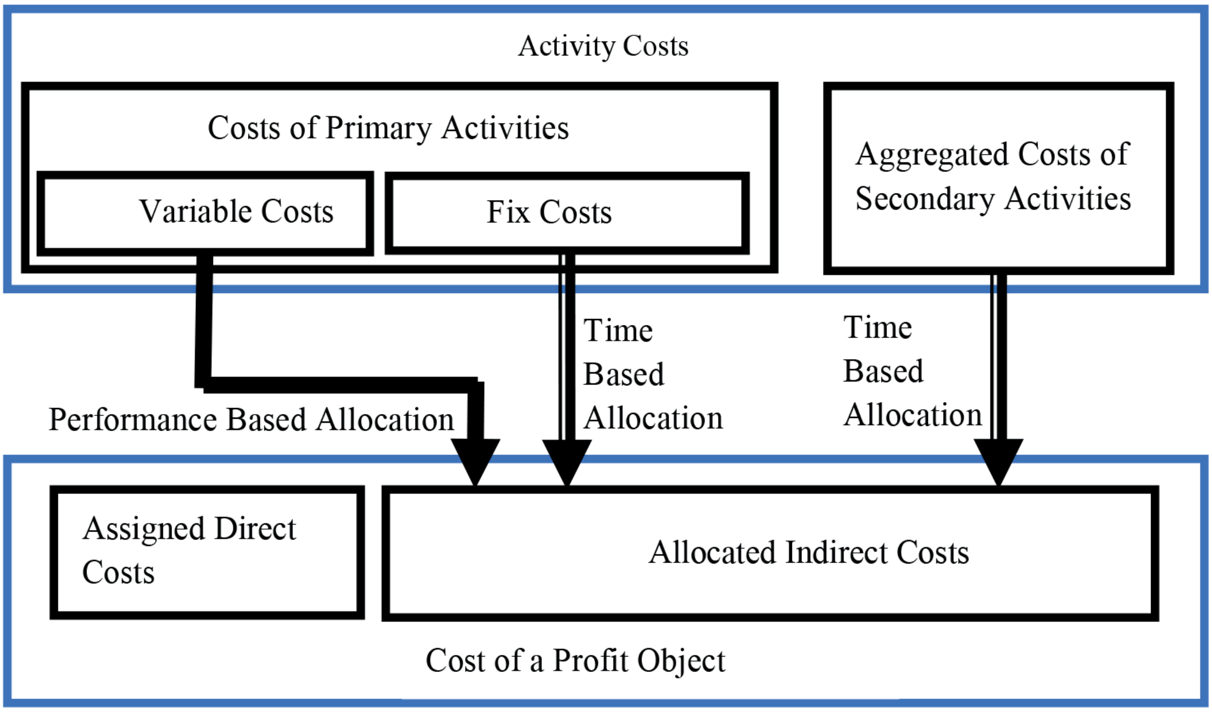


***Figure 2** Activity-based costing model; [44]*

step to the individual entities. The difference between traditional costing and activity-based costing is shown in Figure 1.

Bokor and Markovits-Somogyi [44] present that, given the general characteristics and the current adaptation of the activity-based costing method, the costs of certain logistics services consist of four parts (see Figure 2):

- Direct costs derived from the accounting system.
- Variable indirect costs from primary activities, the allocation is based on performance.
- Fixed indirect costs arising from primary activities, the allocation is based on time consuming.
- Indirect costs from the secondary activities, the allocation is time-based.

Time consuming is the total duration of logistics services (transport, warehousing and sometimes-other activities).

Primary activities are indexed as i = 1 ... n, while profit objects, i.e. logistics services, are indexed as j = 1 ... m. The Equation (1), which consists of four components, is used to calculate costs.

$$C_j = C_j^d + \sum_{i=1}^{n} C_{vi} \frac{P_{ji}}{P_i} + \frac{T_j}{\sum_{j=1}^{m} T_j} \sum_{i=1}^{n} C_{fi} + + \frac{T_j}{\sum_{j=1}^{m} T_j} C^{sa} \, [\text{CZK}] \qquad (1)$$

where:

C_j Cost of profit object j [CZK],
C_j^d Direct cost of profit object j [CZK],
C_{vi} Variable cost of primary activity i [CZK],
P_i Performance of primary activity i [differently expressed power units],
P_{ji} Performance consumption of profit object j at primary activity i [differently expressed power units],
T_j Time consumption of profit object j [hours],
C_{fi} Fix cost of primary activity i [CZK],
C^{sa} Aggregated costs of secondary activities [CZK].

The four components can be merged into three components:

- Assigned direct cost.
- Allocated variable indirect cost, allocation is based on relative performance consumptions.
- Allocated fix indirect cost, allocation is based on the relative time consumption:

$$C_j = C_j^d + \sum_{i=1}^{n} C_{vi} \frac{P_{ji}}{P_i} + \frac{T_j}{\sum_{j=1}^{m} T_j} \cdot \left(\sum_{i=1}^{n} C_{fi} + C^{sa} \right) [\text{CZK}] \qquad (2)$$

The cost efficiency, i.e. the average costs of a primary activity (as service generator) can be calculated as follows:

$$c_i = \frac{C_i}{P_i} = \frac{C_{vi} + C_{fi}}{P_i} \cdot \left[\frac{\text{CZK}}{\text{differently}} \text{ expressed power units} \right] \qquad (3)$$

where: C_i Cost of primary activity in [CZK].

The implementation of the activity-based costing method consists of 6 consecutive steps; these steps are specifically illustrated in Figure 3.

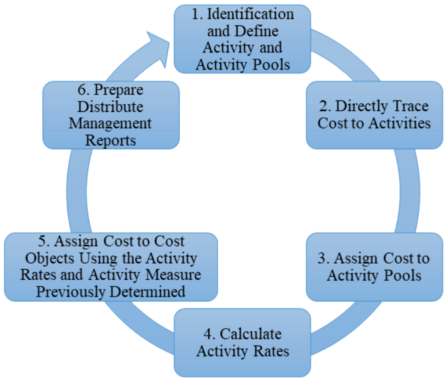


Figure 3 *Six steps of implementing the activity-based costing method; based on [50] and [51]*

3 Results and discussion

The aim of this article is a practical application of the activity-based costing to the logistics cost calculation for warehousing in the automotive industry to a particular logistics service provider. The article highlights the positive and negative use of this method in the practical case study.

The chosen logistics service provider in the automotive industry provides transport services to a large number of customers.

In addition to transport, it provides other logistics services. Services offered in logistics are:

- Internal logistics (warehousing and supply of assemblies).
- Receipt of goods and expedition.
- Warehousing and supply to manufacturing plants.
- Repackaging, pick and pack, material sorting.
- Batch, serial and data reports.
- Picking including kit (i.e. assembling components into sets or kits).
- Sorting and checking all the components.
- FIFO (First In - First Out), Kanban.
- Delivery in JIT (Just in Time) and JIS (Just in Sequence) mode.
- Cross-docking including the added services mentioned above.
- Light pre-production.
- Packaging cleaning, handling and removal of empty packaging.

It is the trend of using new approaches in logistics cost calculations for logistics service providers with regard to the automotive industry in the last few decades. This industry is one of the leading players in advanced economies. A significant competitive advantage can arise with the correct calculation of logistic warehousing costs. Logistics service providers look at the appropriate use of new approaches and use the activity-based costing method. It uses preliminary calculations from the entire computing system to support price decisions as a part of the calculations. Logistics cost calculations always reflect the specific requirements of the automotive customers. It is always a specific type and scope of provided service.

As a part of the calculation of logistics costs, a cost structure is created, more in Table 1. The resulting calculation is always one unit of measure (product, euro pallet). The logistics costs are precisely structured to meet the specific needs of the automotive customers. All the requirements and wishes that the customer has for the required service must always be met.

Logistics cost calculation includes:

- Area.
- Energy.
- Racking system.
- Handling equipment.
- Transport.
- Warehouse staff.
- Other costs.
- Hardware and software.

Area, energy and racking systems are negligible in this particular logistics cost calculation in the automotive industry. It is already rented area and equipped with racking system including the whole energy consumption.

The allocation of handling equipment costs is based on customer product warehousing requirements and the necessary handling equipment to handle the product. These are different types of forklifts, pallet truckers and others pickers and hand pallet trucks.

The transport costs are calculated per km per specific vehicle, which is used for transport within the shuttle. Furthermore, transport costs include a passenger car, the costs of other possible transports.

The logistics service provider calculates the warehouse staff costs per worker in a particular job (white collar, blue collar). Total personnel costs per worker are calculated. In addition to payroll costs, social costs, statutory insurance and liability insurance, costs include protective equipment, training, contributions to cultural and sporting events, and other logistics service provider bonuses.

Other costs include insurance costs, security, facility management, consumables, re-certification and waste costs. Other costs also include unexpected costs

***Table 1** Logistics cost calculation for warehousing in the automotive industry*

OPEN BOOK CALCULATION				Budget/month	Budget/month
Contract: 5 years		EUR exchange rate 25.50 CZK/€		CZK	EUR
Subtotal numb. 1 - Area:				0 CZK	0 €
Racking system					
			leasing fee/month		
racking system			0 CZK	0 CZK	0 €
set-up racking system			0 CZK	0 CZK	0 €
other (rack repair marking)			300 CZK	300 CZK	12 €
Subtotal numb. 2 - Racking system:				300 CZK	12 €
Subtotal numb. 3 - Energy:				0 CZK	0 €
Handling equipment: (rent + service fee + gas)					
type		cost/unit/month	# units		
forklift	1.5 t (max. 3 500 MtH/year)	20 085 CZK	4 x	80 340 CZK	3 151 €
forklift	2.5 t	25 956 CZK	1 x	25 956 CZK	1 018 €
pallet truck	2 t	11 176 CZK	2 x	22 351 CZK	877 €
order picker		6 526 CZK	1 x	6 526 CZK	256 €
hand pallet truck		2 563 CZK	1 x	2 563 CZK	101 €
other (gas forklift)		18 540 CZK	1 x	18 540 CZK	727 €
Subtotal numb. 4 - Handling equipment:				156 276 CZK	6 128 €
Transport					
	type	cost per unit/month	# units		
Shuttle truck incl. drivers -fix costs 3 shifts (32 pal) (9x/day)		205 632 CZK	1 x	205 632 CZK	8 064 €
Shuttle truck incl. drivers -fix costs 3 shifts (36 pal) (21x/day)		205 632 CZK	2 x	411 264 CZK	16 128 €
Transport to more		1 314 CZK	2 x	2 628 CZK	103 €
Car		10 300 CZK	1 x	10 300 CZK	404 €
Subtotal numb. 5 - Transport:				629 824 CZK	24 699 €
Warehouse staff	3 shifts operation				
White collar	leader	72 650 CZK	1 x	72 650 CZK	2 849 €
White collar	administrator	43 136 CZK	6 x	258 817 CZK	10 150 €
Blue collar	warehouseman	37 347 CZK	17 x	634 897 CZK	24 898 €
		Total FTEs	24 x		0 €
Provider employee insurance		121 CZK	24 x	2 892 CZK	113 €
Working protective equipment		288 CZK	24 x	6 922 CZK	271 €
Subtotal numb. 6 - Warehouse staff:				976 178 CZK	38 281 €
Insurance (material, liability, racking system)				2 900 CZK	114 €
Security				2 000 CZK	78 €
Facility management				17 000 CZK	667 €
(warehousing cleaning, road marking, rack and other inspections)					
Consumables (office equipment consumption)				15 000 CZK	588 €
Q - system (recertification)				2 500 CZK	98 €
Other (waste)				8 500 CZK	333 €
Subtotal numb. 7 - Other:				47 900 CZK	1 878 €
Hardware and software				45 000 CZK	1 765 €
EDI				11 320 CZK	412 €
Phone, Internet connection				5 000 CZK	196 €
Other				10 000 CZK	392 €
Subtotal numb. 8 - Hardware and software:				71 320 CZK	2 797 €
Total costs:				1 881 798 CZK	73 796 €
Overheads costs		2%		37 636 CZK	1 476 €
Subtotal + Overheads costs				1 919 434 CZK	75 272 €
Operation profit		6%		115 166 CZK	4 516 €
Total budget				2 034 600 CZK	79 788 €

that may be costs associated with delays in starting production or unexpected situations that may occur.

The costs associated with information technology (hardware and software) are focused on equipping the warehouse with all the information technologies, electronic data interchange, phone, Internet connection and other costs which have connection with information technology.

The last part of the logistics cost calculation is overheads costs (2.00 %), which includes management, accounting, controlling, auditing and personal vehicle management costs. The calculation also includes a 6.00 % operation profit.

4 Conclusion

Logistics coordination and synchronization of material, information and financial flow hits the company at a conflict of partial goals that are monitored by individual organizational units and are very diverse and often contradictory. Logistics is not an end in itself, but it is a part of an entrepreneurial strategy, both a customer-driven business management concept and a rationalizing tool. Warehousing and warehousing costs play an important role in all the aspects of supply chain management. The provision of warehouse services is focused on the level (availability) needed to meet demand. Costs for logistics processes can be characterized as costs associated with logistics activities, respectively business processes. Logistics costs become unproductive, for example, when stockpiles are over-stocked, inappropriate transport mode selection, uncontrolled handling of goods, etc. Optimization of costs in logistic activities, namely processes can be carried out based on the standard tools by reducing costs at a general level, i.e. through the cost reductions, which are measures related to the use of reserves in logistics processes. The main aim of the article was application of the activity-based costing to the logistics cost calculation for warehousing in the automotive industry. The application was shown on the real case study from the field of the automotive industry.

Acknowledgement

The work was created in connection with the scientific research project of the University of Pardubice no. SGS_2019_010. The author is grateful for their support.

References

[1] MARQUEZ, F. P. G., PARDO, I. P. G., NIETO, M. R. M. Competitiveness based on logistic management: a real case study. *Annals of Operations Research* [online]. 2015, **233**(1), p. 157-169. ISSN 0254-5330, eISSN 1572-9338. Available from: https://doi.org/10.1007/s10479-013-1508-z

[2] WIRATCHAI, A., LILAVANICHAKUL, A., PARTHANADEE, P. Analysis of logistics costs for rice mills in improving the aroma of jasmine rice. 3rd International Conference on Agro-Industry - Competitive & Sustainable Agro-Industry: proceedings [online]. 2018. ISSN 2413-0877, p. 146-153. Available from: https://doi.org/10.18502/kls.v4i2.1666

[3] YANG, C. S., LU, C. S., XU, J., MARLOW, P. B. Evaluating green supply chain management capability, environmental performance, and competitiveness in container shipping context. *Journal of the Eastern Asia Society for Transportation Studies* [online]. 2013, **10**, p. 2274-2293. ISSN 1881-1124. Available from: https://doi.org/10.11175/easts.10.2274

[4] WU, D., HUO, J., ZHANG, G., ZHANG, W. Minimization of logistics cost and carbon emissions based on quantum particle swarm optimization. *Sustainability* [online]. 2018, **10**(10), p. 1-15. ISSN 2071-1050. Available from: https://doi.org/10.3390/su10103791

[5] RUTNER, S. M., LANGLEY, C. J. Logistics value: definition, process and measurement. *The International Journal of Logistics Management* [online]. 2000, **11**(2), p. 73-82. ISSN 0957-4093. Available from: https://doi.org/10.1108/09574090010806173

[6] LAMBERT, D. M., BURDUROGLO, R. Measuring and selling the value of logistics. *The International Journal of Logistics Management* [online]. 2000, **11**(1), p. 1-16. ISSN 0957-4093. Available from: https://doi.org/10.1108/09574090010806038

[7] LYNCH, D. F., KELLER, S. B., OZMENT, J. The effects of logistics capabilities and strategy on firm performance. *Journal of Business Logistics*. 2000, **21**(2), p. 47-68. ISSN 2158-1592.

[8] KUCERA, T. Logistics cost calculation of implementation warehouse management system: a case study. *MATEC Web of Conferences* [online]. 2017, **134**, p. 1-7. ISSN 2261-236X. Available from: https://doi.org/10.1051/matecconf/201713400028

[9] QIU, M., MING, Z., LI, J., GAI, K., ZONG, Z. Phase-change memory optimization for green cloud with genetic algorithm. *IEEE Transactions on Computers* [online]. 2015, **64**(12), p. 3528-3540. ISSN 0018-9340. Available from: https://doi.org/10.1109/TC.2015.2409857

[10] XUE, Y., GE, L. Cost optimization control of logistics service supply chain based on cloud genetic algorithm. *Wireless Personal Communications*. 2018, **102**(4), p. 3171-3186. ISSN 0929-6212, eISSN 1572-834X.

[11] BOKOR, Z. A koltseggazdalkodas korszerusitese a kozlekedesben, kulonos tekintettel a kozossegi kozlekedesre / Improving cost calculation in transport with special regard to public transport (in Hungarian). *Kozlekedestudomanyi Szemle / Review of Transportation Sciences*. 2008, **58**(4), p. 31-36. ISSN 0023-4362.

[12] BOKOR, Z. Elaborating cost and performance management methods in transport. *Promet - Traffic&Transportation, Scientific Journal on Traffic and Transportation Research* [online]. 2009, **21**(3), p. 217-224. ISSN 0353-5320, eISSN 1848-4069. Available from: https://doi.org/10.7307/ptt.v21i3.228

[13] BOKOR, Z. Cost calculation in complex transport. *LOGI Scientific Journal on Transport and Logistic*s. 2013, **4**(1), p. 5-22. ISSN 1804-3216, eISSN 2336-3037.

[14] KUCERA, T., HYRSLOVA, J., SOMMERAUEROVA, D. Activity-based costing as an innovative management method to logistics cost calculation for warehousing. 4th International Multidisciplinary Scientific Conference on Social Sciences & Arts SGEM 2017 : proceedings. Book 1, Vol. 5. 2017. ISBN 978-619-7408-17-1, ISSN 2367-5659, p. 25-32.

[15] KUCERA, T., Cost management in logistics of warehousing: the use of activity-based costing in the logistics service provider. International Conference on Traffic and Transport Engineering: proceedings. 2018. ISBN 978-86-916153-4-5, p. 449-453.

[16] MUSCATELLO, J. R., PARENTE, D. H., SWINARSKI, M. Aligning supply chain logistics costs via ERP coordination. *International Journal of Information System Modelling and Design* [online]. 2018, **9**(2), p. 24-43. ISSN 1947-8186. Available from: https://doi.org/10.4018/IJISMD.2018040102

[17] KOVRIZHNYKH, O. E., NECHAEVA, P. A. Analysis of transaction costs in logistics and the methodologies for their information reflection for automotive companies. *Economic and Social Changes-Facts Trends Forecast* [online]. 2016, **44**(2), p. 186-201. ISSN 2307-0331. Available from: https://doi.org/10.15838/esc.2016.2.44.11

[18] SKERLIC, S., MUHA, R. The Importance of systems for controlling logistics costs in the supply chain: a case study from the Slovenian automotive industry. *Promet - Traffic&Transportation, Scientific Journal on Traffic and Transportation Research*. 2016, **28**(3), p. 299-310. ISSN 0353-5320, eISSN 1848-4069.

[19] DE KOSTER, M. B. M. *Recent developments in warehousing*. Rotterdam Erasmus University: Rotterdam School of Management, 1998.

[20] CHOY, K. L., CHOY, E. L. H., POON, T. C. A Real-time database management system for logistics systems: a case study. *Portland International Conference on Management Engineering and Technology* [online] 2008, p. 864-871. ISSN 2159-5100. Available from: https://doi.org/10.1109/PICMET.2008.4599694

[21] ASKARANY, D., YAZDIFAR, H., ASKARY, S. Supply chain management, activity-based costing and organisational factors. *International Journal Production Economics* [online]. 2010, **127**(2), p. 238-248. ISSN 0925-5273, eISSN 1873-7579. Available from: https://doi.org/10.1016/j.ijpe.2009.08.004

[22] KOLOSOWSKI, M., CHWASTYK. P. Process approach in enterprise aided with activity based costing. 20th DAAAM International Symposium on Intelligent Manufacturing and Automation: proceedings. 2009, ISBN 978-1-5108-4001-0, p. 1117-1119.

[23] NIELSEN, L. B., MITCHELL, F., NORREKLIT, H. Management accounting and decision making: two case studies of outsourcing. *Accounting Forum* [online]. 2015, **39**(1), p. 64-82. ISSN 0155-9982. Available from: https://doi.org/10.1016/j.accfor.2014.10.005

[24] STERNAD, M. Metrics of logistics costs in Slovenian companies. 18th International Scientific Conference Business Logistics in Modern Management: proceedings. 2018. ISSN 1849-5931, p. 125-134.

[25] ZENG, A., ROSSETTI, C. Developing a framework for evaluating the logistics costs in global sourcing processes. *International Journal of Physical Distribution & Logistics Management* [online]. 2003, **33**(9), p. 785-803. ISSN 0960-0035. Available from: https://doi.org/10.1108/09600030310503334

[26] FUGATE, B. S., MENTZER, J. T., STANK, T. P. Logistics performance: efficiency, effectiveness, and differentiation. *Journal of Business Logistics* [online]. 2010, **31**(1), p. 43-62. ISSN 2158-1592. Available from: https://doi.org/10.1002/j.2158-1592.2010.tb00127.x

[27] ENGBLOM, J., SOLAKIVI, T., TOYLI, J., OJALA, L. Multiple-method analysis of logistics costs. *International Journal of Production Economics* [online]. 2012, **137**(1), p. 29-35. ISSN 0925-5273, eISSN 1873-7579. Available from: https://doi.org/10.1016/j.ijpe.2012.01.007

[28] SKERLIC, S. The Impact of customers' demands for lower logistics costs in the automotive industry supply chain on companies' business processes. *Zeszyty Naukowe Akademii Morskiej w Szczecinie / Scientific Journals Of the Maritime University of Szczecin* [online]. 2018, **55**(127), p. 86-92. ISSN 1733-8670, eISSN 2392-0378. Available from: https://doi.org/10.17402/305

[29] VON CEIMINSKI, G., KARRER, M., ZUR, M. Designing and implementing a framework for process-oriented logistics-costs measurement in an automotive-supplier group. Advances in Production Management Systems: New Challenges, New Approaches APMS 2009: proceedings. [online]. Vol. 338. IFIP Advances in Information and Communication Technology. Berlin, Heidelberg: Springer, 2010. ISSN 1868-4238, p. 499-505. Available from: https://doi.org/10.1007/978-3-642-16358-6_62

[30] RANTASILA, K., OJALA, L. Measurement of national level logistics costs and performance. 2012 Summit of the International Transport Forum, on Seamless Transport: Making Connections: Discussion Paper, No. 2012-4 [online]. 2012. eISSN 2223439X. Available from: https://doi.org/10.1787/2223439X
[31] HAVENGA, J. Macro-logistics and externality cost trends in South Africa - underscoring the sustainability imperative. *International Journal of Logistics Research and Applications* [online]. 2015, **18**(2), p. 118-139. ISSN 1367-5567. Available from: https://doi.org/10.1080/13675567.2015.1015509
[32] WILSON, R. *Ready for a new route.* CSCMP's 25th Annual State of Logistics Report. 2015.
[33] STERNAD, M., KNEZ, M. *Pomen obvladovanja logisticnih stroskov, logisticni sistemi prihodnosti* (in Slovenian). *The importance of logistics costs management, logistic systems of the future*. Maribor: Visja Prometna Sola, 2008, p. 40-44.
[34] JONSSON, P. *Logistics and supply chain management.* Berkshire: McGraw-Hill Higher Education, 2008. ISBN 978-00-7711-738-2.
[35] OJALA, L., SOLAKIVI, T., HALINEN, H., LORENTU, H., HOFFMANN, T. *Logonbaltic - state of logistics in the Baltic sea region, survey results from eight countries*. LogOn Baltic master reports, 3. Turku: Turku School of Economics, University of Turku, 2007.
[36] BAYKASOGLU, A., KAPLANOGLU, V. Application of activity-based costing to a land transportation company: a case study. *International Journal of Production Economics* [online]. 2008, **116**(2), p. 308-324. ISSN 0925-5273, eISSN 1873-7579. Available from: https://doi.org/10.1016/j.ijpe.2008.08.049
[37] HANSEN, W., HOVI, I. B., VEISTEN, K. Logistics costs in Norway: comparing industry survey results against calculations based on a freight transport model. *International Journal of Logistics Research and Applications* [online]. 2014, **17**(6), p. 485-502. ISSN 1367-5567. Available from: https://doi.org/10.1080/13675567.2014.899568
[38] RANTASILA, K., OJALA, L. National-level logistics costs: an overview of extant research. *International Journal of Logistics Research and Applications* [online]. 2015, **18**(4), p. 313-324. ISSN 1367-5567. Available from: https://doi.org/10.1080/13675567.2015.1016413
[39] FENG, G. Z. *The calculation and evaluation of enterprise logistics cost.* Beijing: Machine Press, 2007. ISSN 1816-6075.
[40] TU, CH., WANG, A. On calculation of enterprise logistics cost with project accounting function of financial software. *Journal of System and Management Sciences.* 2011, **1**(4), p. 71-82. ISSN 1816-6075, eISSN 1818-0523.
[41] YIN, M. Analysis and solutions of enterprises logistic cost management. *Management World.* 2007, **32**, p. 36-41. ISSN 1002-5502.
[42] YUQIN, Z. Measures on reducing enterprise logistic cost. *Logistic Economy.* 2007, **33**, p. 5-12.
[43] LIJUN, Z. Management of logistic cost based on activity analysis. *Commercial Economic.* 2007, **22**, p. 21-28.
[44] BOKOR, Z., MARKOVITS-SOMOGYI, R. Applying activity-based costing at logistics service providers. *Periodica Polytechnica Transportation Engineering* [online]. 2015, **43**(2), p. 98-105. ISSN 0303-7800, eISSN 1587-3811. Available from: https://doi.org/10.3311/PPtr.7700
[45] BOKOR, Z. Improving transport costing by using operation modelling. *Transport* [online]. 2012, **26**(2), p. 128-132. ISSN 1648-4142. Available from: https://doi.org/10.3846/16484142.2011.586111
[46] GRIFUL-MIQUELA, C. Activity-based costing methodology for third-party logistics companies. *International Advances in Economic Research* [online]. 2001, **7**(1), p. 133-146. ISSN 1083-0898, eISSN 1573-966X. Available from: https://doi.org/10.1007/BF02296598
[47] STEVENSON, T. H., CABELL, D. W. E. Integrating transfer pricing policy and activity-based costing. *Journal of International Marketing* [online]. 2002, **10**(4), p. 77-88. ISSN 1547-7215. Available from: https://doi.org/10.1509/jimk.10.4.77.19552
[48] GROS, I., GROSOVA, S. *Dodavatelske systemy / Supply chain management* (in Czech). Prerov: Vysoka skola logistiky, 2012. ISBN 978-80-87179-20-8.
[49] GROS, I., BARANCIK, I., CUJAN, Z. *Velka kniha logistiky / Great book of logistics* (in Czech). Praha: Vysoka skola chemicko-technologicka v Praze, 2016. ISBN 978-80-7080-952-5.
[50] GARRISON, H. R., NOREEN, E. W., BREWER, P. C. *Managerial accounting.* Boston: McGraw-Hill Education, 2017. ISBN 978-12-5930-741-6.
[51] WATANAPA, A, PHOLWATCHANA, S., WIYARATN, W. Activity-based costing analysis for train station's service. *Engineering Journal* [online]. 2016, **20**(5), p. 135-144. ISSN 0125-8281. Available from: https://doi.org/10.4186/ej.2016.20.5.135

Jan Chocholac - Jaroslava Hyrslova - Tomas Kucera - Stanislav Machalik - Roman Hruska

FREIGHT TRANSPORT EMISSIONS CALCULATORS AS A TOOL OF SUSTAINABLE LOGISTIC PLANNING

The freight transport performance is growing. The transport sector is also one of the largest producers of emissions. This must be reflected not only by production companies but also by other stakeholders. The issue of transport emissions is particularly important for city residents, so today the concept of sustainable city logistics is emphasized. Companies should deal with the amount of produced emissions. The use of emission calculators would support operational, tactical and strategic business decision-making. The aim of this article is to analyse the approaches used in available free calculators of emission arising from the freight transport. The focus was on the transport modes that calculators include, input data, output data and methodologies used to calculate emissions. The method of systematic review was used to search analysed freight transport emissions calculators. The method of content analysis was used to analyse inputs, outputs and freight transport emissions calculator's methodologies. The method of qualitative comparative analysis was used to analyse and compare the freight transport emissions calculators.

Keywords: *emission calculator, freight transport, well-to-wheel, tank-to-wheel, well-to-tank*

1 Introduction

Transport is one of the key factors in development of any modern society, not an objective *per se*, but a means of economic development and a precondition for achieving the social and regional cohesion. Transport plays an important role in the social and economic development of the state. However, in relation to the environment it is a source of emissions, noise, vibrations and causes health and safety risks and thanks to transport, there is extensive land use [1]. The negative effects of transport on the environment are conditioned by the increasing transport requirements of society in connection with the process of globalization, which is also reflected in demands for transport infrastructure. Thus, the transport has negative impacts on environment for the two basic reasons: the construction of transport infrastructure and the harmful effects of traffic [1-2]. Transport sector influences all the aspects of human life, research, education, trade, entertainment, manufacturing, defence and culture [2].

Sustainable development is an important factor in development of individual economies. Litman [3] states that the concept of sustainable development is built on three pillars - economic, environmental and social. The current trend is to increase traffic efficiency while eliminating its negative impacts. The production of greenhouse gases, especially carbon dioxide, is the most discussed issue that belong to the environmental pillar. As the European Council of Transport Ministers [4] states, the sustainable development of transport becomes more important in the context of current transport problems, such as:

- unbalanced development of particular modes of transport,
- congestion - as a result of imbalance between modes of transport and the associated bottlenecks in transport infrastructure,
- harmful effects on the environment and public health,
- serious consequences of traffic accidents.

The aim of this article is to analyse the approaches used in free available emission calculators arising from the freight transport. The focus is on the transport modes that calculators include, input data, output data and methodologies used to calculate emissions.

2 Theoretical background

Road transport plays an important role in the consumption of energy and the greenhouse gas emissions in the world [5-7]. The greenhouse gas emissions are a global issue [8-9]. Climate change can be attributed to anthropogenic emissions and are expected to increase further in the future [10-11]. In this sense, emissions from transport sectors (land transport, shipping and aviation) significantly contribute to this effect [11-17]. In the case of the road vehicles, overall emissions from

Jan Chocholac[1,*], Jaroslava Hyrslova[1], Tomas Kucera[2], Stanislav Machalik[3], Roman Hruska[1]
[1]Department of Transport Management, Marketing and Logistics, Faculty of Transport Engineering, University of Pardubice, Czech Republic
[2]Department of Transport Technology and Control, Faculty of Transport Engineering, University of Pardubice, Czech Republic
[3]Department of Informatics in Transport, Faculty of Transport Engineering, University of Pardubice, Czech Republic
*E-mail of corresponding author: jan.chocholac@upce.cz

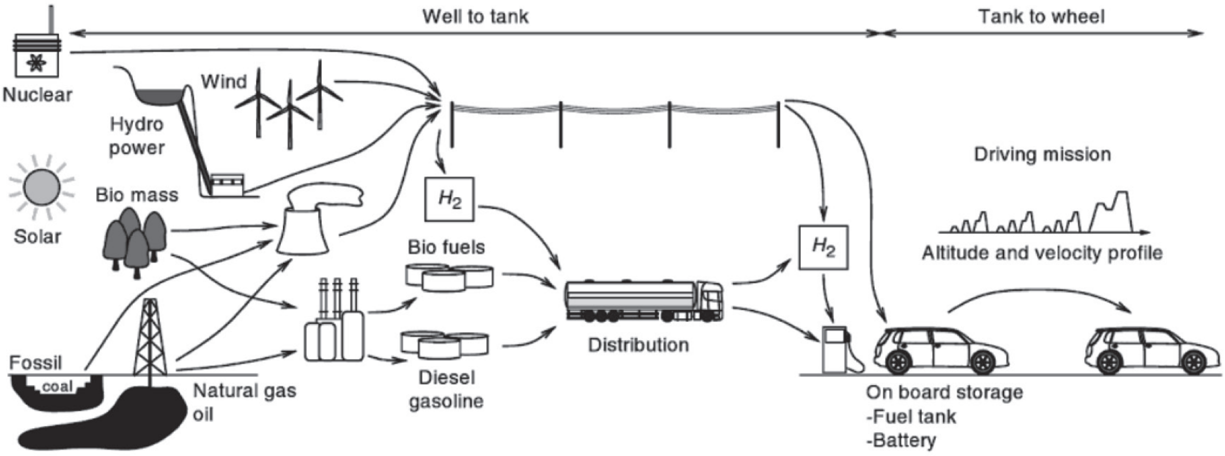


Figure 1 *Well-to-Tank and Tank-to-Wheel [37]*

transport, especially on roads, are one of the main contributors [18-21].

It is well known that the energy consumption in society and emissions of pollutants from transport are affected not only by technical efficiency choice of method and content of carbon and pollutants in the energy sector, but also by the lifestyle and socio-cultural factors [22-23]. Improving the living standard of people will significantly increase energy consumption in the transport sector. In many areas, the environmental and health impacts caused by the transport sector are seriously increasing [24]. The World Economic Forum [25] calculated that the transport and logistics sector was responsible for 5.5% of total emissions from human activity, at around 2 800 mega-tonnes annually. In 2015, the transport sector accounted for approximately 24% of the worldwide CO_2 emissions from fuel combustion [26]. Abbasi and Nilsson [27], Mubarak and Zainal [28] discuss several negative impacts of logistics activities, such as visual pollution, congestion, intimidation, vibration, injuries and accidents.

The issue of the city logistics is addressed in many research areas at present time. New challenges and opportunities of the city logistics to exploit new sources of information are seen with the aim of ensuring sustainable systems primarily for the urban freight transport [29]. Only intelligent city logistics can make a significant contribution to its sustainability. There are many challenges for cities arising from the complex definition of a sustainable freight transport system. It must also ensure access to all modes of the freight transport, while reducing emissions of pollutants and noise and maintaining the economic efficiency of this type of business [30-31].

Reducing the greenhouse gas emissions, of which carbon dioxide is important, has been the major environmental objective for most governments in the developed world [32-33]. Natr [34] notes that carbon dioxide is the most environmentally harmful. He further specifies that several percent CO_2 concentrations cause human breathing difficulties. The long-term effects of CO_2 on the human body can lead to fatal consequences. The increase of the concentration of CO_2 in the air, considered to be the main cause of global warming, is mainly due to the burning of fossil fuels and the decline of forests [35-36]. The CO_2 emissions produced by the road freight transport should therefore be monitored and evaluated. The information obtained can be used to support the decision-making processes at the level of individual transport companies, logistics services providers as well as in the decision-making of state administration bodies and local governments.

European standard EN 16258 Methodology for calculation and declaration of energy consumption and greenhouse gas emissions of transport services (freight and passengers) was approved by the European Committee for Standardisation in 2012 [1, 37]. Currently, there are three main approaches to measuring energy consumption and produced emissions - Well-to-Wheel, Well-to-Tank and Tank-to-Wheel approaches (see Figure 1) [37]:

Well-to-Wheel (sum of total Well-to-Tank and Tank-to-Wheel) - an approach based on the monitoring of energy consumption and associated emissions production that covers the whole process from the generation of electricity or fuel, through the supply to the appropriate transport means through the distribution network, to the consumption associated with the operation of the means of transport. This approach is based on the sum of Tank-to-Wheel and Well-to-Tank values.

Well-to-Tank - energy consumption and production of emissions related to the production of energy or fuel, the indicator covering all activities from the extraction of raw materials through the production of energy or fuel, up to the supply to the respective means of transport through the distribution network. The indicator does not include the transport mode.

Tank-to-Wheel - energy consumption and production of emissions related to the operation of the means of transport. The indicator does not include the next life cycle of the fuel or the transport means.

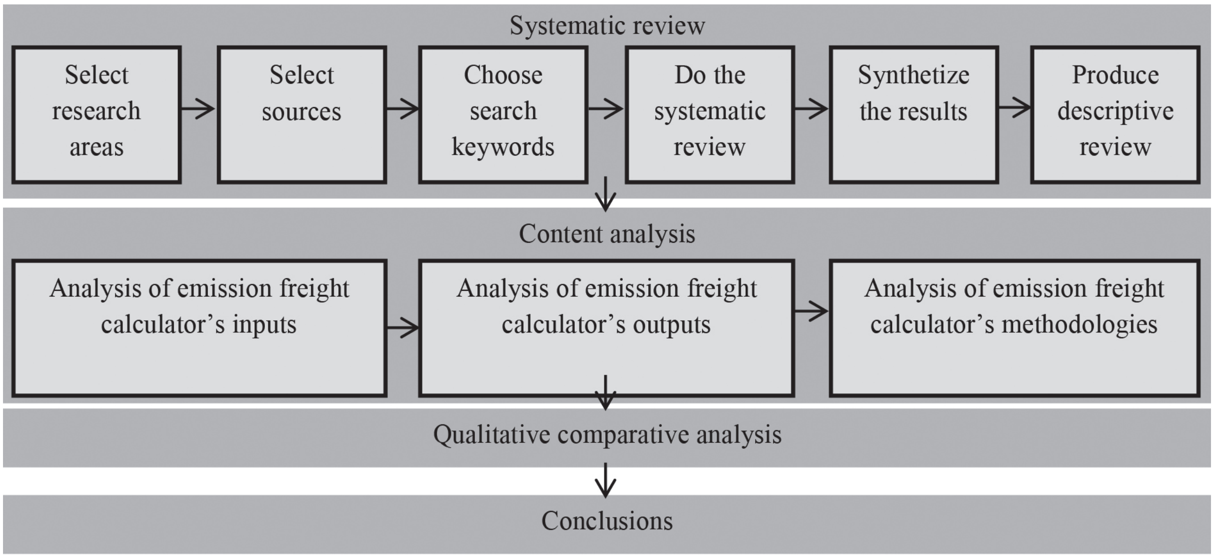


Figure 2 *Processing procedure*

Scientific methods (systematic review, content analysis, and qualitative comparative analysis), results and discussions are presented in the following sections.

3 Methods

The method of systematic review is used to search freight transport emissions calculators. The systematic review method is a systematic, explicit and repeatable procedure designed to identify, evaluate and synthesize the results of researchers, academics and practitioners [38]. The scientific method allows an author of a review to minimize its own personality and influence the content of the text by authors own views [39]. This scientific method is well known and often used by researches, for example [40-42]. The method of systematic review consists of the following steps: select research areas, select sources, choose search terms, do the systematic review, synthetize the results, produce descriptive review [38].

The method of content analysis is used to analyse inputs, outputs and freight transport emissions calculator's methodologies. The method of content analysis is a research technique for making replicable and valid inferences from texts or other meaningful matter to the context of their use [43]. The method of content analysis has been used, for example, in [44-46].

The method of qualitative comparative analysis is used to compare the freight transport emissions calculators obtained using the method of a systematic review. The method of qualitative comparative analysis is a data analysis technique for determining which logical conclusions a data set supports [47]. The qualitative comparative analysis begins with listing all the combinations of variables observed in the data set, followed by applying the rules of logical inference to determine which descriptive inferences or implications the data supports [47]. Figure 2 shows the processing procedure.

The research areas were as follows: "For what transport modes can the emission calculators be used?" and "What inputs, outputs, and methodologies use the freight transport emissions calculators?" The method of systematic review was used to search freight transport emissions calculators. The Google search was used by two independent researchers in January 2019 using the following keywords "emission calculator" and "emission freight calculator". Subsequently, the first ten freight transport emissions calculators were selected based on their position in the search engine. The content analysis of inputs, outputs and methodologies of the freight transport emissions calculators was used by three independent researchers in February 2019.

4 Results

Analysed freight transport emissions calculators selected based on their position in the search engine, were: no. 1 - CO_2 emission calculator - EECA Business [48], no. 2 - Emission calculator and carbon offset - SAS [49], no. 3 - Emissions Calculator - Cargolux [50], no. 4 - Business CO_2 emissions calculator - ClimateCare [51], no. 5 - Freight Emissions Calculator [52], no. 6 - Emission Calculators | Sustainable Freight [53], no. 7 - EcoTransIT World - Calculation [54], no. 8 - Van Donge & De Roo calculator [55], no. 9 - OOCL Carbon Calculator [56], no. 10 - Carbon Calculator | cn.ca [57]. The results of content analysis of the freight transport emissions calculators are presented in Table 1.

The first research area was "For which transport modes can be used emission calculators?" Analysed freight transport emissions calculators can be used for the following modes of transport: six of them for the maritime transport, four of them for the air and road transport, two of them for the railway transport and two of them for the RoRo transport. The RoRo transport is a specific type of maritime transport provided by vessels designed to carry

Table 1 The results of content analysis

No.	Transport modes	Inputs	Outputs	Methodology
1	Unspecified	Fuel type, Amount consumed, Units	Tonnes of CO_2e, Energy content (GJ)	Emission factors of the Ministry for the Environment
2	AiT	From, To, Cargo weight (kg), Aircraft type	Great circle distance, Revenue ton kilometre; Kilograms of CO_2, NO_x, CO, HC, Particles, SO_2; CO_2 offset	Not specified
3	AiT	From, To, Shipment weight (kg)	Kilometres, Tonnes of CO_2	Not specified
4	RoT, AiT, MaT, RoRo	Transport type, Distance (km, miles) / Hours (AiT), Freight weight (t)	Tonnes of CO_2, CO_2 offset	AiT - Aviation Emissions and Offsets; RoT, MaT - UK Government conversion factors
5	RoT	Shipment weight (lbs), Shipment distance (miles)	Tonnes of CO_2	U.S. Department of Energy
6	MaT, RoRo	Ship type, Distance (km), Total cargo (t)	Kilograms of CO_2, Comparison with another ship	CEFIC - Guidelines for Measuring and Managing CO_2
7	RoT, RaT, AiT, MaT	Weight (t, TEU), Net weight (t/TEU), Type of state, Ferry routing, Origin, Destination, Transport mode, Vehicle type, Fuel type, Emission standard, Traction, Load factor, Empty trip factor, Speed reduction	Primary energy consumption (MJ, kWh, diesel equivalents); GHG emissions (CO_2, CO_2e, NO_x, SO_x, NMHC, Particles); Distance (km); Comparison of transport modes	Methodology Report (EcoTransIT World Initiative)
8	MaT	Port of Loading, Port of Destination, Volume, Type of CCWG emission factor	Tonnes of CO_2, Distance (km)	Clean Cargo Working Group (CCWG)
9	MaT	Origin, Destination, Cargo volume (t, TEU)	CO_2 Index (kg CO_2/TEU-km or kg CO_2/t-km, Total distance (km), CO_2 emissions	Clean Cargo Working Group (CCWG)
10	RoT, RaT, MaT	Units (miles/km, t), Shipment weight (t), Vehicle type, Port of Origin, Port of Destination	Tonnes of CO_2e	Transport and Environment Database System

Notes: RoT - road transport, RaT - railway transport, AiT - air transport, MaT - maritime transport, RoRo - Roll-on/roll-off ships, NMHC - Non-methane hydrocarbons, GHG - greenhouse gas

wheeled cargo, such as cars, trucks, semi-trailer trucks, trailers, and railroad cars. A comprehensive multimodal emission calculator has not been found within the analysed calculators. If a user needs to calculate emissions of multimodal transport, transportation must be divided into sections according to the different transport modes. Subsequently, the user has to add the emissions from the individual sections.

The second research area was "What inputs, outputs, and methodologies use the freight transport emissions calculators?" Basic input data of most analysed freight transport emissions calculators was the same or similar, for example: from/origin/port of loading, to/destination/port of destination or direct entry of distance/shipment distance/flight time. Further data is generally related to the weight of the shipment/cargo, weight/freight weight/volume/cargo volume or the net weight. Some freight transport emissions calculators allow the user to enter additional specific input data, for example: fuel type and amount consumed, type of means of transport (aircraft type/ship type/vehicle type etc.), type of goods (light/average/heavy), cargo type (bulk/liquid/other), ferry routing, type of traction, load factor, emission standard, empty trip factor and speed reduction. Most calculators allow the user to choose from several units (km/miles/hours, kg/t/lbs/TEU etc.). All analysed calculators contain output data on CO_2 emissions (calculators differ only in units). Some calculators also included the following output data: energy consumption; amount of CO, HC, NO_x, SO_x, NMHC, particles; the possibility of offsetting emissions; total distance and comparison of transport modes.

Some freight transport emissions calculators do not specify the calculation methodology used. Other freight transport emissions calculators are based on the following approaches: Emission factors of the Ministry for the Environment; Aviation Emissions and Offsets; UK Government conversion factors; U.S. Department of Energy; CEFIC - Guidelines for Measuring and Managing CO_2; Methodology Report (EcoTransIT World Initiative); Clean Cargo Working Group or Transport and Environment Database System.

5 Discussion

After evaluating all the analysed freight transport emissions calculators, the use of EcoTransIT World calculator can be recommended, because that is the most comprehensive freight transport emissions calculator. The EcoTransIT World calculator allows choosing between standard and extended versions. The calculator can be used to calculate emissions from the following modes of the freight transport: road transport (truck), rail transport (train), air transport (airplane), sea and maritime transport (sea ship and barge). The EcoTransIT World calculator also allows specifying a large number of input variables and generates a large number of output variables in tabular and graphical form. This calculator distinguishes the type of output emissions (Well-to-Wheel, Well-to-Tank and Tank-to-Wheel). It transparently refers to the used methodology - Ecological Transport Information Tool for Worldwide Transports: Methodology and Data Update 2018 developed by IVE mbH - Ingenieurgesellschaft fur Verkehrswesen mbH Hannover, Infras AG -Consulting, Analysis and Research and ifeu - Institut fur Energie - und Umweltforschung Heidelberg GmbH.

Some analysed freight transport emissions calculators are available for one mode of transport only (usually for air transport and maritime transport); some calculators do not have a transparently specified methodology for emissions calculation. Most calculators do not allow specifying input variables sufficiently. Nine out of ten freight transport emissions calculators do not distinguish the approach to measuring emissions (Well-to-Wheel, Well-to-Tank and Tank-to-Wheel) as the output variable.

The big problem is the fact that the analysed freight transport emissions calculators do not allow the user to easily calculate the emissions of the multimodal transport, because multimodal transport consists of several modes of transport. If a user needs to calculate emissions of multimodal transport, transportation must be divided into sections according to the different transport modes.

The limit of the research is the number of freight transport emissions calculators studied, because only ten emission calculators were studied. Therefore, all conclusions are valid only for these ten freight transport emissions calculators. On the other hand, it is necessary to emphasize that these freight transport emissions calculators are the best positioned in the Google search engines after entering defined keywords.

6 Conclusion

The issue of the freight transport emissions is a very actual issue. This issue is addressed not only by researches but by companies, as well. Some companies are profiled as a socially responsible and in the context of their business activities take into account environmental and social aspects of their activities, products and services. Companies integrate environmental and social aspects into the decision-making processes at strategic and tactical-operational levels and use appropriate management tools to support the decision-making processes. Emission calculators can be included as logistics planning tools. Their use helps companies to reduce the negative environmental impact of logistics processes. The public and other stakeholders (business partners, employees, the state, etc.) are interested in this issue.

Nowadays, the largest companies have their own emission calculators, but most other companies use freely available emission calculators. This was one of the reasons for the analysis. The aim of the article was to analyse the approaches used in free available emission calculators arising from the freight transport. The focus was on the transport modes that calculators include, input data, output data, and methodologies used to calculate emissions. Use of EcoTransIT World calculator is recommended due to its transparency, complexity, structure of inputs and outputs and user-friendliness. On the other hand, it would be very beneficial to create a similar freight multimodal emission calculator that will be comprehensive and will cover all the emissions resulting from the implementation of multimodal transport. The results of the analysis could also be used to create new types of emission calculators. In the future, emission calculators should become a commonly used logistics planning tool, not only in logistics companies, but also in all the small, medium and large companies, regardless of the business branch. Appropriate tools should also be used at the level of the state administration and local governments as a support to the decision-making processes. The use of these tools could contribute to changing the approach to logistics planning, both within companies and supply chains, as well as within cities, conurbations and regions.

Acknowledgement

This article is published within realization of the project "Cooperation in Applied Research between the University of Pardubice and companies in the Field of Positioning, Detection and Simulation Technology for Transport Systems (PosiTrans)", registration No.: CZ.02.1.01/0.0/0.0/17_049/0008394.

References

[1] PETRO, F., KONECNY, V. calculation of emissions from transport services and their use for the internalisation of external costs in road transport. *Procedia Engineering* [online]. 2017, **192**, p. 677-682. eISSN 1877-7058. Available from: https://doi.org/10.1016/j.proeng.2017.06.117

[2] DANISH, BALOCH, M. A., SUAD, S. Modelling the impact of transport energy consumption on CO_2 emission in Pakistan: evidence from ARDL approach. *Environmental Science and Pollution Research* [online]. 2018, **25**(10), p. 9461-9473. ISSN 0944-1344, eISSN 1614-7499. Available from: https://doi.org/10.1007/s11356-018-1230-0

[3] LITMAN, T. A. *Sustainable transportation indicators*. Sustainable Transportation Indicators Subcommittee of the Transportation Research Board, 2008.

[4] Assessment and decision making for sustainable transport - European Council of Ministers of Transport [online]. Paris Cedex: OECD Publications, 2004. ISBN 92-821-1311-6. Available from: https://www.itf-oecd.org/sites/default/files/docs/04assessment.pdf

[5] PENG, T., OU, X., YUAN, Z., YAN, X., ZHANG, X. Development and application of China provincial road transport energy demand and GHG emissions analysis model. *Applied Energy* [online]. 2018, **222**, p. 313-328. ISSN 0306-2619. Available from: https://doi.org/10.1016/j.apenergy.2018.03.139

[6] CO_2 emissions from fuel combustion highlights 2015 - International Energy Agency, OECD [online]. Paris Cedex: International Energy Agency and Organization for Economic Cooperation and Development, 2015. Available from: https://iea.org/publications/freepublications/publication/CO2EmissionsfromFuelCombustionHighlights2017.pdf

[7] CO_2 emissions from fuel combustion highlights 2016 - International Energy Agency, OECD [online]. Paris Cedex: International Energy Agency and Organization for Economic Cooperation and Development, 2016. Available from: https://emis.vito.be/sites/emis.vito.be/files/articles/3331/2016/CO2EmissionsfromFuelCombustion_Highlights_2016.pdf

[8] LLANO, C., PEREZ-BALSALOBRE, S., PEREZ-GARCIA, J. Greenhouse gas emissions from intra-national freight transport: measurement and scenarios for greater sustainability in Spain. *Sustainability* [online]. 2018, **10**(7), p. 1-33. eISSN 2071-1050. Available from: https://doi.org/10.3390/su10072467

[9] YOON, Y., YANG, M., KIM, J. An analysis of CO_2 emissions from international transport and the driving forces of emissions change. *Sustainability* [online]. 2018, **10**(5), p. 1-18. eISSN 2071-1050. Available from: https://doi.org/10.3390/su10051677

[10] STOCKER, T. F., QIN, D., PLATTNER, G.-K., TIGNOR, M., ALLEN, S. K., BOSCHUNG, J., NAUELS, A., XIA, Y., BEX, V., MIDGLEY, P. M. (eds.) *Climate change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change*. Cambridge, United Kingdom and New York, USA: Cambridge University Press, 2013. ISBN 978-1-107-05799-1.

[11] HENDRICKS, J., RIGHI, M., DAHLMANN, K., GOTTSCHALDT, K., GREWE, V., PONATER, M., SAUSEN, R., HEINRICHTS, D., WINKLER, Ch., WOLFERMANN, A., KAMPFFMEYER, T., FRIEDRICH, R., KLOETZKE, M., KUGLER, U. Quantifying the climate impact of emissions from land-based transport in Germany. *Transportation Research Part D-Transport and Environment* [online]. 2018, **65**, p. 825-845. ISSN 1361-9209, eISSN 1879-2340. Available from: https://doi.org/10.1016/j.trd.2017.06.003

[12] FUGLESTVEDT, J. S., BERNTSEN, T., MYHRE, G., RYPDAL, K., SKEIE, R. B. Climate forcing from the transport sectors. *Proceedings of the National Academy of Sciences of the United States of America* [online]. 2008, **105**, p. 454-458. ISSN 0027-842, eISSN 1091-6490. Available from: https://doi.org/10.1073/pnas.0702958104

[13] EYRING, V., ISAKSEN, I. S. A., BERNTSEN, T., COLLINS, W. J., CORBETT, J. J., ENDRESEN, O., GRAINGER, R. G., MOLDANOVA, J., SCHLAGER, H., STEVENSON, D. S. Transport impacts on atmosphere and climate: shipping. *Atmospheric Environment* [online]. 2010, **44**, p. 4735-4771. ISSN 1352-2310. Available from: https://doi.org/10.1016/j.atmosenv.2009.04.059

[14] LEE, D. S., PITARI, G., GREWE, V., GIERENS, K., PENNER, J. E., PETZOLD, A., PRATHER, M. J., SCHUMANN, U., BAIS, A., BERNSTEN, T., IACHETTI, D., LIM, L. L., SAUSEN, R. Transport impacts on atmosphere and climate: aviation. *Atmospheric Environment* [online]. 2010, **44**, p. 4678-4734. ISSN 1352-2310. Available from: https://doi.org/10.1016/j.atmosenv.2009.06.005

[15] SAUSEN, R. Transport impacts on atmosphere and climate. *Atmospheric Environment* [online]. 2010, 44, p. 4646-4647. ISSN 1352-2310. Available from: https://doi.org/10.1016/j.atmosenv.2010.02.033

[16] UHEREK, E., HALENKA, T., BORKEN-KLEEFELD, J., BALKANSKI, Y., BERNSTEN, T., BORREGO, C., GAUSS, M., HOOR, P., JUDA-REZLER, K., LELIEVELD, J., MELAS, D., RYPDAL, K., SCHMID, S. Transport impacts on atmosphere and climate: land transport. *Atmospheric Environment* [online]. 2010, **44**, p. 4772-4816. ISSN 1352-2310. Available from: https://doi.org/10.1016/j.atmosenv.2010.01.002

[17] SAUSEN, R., GIERENS, K., EYRING, V., HENDRICKS, J., RIGHI, M. Climate impact of transport. In: SCHUMANN, U. (Ed.) *Atmospheric physics. Background - methods - trends*. Berlin, Heidelberg: Springer, 2012. p. 711-725. ISBN 978-3-642-30183-4.

[18] SINGH, V., SAHU, S. K., KESARKAR, A. P., BISWAL, A. Estimation of high resolution emissions from road transport sector in a megacity Delhi. *Urban Climate* [online]. 2018, **26**, p. 109-120. eISSN 2212-0955. Available from: https://doi.org/10.1016/j.uclim.2018.08.011

[19] GURJAR, B. R., RAVINDRA, K., NAGPURE, A. S. Air pollution trends over Indian megacities and their local-to-global implications. *Atmospheric Environment* [online]. 2016, **142**, p. 475-495. ISSN 1352-2310. Available from: https://doi.org/10.1016/j.atmosenv.2016.06.030

[20] SINGH, V., SOKHI, R. S., KUKKONEN, J. PM2.5 concentrations in London for 2008 - A modelling analysis of contributions from road traffic. *Journal of the Air and Waste Management Association* [online]. 2014, **64**(5), p. 509-518. ISSN 1096-2247, eISSN 2162-2906. Available from: https://doi.org/10.1080/10962247.2013.848244

[21] GUTTIKUNDA, S. K., CALORI, G. GIS Based emissions inventory at 1 km x 1 km spatial resolution for air pollution analysis in Delhi, India. *Atmospheric Environment* [online]. 2013, **67**, p. 101-111. ISSN 1352-2310. Available from: https://doi.org/10.1016/j.atmosenv.2012.10.040

[22] BRAND, C., ANABLE, J., MORTON, C. Lifestyle, efficiency and limits: modelling transport energy and emissions using a socio-technical approach. *Energy Efficiency* [online]. 2019, **12**(1), p. 187-207. ISSN 1570-646X, eISSN 1570-6478. Available from: https://doi.org/10.1007/s12053-018-9678-9

[23] YANG, C., MCCOLLUM, D., MCCARTHY, R., LEIGHTY, W. Meeting an 80% reduction in greenhouse gas emissions from transportation by 2050: a case study in California. *Transportation Research Part D: Transport and Environment* [online]. 2009, **14**(3), p. 147-156. ISSN 1361-9209, eISSN 1879-2340. Available from: https://doi.org/10.1016/j.trd.2008.11.010

[24] LIU, L., WANG, K., WANG, S., ZHANG, R., TANG, X. Assessing energy consumption, CO_2 and pollutant emissions and health benefits from China's transport sector through 2050. *Energy Policy* [online]. 2018, **116**, p. 382-396. ISSN 0301-4215, eISSN 1873-6777. Available from: https://doi.org/10.1016/j.enpol.2018.02.019

[25] Supply chain decarbonization: the role of logistics and transport in reducing supply chain carbon emission - World Economic Forum [online]. Geneva, Switzerland: The Framework of the Logistics and Transport Partnership Programme, 2009. Available from: http://www3.weforum.org/docs/WEF_LT_SupplyChainDecarbonization_Report_2009.pdf

[26] CO_2 emissions from fuel combustion 2017 - International Energy Agency [online]. 2017. Available from: http://www.indiaenvironmentportal.org.in/files/file/CO2EmissionsfromFuelCombustionHighlights2017.pdf

[27] ABBASI, M., NILSEN, F. Developing environmentally sustainable logistics: exploring themes and challenges from a logistics service providers' perspective. *Transportation Research Part D: Transport and Environment* [online]. 2016, **46**, p. 273-283. ISSN 1361-9209, eISSN 1879-2340. Available from: https://doi.org/10.1016/j.trd.2016.04.004

[28] MUBARAK, A., FACHRUDDIN, Y. Development of a framework for the calculation of co_2 emissions in transport and logistics in Southeast Asia. *International Journal of Technology* [online]. 2018, **9**(4), p. 787-796. ISSN 2086-9614, eISSN 2087-2100. Available from: https://doi.org/10.14716/ijtech.v9i4.1432

[29] TANIGUCHI, E., THOMPSON, R. G., YAMADA, T. New opportunities and challenges for city logistics. *Transportation Research Procedia* [online]. 2015, **12**, p. 5-13. ISSN 2352-1465. Available from: https://doi.org/10.1016/j.trpro.2016.02.004

[30] OSKARBSKI, J., KASZUBOWSKI, D. Applying a mesoscopic transport model to analyse the effects of urban freight regulatory measures on transport emissions - an assessment. *Sustainability* [online]. 2018, **10**(7), p. 1-18. eISSN 2071-1050. Available from: https://doi.org/10.3390/su10072515

[31] BEHRENDS, S., LINDHOLM, M., WOXENIUS, J. Impact of urban freight transport: a definition of sustainability from an actor's perspective. *Transportation Planning and Technology* [online]. 2008, **31**(6), p. 693-713. ISSN 0308-1060. Available from: https://doi.org/10.1080/03081060802493247

[32] WADUD, Z., CHINTAKAYALA, P. K. Personal carbon trading: trade-off and complementarity between in-home and transport related emissions reduction. *Ecological Economics* [online]. 2019, **156**, p. 397-408. ISSN 0921-8009, eISSN 1873-6106. Available from: https://doi.org/10.1016/j.ecolecon.2018.10.016

[33] LIU, F., ZHAO, F., LIU, Z., HAO, H. The impact of fuel cell vehicle deployment on road transport greenhouse gas emissions: the China case. *International Journal of Hydrogen Energy* [online]. 2018, **43**(50), p. 22604-22621. ISSN 0360-3199. Available from: https://doi.org/10.1016/j.ijhydene.2018.10.088

[34] NATR, L. *Earth like a glass: why are you afraid of* CO_2? (In Czech). Praha: Academia, 2006. ISBN 80-200-1362-8.

[35] United Nations framework convention on climate change - Ministry of the Environment of the Czech Republic [online]. 2014. Available from: https://www.mzp.cz/en/climate_energy

[36] CICHOSZ, M., PLUTA-ZAREMBA, A. How to improve freight transport emissions management? *Logforum* [online]. 2019, **15**(1), p. 93-105. ISSN 1734-459X. Available from: https://doi.org/10.17270/J.LOG.2019.312

[37] ERIKSSON, L., NIELSEN, L. *Modelling and control of engines and drivelines* [online]. Chennai, India: John Wiley and Sons, 2014. ISBN 978-1-118-47999-5. Available from: https://doi.org/10.1002/9781118536186.fmatter

[38] FINK, A. *Conducting research literature reviews: from the internet to paper*. Los Angeles: Sage, 2014. ISBN 978-1-452-25949-9.

[39] PETTICREW, M., ROBERTS, H. *Systematic reviews in the social sciences: a practical guide*. Oxford: John Wiley & Sons, 2008. ISBN 978-1-405-12110-1.

[40] REZAZADEH, F., PARIA, D., JAFARPOUR, D. Laser effects on the prevention and treatment of dentinal hypersensitivity: a systematic review. *Journal of Lasers in Medical Sciences* [online]. 2019, **10**(1), p. 1-11. I SSN 2008-9783, eISSN 2228-6721. Available from: https://doi.org/10.15171/jlms.2019.01

[41] ENGELEN, L., CHAU, J., YOUNG, S., MACKEY, M., JEYAPALAN, D., BAUMAN, A. Is activity-based working impacting health, work performance and perceptions? A systematic review. *Building Research and Information* [online]. 2019, **47**(4), p. 468-479. ISSN 0961-3218, eISSN 1466-4321. Available from: https://doi.org/10.1080/09613218.2018.1440958

[42] PERERA, H.-N., HURLEY, J., FAHIMNIA, B., REISI, M. The human factor in supply chain forecasting: a systematic review. *European Journal of Operational Research* [online]. 2019, **274**(2), p. 574-600. ISSN 0377-2217. Available from: https://doi.org/10.1016/j.ejor.2018.10.028

[43] KRIPPENDORFF, K. *Content analysis: an introduction to its methodology*. Thousand Oaks: Sage Publications, 2003. ISBN 978-0761915447.

[44] SOULE, E. K., SAKUMA, K.-L. K., PALAFOX, S., POKHREL, P., HERZOG, T. A., THOMPSON, N., FAGAN, P. Content analysis of internet marketing strategies used to promote flavored electronic cigarettes. *Addictive Behaviors* [online]. 2019, **91**, p. 128-135. ISSN 0306-4603, eISSN 1873-6327. Available from: https://doi.org/10.1016/j.addbeh.2018.11.012

[45] SOLDATENKO, D., BACKER, E. A content analysis of cross-cultural motivational studies in tourism relating to nationalities. *Journal of Hospitality and Tourism Management* [online]. 2019, **38**, p. 122-139. ISSN 1447-6770. Available from: https://doi.org/10.1016/j.jhtm.2018.12.004

[46] KRAJEWSKI, J. M. T., SCHUMACHER, A. C., DALRYMPLE, K. E. Just turn on the faucet: a content analysis of PSAs about the global water crisis on YouTube. *Environmental Communication* [online]. 2019, **13**(2), p. 255-275. ISSN 1752-4032, eISSN 1752-4040. Available from: https://doi.org/10.1080/17524032.2017.1373137

[47] RAGIN, CH. C. *The comparative method: moving beyond qualitative and quantitative strategies*. Oakland: University of California Press, 1987. ISBN: 978-0-520-28003-8.

[48] CO_2 emission calculator - EECA Business [online]. [Viewed 2019-01-03]. Available from: https://www.eecabusiness.govt.nz/tools/wood-energy-calculators/co2-emission-calculator/

[49] Emission calculator and carbon offset - SAS [online]. [Viewed 2019-01-05]. Available from: https://www.sasgroup.net/en/emission-calculator-and-carbon-offset/

[50] Emissions calculator - Cargolux [online]. [Viewed 2019-01-06]. Available from: https://www.cargolux.com/Our-Expertise/e-services/Emissions-Calculator

[51] Business CO_2 emissions calculator - ClimateCare [online]. [Viewed 2019-01-08]. Available from: http://www.climatecare.org/business/business-co2-calculator/

[52] Freight emissions calculator - Delivered GrEAn [online]. [Viewed 2019-01-10]. Available from: http://www.freightemissionscalculator.com/

[53] Ship type carbon emissions calculator - Sustainable freight [online]. [Viewed 2019-01-12]. Available from: http://www.sustainablefreight.com.au/tools-and-programs/emission-calculators/ship-type-carbon-emissions-calculator

[54] Calculation - EcoTransIT World [online]. [Viewed 2019-01-13]. Available from: https://www.ecotransit.org/calculation.en.html

[55] CO_2 calculator - Van Donge & De Roo Group [online]. [Viewed 2019-01-16]. Available from: https://www.vandongederoo.com/co2-calculator/

[56] OOCL carbon calculator - Orient Overseas Container Line [online]. [Viewed 2019-01-19]. Available from: https://www.oocl.com/eng/aboutoocl/Environmentalcare/ooclcarboncalculator/Pages/default.aspx

[57] Carbon calculator - Canadian National Railway Company [online]. [Viewed 2019-01-24]. Available from: https://www.cn.ca/en/delivering-responsibly/environment/emissions/carbon-calculator/

Kamil Krasuski

APPLICATION THE SINGLE DIFFERENCE TECHNIQUE IN AIRCRAFT POSITIONING USING THE GLONASS SYSTEM IN THE AIR TRANSPORT

The article presents the possibility of using the Between Satellite Single Difference method (BSSD) in the precise determination of the aircraft position in the Global Navigation Satellite System GLONASS navigation system. The paper presents the mathematical model of the BSSD method, describes the research test and presents the results of conducted examinations. The research test was conducted within the implementation of the GLONASS satellite technique in air navigation. The test research uses the actual GLONASS navigation data registered by the Topcon HiperPro receiver, mounted onboard a Cessna 172 aircraft. Obtained findings of the research work are interesting from the perspective of implementation of the GLONASS satellite technique in aviation. It should be emphasized that standard deviations of the determined position of the Cessna 172, using the BSSD method, do not exceed 2 m. The article also determines the accuracy of a position of the Cessna 172 in the GLONASS solution with reference to a solution in the GPS navigation system.

Keywords: *GLONASS, ICAO, accuracy, GPS, aviation test*

1 Introduction

Numbers of aeronautical operations in the air transport are still growing up on the world [1]. In addition, the aircraft position in different phase of flight should be permanently monitored in aeronautical operation [2-3]. The GNSS satellite technique is applied in monitoring of aircraft position in the air transport. The concept of using the GNSS satellite navigation systems in aviation has been developed and implemented by the ICAO [4]. In accordance with the ICAO recommendations, the GNSS satellite systems only supplement on-board aircraft avionics. In order to improve the performance of GNSS navigation systems, it is necessary to implement the augmentation products for conducting the air navigation. The ICAO has identified certification for the GPS and GLONASS satellite systems as additional systems for on-board avionics. Moreover, in order to improve the performance of GNSS navigation systems in aviation, the ICAO organization implemented ABAS, SBAS, GBAS augmentation systems [5]. The GLONASS satellite system can be used as an independent navigation sensor used in precise aircraft positioning [6], an external module for the ABAS augmentation system coupled with the RAIM controller belonging to the computational subassemblies of the on-board computer FMS [7], navigation sensor working with the geostationary satellite systems, which is to facilitate positioning in the SBAS system [8], navigation sensor working with ground radio systems, which support positioning in the GBAS system [9], acting as the hybrid GNSS/INS navigation system [10]. The GLONASS satellite system plays a major role in the air navigation, complementing the NAVSTAR GPS navigation system. It should be noted that the GLONASS system is constantly being upgraded, thus the number of satellites in the GLONASS constellation is often changing [11].

The main aim of this article is to assess the accuracy and reliability of determining an aircraft position in the GLONASS system. In particular, in the numerical analysis the authors attempted at recovering the position of the Cessna 172 during a test flight over the aerodrome EPDE in Deblin, Poland. The position of the Cessna 172 is calculated based on the differential positioning BSSD method (Difference Between Single Satellite) for the GLONASS code observations. The test research uses the GLONASS code observations registered by the Topcon HiperPro receiver, mounted on-board the Cessna 172 aircraft. The article is divided into 5 parts: part one is an introduction relating to description of research problems, part two is a description of the research BSSD model, chapter three is a description of the research experiment, section four contains research results and discussion, chapter five comprises final conclusions.

2 Mathematical model of the BSSD method in the GLONASS system

The basic equation of the mathematical model for the BSSD positioning method can be represented as follows [12]:

$$\begin{aligned}\Delta P1_{ij} = \Delta\rho_{ij} + c\cdot\Delta dts_{ji} + \Delta I_{ij} + \Delta T_{ij} + \\ + \Delta SIFCB_{ij,L1} + \Delta M_{ij,L1}\end{aligned}, \qquad (1)$$

Kamil Krasuski*
Department of Air Navigation, Faculty of Aviation and Aeronautics, Polish Air Force University, Deblin, Poland
*E-mail of corresponding author: k.krasuski@law.mil.pl

where: Δ - the single difference operator for the GLONASS code measurements allows determining the difference in code measurements from two satellites tracked by one receiver in the same measurement period,
$P1_{ij} = P1_i - P1_j$ - the value of a single code difference between satellites i and j on L1 frequency in the GLONASS system (expressed in meters),
i - GLONASS satellite index,
j - GLONASS satellite index,
c - light speed (expressed in m/s),
$\rho_{ij} = \rho_i - \rho_j$ - difference in geometry distance between satellites i and j on L1 frequency in the GLONASS system (expressed in meters),

$$\rho_i = \sqrt{(x - X_i)^2 + (y - Y_i)^2 + (z - Z_i)^2},$$

$$\rho_j = \sqrt{(x - X_j)^2 + (y - Y_j)^2 + (z - Z_j)^2},$$

(x,y,z) - coordinates of the aircraft in the XYZ geocentric frame (expressed in meters),
(X_i,Y_i,Z_i) - i-th satellite coordinates in the GLONASS system (expressed in meters),
(X_j,Y_j,Z_j) - j-th satellite coordinates in the GLONASS system (expressed in meters),
dts_{ji} - difference in satellites tracking between i and j satellites on L1 frequency in theGLONASS system (expressed in seconds),
I_{ij} - difference in ionosphere delay between i and j satellites on L1 frequency in GLONASS system (expressed in meters),
T_{ij} - difference between values of the troposphere delay between satellites i and j on L1 frequency in the GLONASS system (expressed in meters),
$SIFCB_{ij,L1}$ - difference between Satellite Inter-Frequency Code Biases values between satellites i and j on L1 frequency in the GLONASS system (expressed in meters),
$M_{ij,L1}$ - difference in value of multipath effect and measurement noise between satellites i and j on L1 frequency in the GLONASS system (expressed in meters).

Equation (1) is resolved on the basis of the method of least squares as below [13]:

$$\begin{cases} \mathbf{Q_x} = \mathbf{N}^{-1} \cdot \mathbf{L} \\ \mathbf{v} = \mathbf{A} \cdot \mathbf{Q_x} - \mathbf{dl} \\ m0_{post} = \sqrt{\dfrac{[\mathbf{pvv}]}{n-k}} \\ \mathbf{C_{Qx}} = m0_{post}^2 \cdot \mathbf{N}^{-1} \\ \mathbf{m_{Qx}} = diag(\sqrt{\mathbf{C_{Qx}}}) \end{cases}, \tag{2}$$

where:
$\mathbf{Q_T}$ - vector with unknown parameters;
$\mathbf{N} = \mathbf{A^T} \cdot \mathbf{p} \cdot \mathbf{A}$ - matrix of the normal equations frame;
$\mathbf{A}$ - matrix of coefficients, matrix is full rank;
$\mathbf{p}$ - matrix of weights;
$\mathbf{L} = \mathbf{A^T} \cdot \mathbf{p} \cdot \mathbf{dl}$ - vector of absolute terms;
$\mathbf{dl}$ - vector with difference between measurements and modelled parameters;
$m0_{post}$ - standard error of unit weight a posteriori;
n - number of observations in each measurement period;
k - number of designated parameters in each measurement epoch;
$\mathbf{v}$ - vector of residuals;
$\mathbf{C_{Qx}}$ - variance-covariance matrix of parameters designated in the XYZ geocentric frame;
$\mathbf{m_{Qx}}$ - standard deviations of the designated parameters referenced to the XYZ geocentric frame.

In the least squares method, the aircraft coordinates are determined as parameters (x,y,z) referred to the geocentric frame XYZ. It should be stressed that, due to a single difference operator from the observation Equation (1), the parameter of the receiver clock error is eliminated as a product of the precise time transfer. It is also worth noting that from the difference of the observation Equation (1), the Receiver Inter-Frequency Code Bias (RIFCB) was eliminated, as well, specifying the time of the code signal travelling from the phase centre of the receiver antenna to the onboard receiver oscillator. It must be mentioned that use of a single difference operator reduces the influence of atmospheric delays (ionospheric and tropospheric delays) to determine the position of the aircraft. Moreover, in the process of developing the GLONASS code observations, it is possible to exploit the IGS precision products, such as precise satellite orbits and satellite clocks, which increase aircraft positioning accuracy. The multipath parameter in the computation process may be determined from the model or disregarded when developing the GLONASS observations. A key element in the method of least squares is to determine the aircraft positioning precision. Precision is determined by parameters of standard deviation $\mathbf{m_{Qx}}$ for all the three designated aircraft coordinates. The process of determining an aircraft position is conducted using a stochastic model in the method of least squares. In addition, the position of an aircraft is determined in an iterative process, taking into account the value of the coefficient of variation $m0_{post}$.

3 Research experiment

The practical application of the BSSD positioning method for the GLONASS satellite system in the air navigation was verified and subjected to a thorough analysis for the navigation data derived from the experiment conducted in Deblin, in south-east Poland. In the air experiment, the operation and use of the GNSS navigation systems for the airport EPDE in Deblin, Poland underwent testing. In the air experiment, the aircraft Cessna 172 was used to make a trial flight around the airport EPDE in Deblin. It needs to be mentioned that on board the Cessna 172 in the cockpit, there was a dual frequency receiver Topcon HiperPro. Due to the GPS/GLONASS satellite observations, stored and registered by the receiver Topcon HiperPro, it was possible to recover the position of the aircraft Cessna 172 in the post-processing mode. The numerical calculations to determine the position of the Cessna 172 were made in the author's original software APS (Aircraft Positioning Software) Toolbox

[14]. The APS programme (Aircraft Positioning Software) was written in the language Scilab 6.0.0 environment for the Windows operating system. The APS is a free programming tool to develop kinematic GNSS observations in the post-processing mode. The APS programme enables implementation of the GNSS code observations for the GPS and GLONASS systems. Furthermore, the APS software has 4 basic calculation modules and one descriptive module, i.e.: SPP (Single Point Positioning) module: absolute positioning with L1-C/A code observations in the satellite systems GPS and GLONASS; BSSD SPP (Between Single Satellite Difference of SPP) module: a single difference technique of the code observations L1-C/A in the navigation systems GPS and GLONASS within the SPP positioning method; IF LC (Ionosphere-Free linear combination) module: linear combination "Ionosphere-Free" for P1/P2 code observations in the satellite systems GPS and GLONASS; BSSD IF LC (Difference Between Single Satellite of IF LC) module: a single difference technique of the linear combination "Ionosphere-Free" for the code observations P1/P2 in the navigation system GPS and GLONASS; Info module: text module with a description of the operation and functioning of the APS programme. In the presented scientific article, the P1 code observations in the GLONASS system were used to recover the position of the Cessna 172 in the APS programme. For the sake of making numeric calculations, the "APS programme was configured as follows [14]:

- GNSS system: GLONASS system,
- type of observations: P code at 1st frequency,
- type of RINEX file: 2.10,
- source of satellite ephemeris data: precise ephemeris from the IGS service,
- source of satellite clock data: precise ephemeris from the IGS service,
- method of satellite position computation: 9-degrees Lagrange polynomial,
- method of the satellite clock bias computation: 9-degrees Lagrange polynomial,
- the satellite clock bias correction: satellite clock bias from precise ephemeris is corrected using Inter-Frequency Code Biases for code observations in the BSSD method,
- effect of Earth rotation and time of pseudorange travelling through atmosphere: applied,
- relativistic effect: applied,
- ionosphere source: Klobuchar model,
- troposphere source: Simple model,
- Satellite Inter-Frequency Code Biases (SIFCB): applied,
- instrumental bias for receiver: eliminated,
- receiver clock bias: eliminated,
- multipath and measurement noise: not applied,
- satellite and receiver phase center offset: based on ANTEX file from IGS service,
- Sagnac effect: applied,
- cutoff elevation: 5^0,
- positioning mode: kinematic,
- computation mode: post-processing,
- mathematical model of solution: least square estimation in iterative scheme,
- adjustment processing: applied,
- maximum number of iteration in single measurement epoch: N=10,
- number of unknown parameters: k = 3, for each measurement epoch,
- number of observations: n > 3, for each measurement epoch,
- interval of computations: 1 s,
- initial coordinates of aircraft position: based on header of the RINEX file,
- time of GNSS system: GPS Time,
- reference frame: IGS'08,
- format of output coordinates: geocentric XYZ and ellipsoidal BLh,
- local test of residuals: applied,
- global statistical test: test Chi-square,
- value of $m0_{post}$ after adjustment processing: $m0_{post} \in (0.9:1.1)$,
- significance level: $(1-\alpha)=0.95$,
- DOP coefficients: estimated,
- coefficients value for HPL and VPL level: $k_{HPL}=6.18$ and $k_{VPL}=5.33$.

4 Results and discussion

This section of the study presents the results of positioning the Cessna 172, based on the GLONASS observations for the BSSD method in the APS programme. The numerical analysis for Figures 1 and 2 concerns with determination of the internal reliability and precision of the Cessna 172 positioning for the research BSSD method in the GLONASS system. Figure 1 shows the average error values of the Cessna 172 as parameters of the standard deviation for the designated coordinates of the aircraft (x,y,z). Values of the parameters in Figure 1 are respectively: mx - standard deviation along the X axis, my - standard deviation along the Y axis, mz - standard deviation along the Z axis. Values of the parameters (mx,my,mz) are determined from the vector $\mathbf{m_{Qx}}$, as shown below [15]:

$$mx = \mathbf{m_{Qx}}(1,1);\ my = \mathbf{m_{Qx}}(2,1);\ mz = \mathbf{m_{Qx}}(3,1), \tag{3}$$

Values of the parameter mx range from 0.1 m to 1.5 m. Furthermore, the mean value of the parameter mx is equal to 0.4 m, with the statistical median also being equal to 0.4 m. Values of the parameter my range from 0.1 m to 1.2 m. Furthermore, the mean value of the parameter my is approximately 0.3 m, with the statistical median also being equal to 0.3 m. Values of the parameter mz range from 0.1 m to 1.8 m. Moreover, the mean value mz of the parameter is equal to 0.5 m, with the statistical median also being equal to 0.5 m. It should be emphasized that over 99% of all the parameter results (mx,my,mz) do not exceed the level of 1 m.

Figure 2 shows values of the dilution of precision (DOP) coefficients for the performed experimental test. It

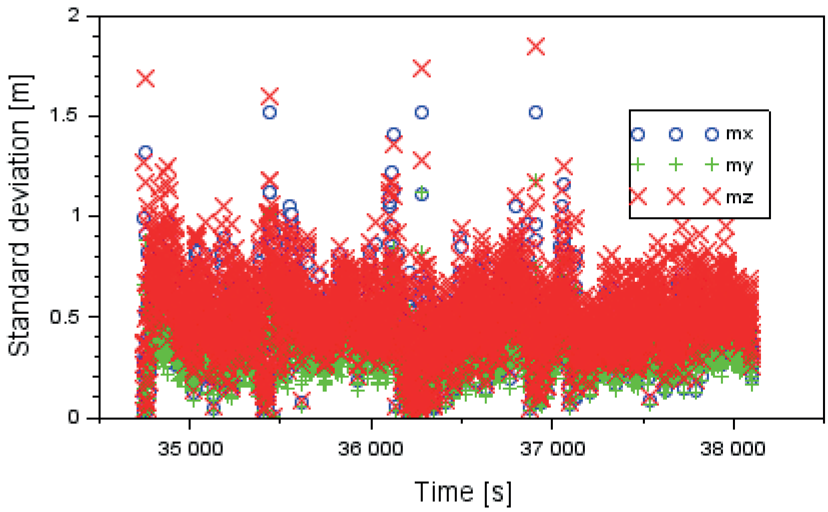


Figure 1 *Standard deviations of the Cessna 172 in the XYZ geocentric frame*

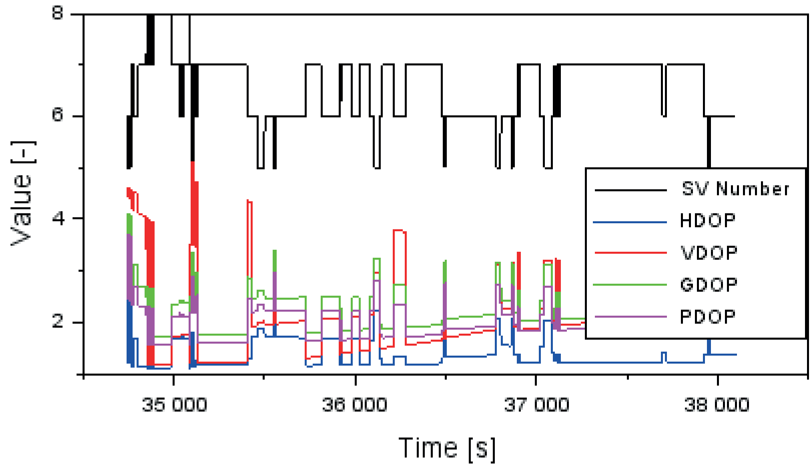


Figure 2 *Results of the DOP coefficients*

should be stressed that values of the dilution of precision are presented as a function of number of the visible GLONASS satellites. Overall, in Figure 2 the DOP coefficients are in the form of parameters: GDOP, HDOP, PDOP and VDOP [14, 16]. The value of the GDOP parameter ranges from 1.7 to 4.1. In addition, the average GDOP value is 2.2, with the median being equal to 2.1. The value of the PDOP parameter ranges from 1.5 to 3.7. In addition, the average PDOP value is 2.0, with the median being equal to 1.9. The value of the HDOP parameter ranges from 1.1 to 3.0. Moreover, the average HDOP value is 1.4, with the median being equal to 1.2. The value of the VDOP parameter ranges from 1.1 to 5.1. In addition, the average VDOP parameter value is approximately 2.0, with the median also being equal to 2.0.

Figure 2 also shows changes in the availability parameter of the navigation solution of the aircraft position in the form of a number of tracked GLONASS satellites. In this case, the number of GLONASS satellites being tracked ranged from 5 to 8 during the test flight. However, the number of GLONASS satellites facilitated continuous satellite positioning in the air transport, which means that the parameter of availability was 100% during the air experiment. Maintaining the availability parameter is vitally important in the air transport, as it ensures continuous tracking of the GLONASS signals by the onboard navigation receiver, for the pilot.

Figure 3 shows the HPL and VPL values, obtained for navigation calculations, using the GLONASS navigation system. The HPL parameter values were determined based on the relationship [17]:

$$\begin{cases} HPL = k_{HPL} \cdot \sqrt{mx^2 + my^2} = 6.18 \cdot \sqrt{mx^2 + my^2} \\ VPL = k_{VPL} \cdot mz = 5.33 \cdot mz \end{cases}. \quad (4)$$

The HPL parameter values range from 0.1 m to 9.2 m. On the other hand, the VPL parameter values range from 0.1 m to 11.8 m. The average value of the HPL parameter equals 2.7 m, whereas for the VPL parameter, it is 3.3 m. The parameters HPL and VPL specify the level of reliability of the designated aircraft position in the air transport. It can be concluded that the obtained HPL and VPL safety levels are very good and relatively low. The smaller the value of the HPL and VPL levels, the more reliable it is to determine the position of the aircraft. The reliability of HPL and

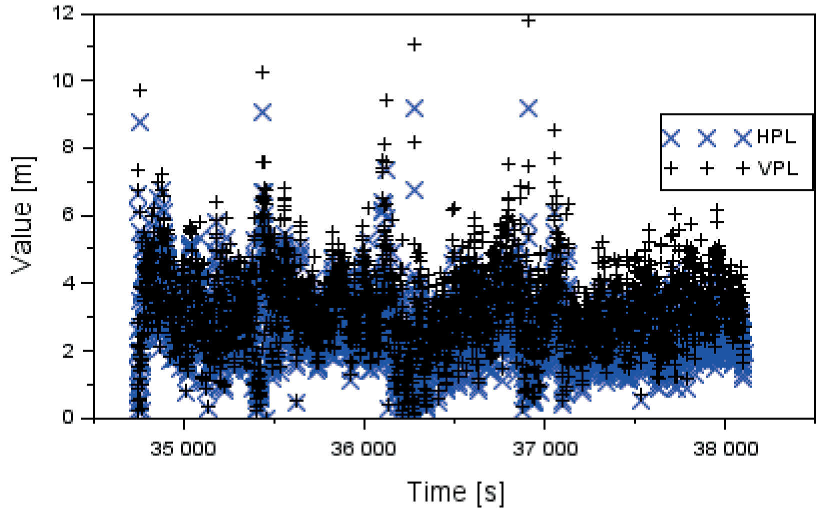


Figure 3 *Results of the HPL and VPL terms*

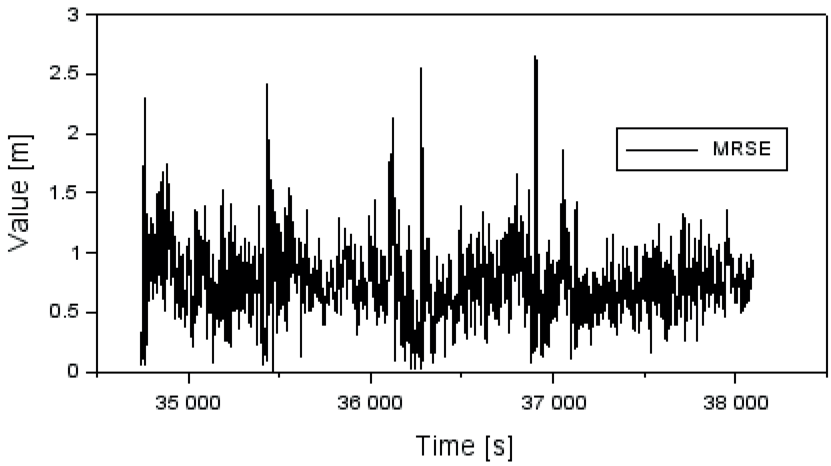


Figure 4 *Results of the MRSE term*

VPL safety levels is, in the age of the air transport, a key parameter of quality of the satellite positioning in aviation.

Figure 4 shows results of the MRSE parameter, specifying the resultant error of the Cessna 172 position in the 3D space. The MRSE parameter can be calculated from the mathematical formula [15-16]:

$$MRSE = \sqrt{mx^2 + my^2 + mz^2}\,. \tag{5}$$

The values of the MRSE parameter in the conducted experimental test ranged from 0.1 m to 2.7 m. Besides that, the average value of the MRSE parameter is 0.8 m, with the statistical median being equal to 0.7 m. It must be stressed that over 84% of all the results of the MRSE parameter do not exceed the level of 1 m and approximately 99% of all the results of the MRSE parameter do not exceed the limit of 2 m.

At a later stage, the authors determined the accuracy of designating the Cessna 172 coordinates for the BSSD method, in the GLONASS system. In particular, the authors made a comparison of the designated coordinates of the Cessna 172 in the GLONASS system to the solution in the GPS navigation system for the same research method. The GPS navigation solution of the Cessna 172 position for the BSSD research method has also been designated in the APS Toolbox software package. In the assessment of the accuracy of solutions of the Cessna 172, a comparison of geocentric coordinates (x,y,z) in the GLONASS and GPS solution was made. Moreover, the difference for these coordinates was determined, see below [18]:

$$\begin{aligned} dx &= x_{GLO} - x_{GPS} \\ dy &= y_{GLO} - y_{GPS} \\ dz &= z_{GLO} - z_{GPS} \end{aligned} \tag{6}$$

where:

x_{GLO} - x coordinate of aircraft based on the GLONASS solution, see Equation (1),

x_{GPS} - x coordinate of aircraft based on the GPS solution,

y_{GLO} - y coordinate of aircraft based on the GLONASS solution, see Equation (1),

y_{GPS} - y coordinate of aircraft based on the GPS solution,

z_{GLO} - z coordinate of aircraft based on the GLONASS solution, see Equation (1),

z_{GPS} - z coordinate of aircraft based on the GPS solution.

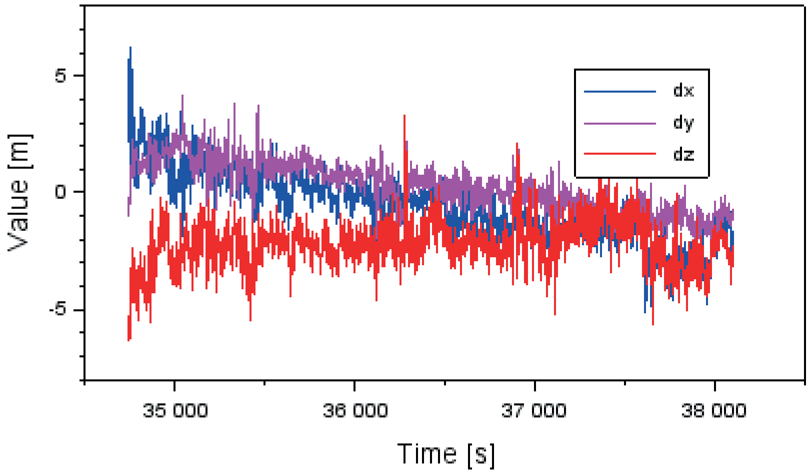


Figure 5 *Comparison of the Cessna 172 coordinates based on the GLONASS and GPS data*

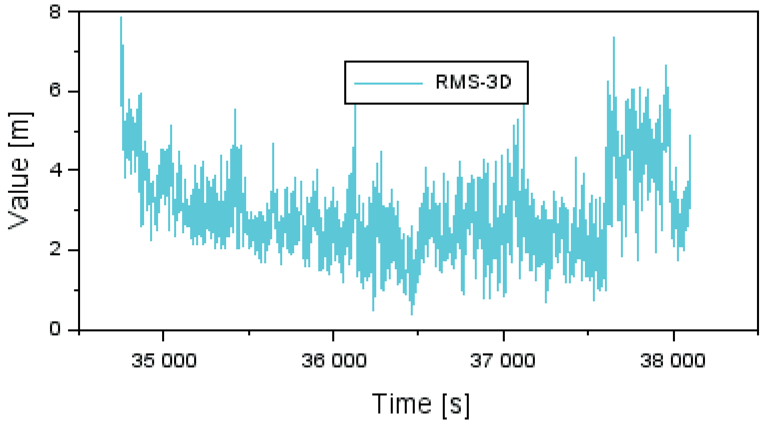


Figure 6 *Results of the 3D-error parameter*

Obtained values of the parameters (dx,dy,dz) have been presented in Figure 5. The mean value of the parameter dx is - 0.6 m, with the RMS error being equal to 1.5 m. Furthermore, the dispersion of the obtained parameter results dx ranges from - 5.2 m to + 6.3 m. The mean value of the parameter dy is + 0.27 m, with the RMS error being equal to 1.1 m. Moreover, the dispersion of the obtained results of the parameter dy ranges from - 2.5 m to + 4.2 m. The mean value of the parameter dz is - 2.2 m, with the RMS error being equal to 1 m. Besides that, the dispersion of the obtained results of the parameter dz is between - 6.4 and + 3.3 m. The parameter of accuracy is one of the factors determining the quality of the satellite positioning in transport. It can be concluded that the accuracy of positioning is officially certified by the ICAO for the GLONASS system. For pilots, it is important information since it determines which GNSS navigation system can be used while executing the air operations. Besides that, the ICAO certification guarantees that the quality of the navigation data from the GLONASS satellite system is sufficient for proper navigation in the horizontal plane LNAV and in the vertical VNAV plane, respectively. Therefore, the limits of accuracy for the LNAV and VNAV navigation must have official recommendation to be used in the air transport.

In another accuracy test, the authors determined the shift vector of coordinates in the 3D space, between the GPS and GLONASS solutions, in the form of the 3D-error parameter, as below [19-20]:

$$3D - error = \sqrt{dx^2 + dy^2 + dz^2}\,. \tag{7}$$

Values of the 3D-error parameter are presented graphically in Figure 6. Value of the 3D-error parameter ranges from 0.4 m to 7.9 m. In addition, the mean value of the 3D-error parameter is 2.9 m, with the median being equal to 2.8 m. It should be emphasized that approximately 17% of all the results of the 3D-error parameter do not exceed 2 m, and approximately 85% of all the results of the 3D-error parameter do not exceed the limit of 4 m.

5 Conclusions

The article assesses the accuracy and reliability of determining the position of the aircraft Cessna 172, using the positioning technique Difference Between Single Satellite (BSSD) in the GLONASS system. The numerical calculations were carried out in the author's original software Aircraft Positioning Software (APS), adapted to the development of the GNSS observations, for the needs of air navigation. In the numerical calculations, the authors used real GLONASS navigation data from the receiver Topcon HiperPro, mounted on board the aircraft Cessna 172. The article presents the values of standard deviations of the designated coordinates of the aircraft Cessna 172 in the XYZ geocentric frame, as well as of the MRSE position error. The values of standard deviations are under 2 m. On the other hand, values of the MRSE parameter are less than 3 m. Furthermore, in the article the authors verified the designated coordinates of the Cessna 172 in order to determine the accuracy of the research method. The article compares the coordinates of the Cessna 172 from the GLONASS and GPS solutions. The RMS error of comparing the coordinates of the Cessna 172 in the GPS and GLONASS solutions does not exceed 1.5 m along all the axes of the XYZ geocentric frame. The results of the research work on use of the GLONASS system in aviation are very promising. In the future, the authors plan to further develop the use of the GLONASS satellite navigation system for the air navigation.

Acknowledgements

This paper was supported by Polish Air Force University for 2019 year.

References

[1] MCCONNACHIE, D., BONNEFOY, P., BELLE, A. Investigating benefits from continuous climb operating concepts in the national airspace system: data and simulation analysis of operational and environmental benefits and impacts. 11th USA/Europe Air Traffic Management Research and Development Seminar ATM 2015: proceedings. 2015.

[2] ERRICO, A., VITO, V. D., FEDERICO, L. Study on continuous descent operation for efficient air transport system. 16th AIAA Aviation Technology, Integration, and Operations Conference : proceedings. 2016.

[3] NOVAK, D., BUCAK, T., RADISIC T. Development, Design and flight test evaluation of continuous descent approach procedure in FIR Zagreb. *Promet - Traffic & Transportation* [online]. 2012, **21**(5), p. 319-329. ISSN 0353-5320, eISSN 1848-4069. Available from: https://doi.org/10.7307/ptt.v21i5.247.

[4] ERRICO, A., DI VITO, V. Performance-based navigation (PBN) with continuous descent operations (CDO) for efficient approach over highly protected zones. 24th Saint Petersburg International Conference on Integrated Navigation Systems ICINS 2017 : proceedings [online]. 2017. ISBN 978-1-5386-0978-1. Available from: https://doi.org/10.23919/ICINS.2017.7995612.

[5] ICAO, ICAO standards and recommended practices (SARPS), annex 10 volume I (radio navigation aids) - ICAO [online]. 2006. [Viewed 2018-10-15]. Available from: www.ulc.gov.pl/pl/prawo/prawo-mi%C4%99dzynarodowe/206-konwencje.

[6] KRASUSKI, K., WIERZBICKI D., JAFERNIK, H. Utilization PPP method in aircraft positioning in post-processing mode. *Aircraft Engineering and Aerospace Technology* [online]. 2018, **90**(1), p. 202-209. ISSN 0002-2667. Available from: https://doi.org/10.1108/AEAT-05-2016-0078.

[7] WALTER, T., BLANCH, J., CHOI, M. J., REID, T., ENGE, P. Incorporating GLONASS into aviation RAIM receivers. *International Technical Meeting of the Institute of Navigation : proceedings.* 2013, p. 239-249.

[8] CHIN, G. Y., KRAEMER, J. H., NIM, G. C., VAN DYKE K. L. GPS/GLONASS RAIM augmentation to WAAS for CAT I precision approach. 53rd Annual Meeting of the Institute of Navigation : proceedings. 1997, p. 461-472.

[9] MISRA, P., PRATT, M., BURKE, B. Augmentation of GPS/LAAS with GLONASS: performance assessment. 11th International Technical Meeting of the Satellite Division of the Institute of Navigation : proceedings. 1998, p. 495-502.

[10] REDDY, G. S., SARASWAT, V. K. Advanced navigation system for aircraft applications. *Defence Science Journal* [online]. 2013, **63**(2), p. 131-137. ISSN 0011-748X. Available from: https://doi.org/10.14429/dsj.63.4254.

[11] KRASUSKI, K., CWIKLAK, J. Application of the GLONASS code observations for the designation of coordinates of an aircraft in flight test mode: a case study. *Scientific Journal of Silesian University of Technology. Series Transport* [online]. 2017, **97**, p. 69-80. ISSN 0209-3324, eISSN 2450-1549. Available from: https://doi.org/10.20858/sjsutst.2017.97.7

[12] BERAN, T. *Single-frequency, single-receiver terrestrial and space borne point positioning.* Technical Report no. 257, Department of Geodesy and Geomatics Engineering, University of New Brunswick, 2008, p. 34-36.

[13] SANZ SUBIRANA, J., JUAN ZORNOZA, J. M., HERNANDEZ-PAJARES, M. *GNSS data processing. Volume I: Fundamentals and algorithms.* Noordwijk, Netherlands: ESA Communications, ESTEC, 2013. ISBN 978-92-9221-886-7, p. 139-144.

[14] KRASUSKI, K. Aircraft positioning using SPP method in GPS system, *Aircraft Engineering and Aerospace Technology* [online]. 2018, **90**(8), p. 1213-1220. ISSN 0002-2667. Available from: https://doi.org/10.1108/AEAT-03-2017-0087.

[15] OSADA, E. *Geodesy* (in Polish). Wroclaw: Oficyna Wydawnicza Politechniki Wroclawskiej, 2011. ISBN 83-7085-663-2, p. 237-241.

[16] SEEBER, G. *Satellite geodesy. 2nd completely revised and extended edition.* Berlin, Germany: Walter de Gruyter GmbH & Co. KG, 2003. ISBN 3-11-017549-5, p. 300-303.

[17] JOKINEN, A., FENG, S., MILNER, C., SCHUSTER, W., OCHIENG, W., HIDE, C., MOORE, T., HILL, C. Precise point positioning and integrity monitoring with GPS and GLONASS. European Navigation Conference : proceedings. 2011, p. 1-12.

[18] BAKULA, M. Static code DGPS positioning based on three reference stations. *Geodesy and Cartography*. 2005, **54**(2), p. 81-92. ISSN 1648-3502.

[19] PIRTI, A., YUCEL, M. A., GUMUS, K. Testing real time kinematic GNSS (GPS and GPS/GLONASS) methods in obstructed and unobstructed sites. *Geodetski vestnik* [online]. 2013, **57**(3), p. 498-512. ISSN 0351-0271, e-ISSN 1581-1328. Available from: https://doi.org/10.15292/geodetski-vestnik.2013.03.498-512.

[20] RODRIGUEZ-BILBAO, I., RADICELLA, S. M., RODRIGUEZ-CADEROT, G., HERRAIZ, M. Precise point positioning performance in the presence of the 28 October 2003 sudden increase in total electron content. *Space Weather* [online]. 2015, **13**, p. 698-708. ISSN 1539-4964. Available from: https://doi.org/10.1002/2015SW001201.

Annex

Abbreviation	Full name
GLONASS	Global Navigation Satellite System
NAVSTAR GPS	NAVigational Satellite Time And Ranging Global Positioning System
BSSD	Between Satellite Single Difference
ICAO	International Civil Aviation Organization
GNSS	Global Navigation Satellite System
ABAS	Aircraft Based Augmentation System
SBAS	Satellite Based Augmentation System
GBAS	Ground Based Augmentation System
RAIM	Receiver Autonomous Integrity Monitoring
FMS	Flight Management System
INS	Inertial Navigation System
EPDE	ICAO airport code
RIFCB	Receiver Inter-Frequency Code Bias
SIFCB	Satellite Inter-Frequency Code Bias
APS	Aircraft Positioning Software
SPP	Single Point Positioning
IF LC	Ionosphere-Free linear combination
IGS	International GNSS Service
ANTEX	Antenna Exchange Format
RINEX	Receiver Independent Exchange System
HPL	Horizontal Protection Level
VPL	Vertical Protection Level
DOP	Dilution of Precision
GDOP	Geometric DOP
PDOP	Position DOP
VDOP	Vertical DOP
HDOP	Horizontal DOP
MRSE	Mean Radial Spherical Error
LNAV	Lateral Navigation
VNAV	Vertical Navigation

Vladimir Karpichev - Konstantin Sergeev - Aleksandra Bolotina

MODELING OF TECHNOLOGICAL PROCESSES OF MACHINE-BUILDING AND REPAIR MANUFACTURE

The proposed methods of constructing models of technological processes (TP) of production, repair and technical maintenance of objects in machine buildings, such as railway rolling stock, serves as the basis for development of information, mathematical and methodological support of the CAD system TP.

Applying of information technology to solve the problems of technological design has recently received intensive development. The research results show the effectiveness of the optimization approach to solving technological problems. Automation of the design of technological processes, based on use of digital technologies allows reducing the time for introducing new technical means and technologies into production, increasing the efficiency of production, repair and maintenance of objects in machine buildings.

Keywords: *objects in machine buildings, railway rolling stock, production, repair and technical maintenance, technical designing, optimization methods, mathematical model of the technological process, digital technology, computer-aided design*

1 Introduction

The systematic approach is the most general approach to designing complex objects. For a specialist in the field of systems engineering, they are obvious and natural, but their compliance and implementation are often associated with certain difficulties, due to the designing features. Mechanical engineers and repair enterprises use a systematic approach without recourse to system analysis manuals, but an intuitive approach without applying the rules of system analysis may not be sufficient to solve increasingly complex engineering problems.

2 Methodology

Methodical support for the design of technological processes (TP) should be based on the theory of technical systems. Therefore, it seems necessary to use the apparatus of this theory to formalize the basic concepts and principles of the technological processes design [1]. There are various definitions of the term "system". In this case, the aggregate of a finite set of interrelated elements, picked out from the environment and interacting with it, as a single whole, to solve a specific problem, is named a system.

The elements of a technological process system are actions or elements of the type "process" (operations, transitions). The relations connecting the elements of the type "process" in the system are temporary. There are serial, parallel and parallel-serial types of relations.

2.1 Analysis of technological process of manufacturing the roller of brake rigging of the railway wagon

Designing of models is considered on the simplest example of the technological process of manufacturing the roller of brake rigging of the railway wagon.

Let the technological process consists of one operation, which includes four transitions:
Transition No. 1 - installation of the workpiece on a lathe,
Transition No. 2 - surface treatment,
Transition No. 3 - control,
Transition No. 4 - the removal of the part.

Consider the systematized logical model. This technological process can be represented as follows:

$$TP1 = \{Ind, Prp, Atr, Inp, Out, Str\}, \tag{1}$$

where:
Ind - system designation and name,
Prp - targets of system,
Atr - attributes or system-wide characteristics,
Inp - system input,
Out - system output,
Str - system structure.

All the characteristics of the system for this case are here described in more details.

1. *Ind*
   1.1 The name of the system is "Technological process of manufacturing the roller of brake rigging of wagon".
   1.2 System Designation - «*TP1*».

Vladimir Karpichev, Konstantin Sergeev, Aleksandra Bolotina*
Russian University of Transport (MIIT), Moscow, Russia
*E-mail of corresponding author: abbolotina-work@yandex.ru

2. *Prp* - the purpose of the system is to manufacture the part in accordance with the requirements of the design documentation.
3. *Atr* - attributes or the system-wide characteristics are the signs by which systems can be classified and identified. These signs include the type of the details for manufacturing - the roller, the type of the processing - processing by cutting and the complexity of the technological process - simple.
4. *Inp* - the input of the technological process comes billet of detail with certain properties, as well as some production resources.
5. *Out* - the output of the technological process is the manufactured detail, as well as the production waste.
6. *Str* = <*E*, *R*>, where:
   E - set of elements of the system,
   R - set of relations connecting elements of the system.

A systematic process model can be represented graphically using a schematic (see Figure 1).

In Figure 1 are marked:
$P_W = \{P_W^1, P_W^2, \ldots, P_W^n\}$ - parameters of the workpiece,
$P_P = \{P_P^1, P_P^2, \ldots, P_P^n\}$ - parameters of the product,
R - production resources.

Production resources can be represented by the following four characteristics:

$$R=\langle D,T,L,M\rangle, \tag{2}$$

where:
$D=\{D1, D2, \ldots, Dn\}$ - technological equipment,
$T=\{T1, T2, \ldots, Tn\}$ - technological rigging,
$L=\{L1, L2, \ldots, Ln\}$ - labor resources,
$M=\{M1, M2, \ldots, Mn\}$ - materials and components.

The state of the object in the manufacturing process is determined using operations of control. Those operations change the amount of information about manufactured object state without changing the physical state or its location.

2.2 Creating a conceptual model

The next step in modeling the technological process is to create its conceptual model [2], which determines the structure of the system. The structure of the system can be represented as a hierarchy diagram (see Figure 2):

$$Str = \langle E, R\rangle, \tag{3}$$

where:
$E=\{e_1, e_2, e_3, e_4\}$ - the transitions of the technological process which are represented as the set of vertices of the hierarchy diagram of system structure (*Str*),
e_1 - installation of the workpiece on a lathe,
e_2 - surface treatment,
e_3 - control,
e_4 - part removing,
$R\{r_1, r_2, r_3\}$ - the set of edges of the hierarchy diagram of the system structure *Str*, connecting in time the transitions of the technological process, $r_1=(e_1, e_2)$; $r_1=(e_2, e_3)$; $r_1=(e_3, e_4)$.

This model can be represented by a set of related tables with parameters of elements of the technological process. The parameters for each element (transition) must uniquely identify it. The relationship of the transition parameter tables is determined by the time sequence of their execution [3].

In the technological process of manufacturing the roller of brake rigging of the railway wagon transitions are made sequentially and the parameters of the transitions are shown in Table 1.

2.3 The construction of mathematical models

The construction of mathematical models is considered next. To simulate this technological process, the two types of mathematical models are used: structural and functional.

The structural mathematical model can be represented as a hierarchy diagram (Figure 3).

$$T = \langle S, E\rangle, \tag{4}$$

where:
$E=\{e_1, e_2, e_3, e_4\}$ - are denoted transitions in the form of a set of arcs,
$S=\{s_1, s_2, s_3, s_4, s_5\}$ - vertex set marking the state of the part,
for this technological process:
$s_1= P_W$ - parameters characterizing the initial state of the part,
s_2 - parameters characterizing the state of the part after the first transition (the workpiece is installed on the machine),
$s_3= s_4$ - parameters characterizing the state of the part after the second and third transition, since the control could not change the state of the part,
$s_5= P_P$ - parameters characterizing the state of the finished product.

The final step in creating a model of the technological process is the compilation of functional mathematical models of its elements. The task of modeling at this level is a quantitative analysis of the properties of objects, that is, the definition of dependencies of some parameters on others.

In particular, for the transition number 2 “Surface Treatment”, one can create a mathematical functional model expressing the dependence of the basic time on

***Table 1** The parameters of the technological process of manufacturing the roller of brake rigging of the railway wagon transitions*

Transition No. 1 - installation of the workpiece on a lathe (vertex e_1)	
N	number of transition
T1	device code
T2	code of assembly and locksmith's tool
O	transition content
T_{time}	transition time
Transition No. 2 - surface treatment (vertex e_2)	
N	number of transition
M	material grade code
T	tool code
D	detail diameter
L	length of working stroke
t	cutting depth
i	number of passes
S	cutting tool feed
n	rotation frequency of a spindle
v	cutting speed
t_a	auxiliary transition time
t_m	the main transition time
Transition No. 3 – control (vertex e_3)	
N	number of transition
T	measuring instrument code
O	transition content
Transition No. 4 - the removal of the part (vertex e_4)	
N	number of transition
T	code of assembly and locksmith's tool
O	transition content

the transition from the length of the working stroke, the spindle rotationalspeed and feed:

$$t_O = \frac{L}{n \cdot S}, \tag{5}$$

where:
t_0 - main transition time, minutes,
L - length of the working stroke, mm,
n - rotation frequency of the spindle, rotation per minute,
S - cutting tool feed, mm per rotation.

3 Conclusions

It should be noted that application of the proposed methods for constructing models of technological processes of production, repair and manufacture of objects in machine buildings, for developing the mathematical models of CAD systems, allows estimating the time costs at each production stage, as well as optimizing the process by combining operations and transitions at the design stage.

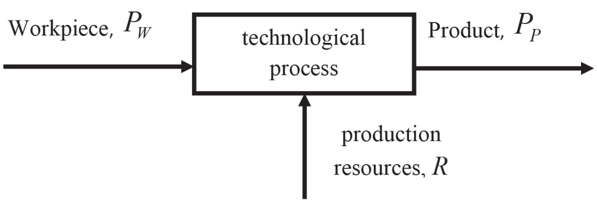


***Figure 1** Process flow scheme*

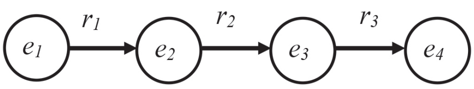


***Figure 2** Technological process structure*

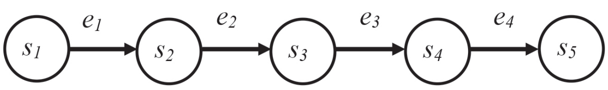


***Figure 3** Structural mathematical model of the technological process*

Acknowledgement

The above methodology is used at the "non-traction rolling stock" department of Russian University of Transport (RUT MIIT) when developing elements of the computer-aided design system for technological processes of production, repair and technical maintenance of objects machine buildings, such as the railway rolling stock.

References

[1] SERGEEV, K. A. Informatization of technological preparation of wagon-repair production (in Russian). *Zheleznodorozhnyi transport*. 2004, **10**, p. 74. ISSN 0044-4448.
[2] SERGEEV, K. A. Modern approach to the formation of models of technological processes of wagon repairs (in Russian). *Bulletin of the All-Russian Research Institute of Railway Transport*. 2005, **1**, p. 3. ISSN 2223-9731.
[3] SERGEEV, K. A., GUNDAEV, I. V., SIDOROV, E. S. Information and software technologist repair company (in Russian). *Science and Technology of Transport*. 2011, **2**, p. 97-101. ISSN 2074-9325.

Sunil Kumar Meluru Ramesha - Eva Schmidova

STRENGTH AND FRACTURE BEHAVIOUR OF DUAL PHASE STEEL DP450 IN STATIC AND DYNAMIC CONDITIONS

In this work, strength and plastic deformation effect of the dual phase steel are analysed in the static and dynamic conditions. Since the dual phase steel is extensively used in the outer body parts of the automotive vehicles, its dynamic strength and plastic strain energy absorption during the crash are essential. Dynamic strength of the dual phase steel is examined using the pendulum impact hammer tester machine. Spread of the plastic strain during the crash is an important factor for the energy absorption to passive safety, which is examined using the local hardness measurement using the Vickers hardness and local indentation yield strength is calculated using cylindrical indenter and obtained force-depth results are analysed using the Hencky theory for the plane strain indentation. Further, tested samples are observed using scanning electron microscopy for the fracture response after the static and dynamic tests.

Keywords: *dual phase steel, plastic deformation, indentation, fracture response and Hencky theory*

1 Introduction

Increased demand for fuel efficiency and environmental concern forced the automotive industry to reduce the gross weight of a vehicle. This factor forced the steel manufacturing industry to develop new high strength steel, which has higher strength and lower weight compared to normal steel. Different types of high strength steels are being used in the automotive industry for several decades especially in outer body components. The usage of the dual phase steel in the outer body parts is constantly increasing. In this work, the HCT 450X ferritic-martensitic dual phase steel is used for analysis of strength and plastic deformation ability in static and dynamic conditions. Along with the ferritic-martensitic structure, it has manganese to increase the strength and stabilize the austenite, silicon to enhance the ferrite transformation. The dual phase steel examined here is extensively used in the outer body parts of the automotive applications. Since the outer body parts are exposed to the environment and first form of resistance during the crash and minor accidents, these steels are required to have good corrosion resistance ability, high strength to weight ratio, better weldability, high formability and high strain energy. The higher strain energy is one of the important factors to be considered during the passive safety of automobiles. Presence of higher martensite content increases the strength of the DP steel but further increase in the content of martensite reduces the formability [1-3].

Huang et al. [4] have examined the dual phase strain hardening behaviour and their grain structure changes. Ghassemi-Armaki et al. [5] have worked on the deformation behaviour of martensite and ferrite in the dual phase steel.

In this work, static and dynamic strengths, as well as the plastic strain spread of the dual phase steel are examined. The strength of the dual phase steel is examined in static and dynamic conditions using the universal tensile testing machine and dynamic pendulum impact tester machines. The spread of the plastic deformation is the key factor in determining the strain energy absorption during the crash, which is analysed by measuring the hardness and micro-indentation yield strength after the testing of samples. Variation of the local hardness and local indentation yield strength are the important parameters to analyse the spread of the plastic strain after the static and dynamic tests. Local hardness is measured using Vickers indenter and local indentation yield strength is measured using the cylindrical indenter and evaluated from the Hencky theory for plane strain indentation.

2 Materials and methods

Table 1 shows the chemical composition of the examined dual phase steel HCT 450X and Figure 1 shows the SEM image with artificial colour of the dual phase steel having ferritic-martensitic phases. Yellow colour phase is the martensitic phase and black colour phase is ferrite.

2.1 The dual phase steel strength in the static and dynamic conditions

To find out the strength of the dual phase steel in the static condition, the standard static tensile test has been performed using the Zwick universal tensile testing machine. The force-displacement graph yield strength and ultimate tensile strength are recorded in computers.

Sunil Kumar Meluru Ramesha*, Eva Schmidova
Faculty of Transport Engineering, University of Pardubice, Czech Republic
*E-mail of corresponding author: Sunilmr21@gmail.com

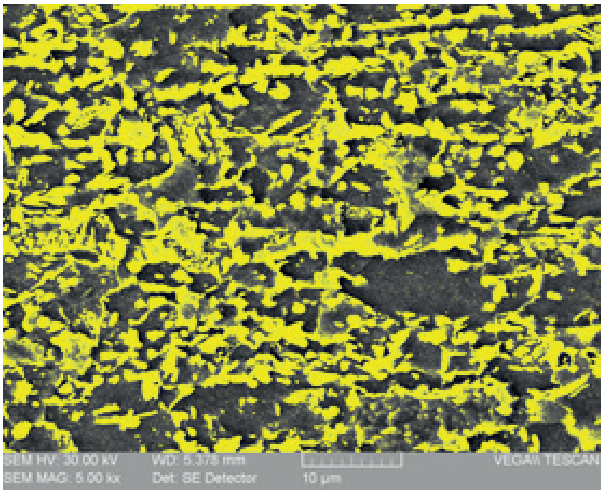
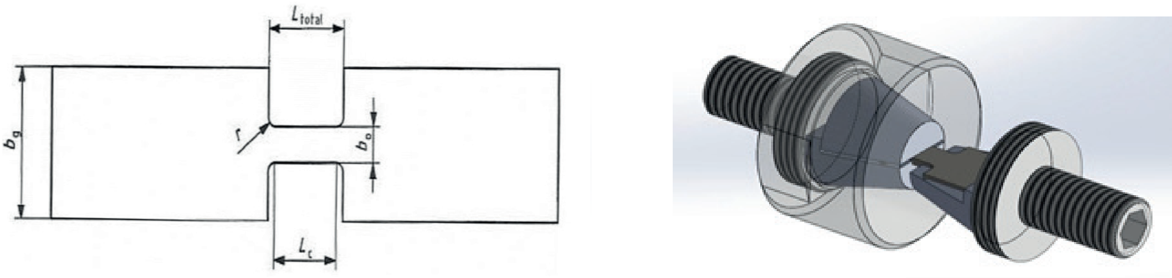


Figure 1 *Dual phase steel SEM image*

Table 1 *Chemical composition of the dual phase steel*

Element	Weight percentage
C	0.130
Mn	1.933
Si	0.200
P	0.022
S	0.002
Cr	0.187
Ni	0.018
Cu	0.017
Ti	0.026
Al	0.022



(a) *(b)*

Figure 2 *(a) Test specimen for the dynamic impact test and (b) special holder*

The dynamic strength test of the dual phase steel is performed in the Zwick pendulum impact hammer tester. The specimen dimensions are b_g = 15 mm, b_0 = 5 mm, L_{total} = 9 mm, L_c = 5 mm, r = 2 mm. The used samples including holder are presented in Figures 2(a) and 2(b), respectively. A special type of holder is designed in the laboratory to perform the impact test for the dual phase steel in the pendulum impact tester.

2.2 Hardness measurement and fracture behavior of the dual phase steel

Energy absorption during the collision is the key factor. The strain energy absorption during the collision is dependent on the plastic deformation and strain hardening ability of the material. To approximate the residual hardening and spread of the plastic deformation after the static test, the Zwick hardness testing machine is used. After the tensile test, the specimen is cut in the longitudinal direction then grinded and polished. The hardness of the sample is measured from the fractured end to the unaffected end, using the Vickers method. To see the fracture response in the sample after the static and dynamic tests, images are taken in the optical and electron microscope at different magnifications to analyze the fracture type and microscopic fracture behaviour.

2.3 The yield strength using macro-indentation

While the hardness as a material parameter can be employed as comparative information of UTS, it doesn't reflect the complex transition micro versus macro-plasticity in steel. A complex elastic-plastic response, as comprehensive information about the material response to loading, is required for the real interpretation of the process, which took place during the static versus dynamic loading. The local yield strength must be evaluated in tight connection with microstructure characterization of the loading volume of steel.

To find out the better distribution of plastic deformation and residual hardening effect of the fracture, the macro-indentation technique is used to determine the local yield strength with 0.5 mm diameter cylindrical indenter. Based on the elastic-plastic transition of the curve in the force-depth graph, the yield strength is calculated [6].

The indentation force level at the transition from elastic to plastic state is calculated using the simple curve deviation technique. The Hencky theory for plane strain indentation slip is used to calculate the real yield strength. The ratio of indentation yield strength to normal yield strength is 2.57 according to Hencky equations for the plane strain indentation [7-8]. Pressure relative to the shear yield strength is $P_{indent}/2k=2.57$. Calibration was performed to get precise results for tested steel by the standard tensile test of uninfluenced steel. Figure 3 shows the calculation

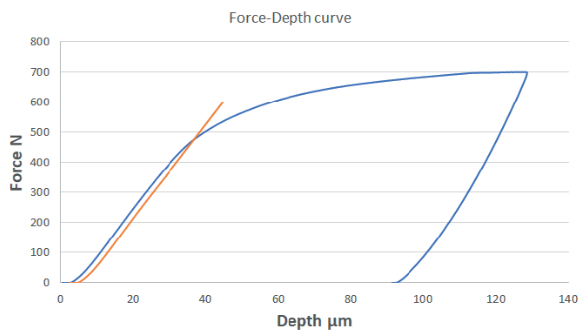


***Figure 3** Force-depth curve from indentation test*

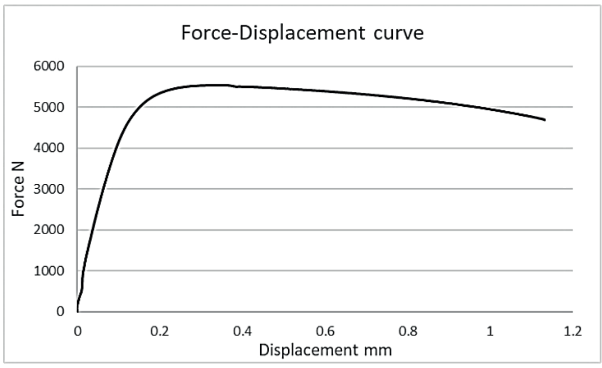


***Figure 5** Force-displacement graph for the static tensile test*

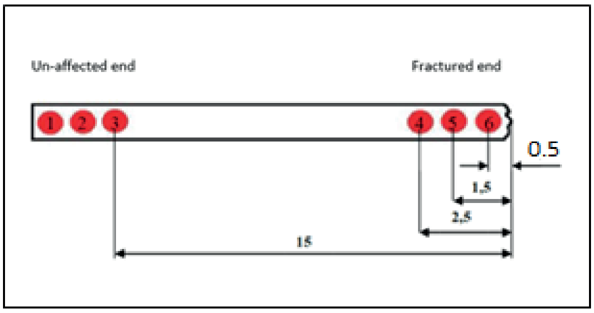


***Figure 4** Yield strength measurement positions using indentation technique [9]*

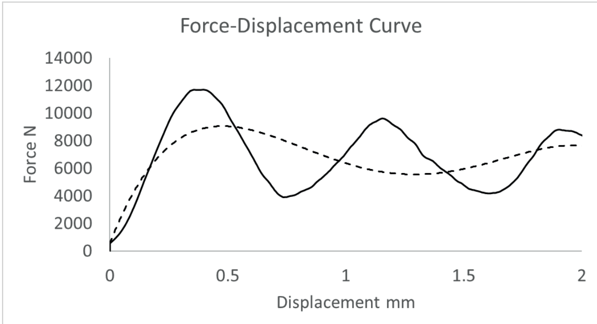


***Figure 6** Dynamic test results from impact pendulum tester*

of elastic-plastic transition force using the force-depth indentation curve.

Figure 4 shows the indentation yield strength measurement of the dual phase steel sample after the static tensile or dynamic impact test. Three indentation readings are measured close to the fractured end with a gap of 1 mm each. Another three hardness measurements are made at the unaffected end to have a better comparison of hardness values.

3 Results and discussions

3.1 Strength of the dual phase steel

Figure 5 shows the static test results of the dual phase steel performed using the universal tensile testing machine. The average yield strength of the dual phase steel is about 670 MPa and the average ultimate tensile stress is about 770 MPa. The values clearly indicate the higher strength of the dual phase steel compared to interstitial free steel, bake hardened and the high strength steel but still lower than TWIN and advanced high strength steel.

Figure 6 shows the dynamic impact test results of the dual phase steel performed using the pendulum hammer impact tester. The average ultimate tensile strength in dynamic conditions is about 1100 MPa. Values of the UTS in the dynamic conditions are considerably higher than in the static conditions. A special type of holder is designed for the smaller sample size and to reduce the vibrations. The vibrations' effect of the dynamic impact test is eliminated using the polynomial equations of the higher order and the sample having the minimum of three waves are selected based on the literature review.

3.2 Fracture response of the DP steel in static and dynamic conditions

Figure 7 shows the SEM image of the fractured surface of dual phase steel after the static tensile test. Fractured surface clearly indicates the ductile fracture mode with the coalescence of micro voids.

Figure 8 shows the SEM image of the fractured surface of the dual phase steel after the dynamic impact test. A clear ductile fracture can be seen even after the impact test with the presence of the transverse cracks. It has pointed to the increased sensitivity of the steel to internal imperfections. Important results towards the current application are the fact that even at the maximal tested strain rate of 1060 /s, the ductile mechanism was retained. The real states of metallurgy quality did not lead to transition to the brittle fracture mode. The critical issue from this point of view can be the presence of brittle, sharp secondary phases and imperfections, e.g. carbonitrides, complex oxides. Sulfides are not commonly critical, except for the case intensive plastic deformation. All observed critical parts were checked and based on that it can be stated that the tested steel has no tendency to transition fracture behaviour inside the analyzed range of strain rate. The energy consumption is driven much more by the spread of plasticity, restricted according to the dynamic loading conditions.

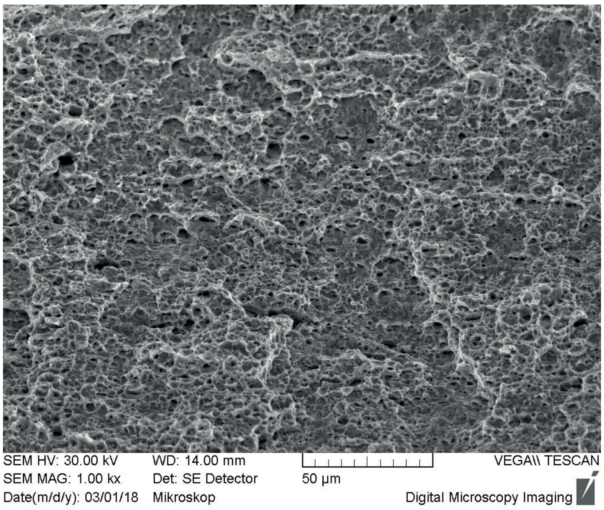


Figure 7 *The SEM image of the fractured surface after the static test*

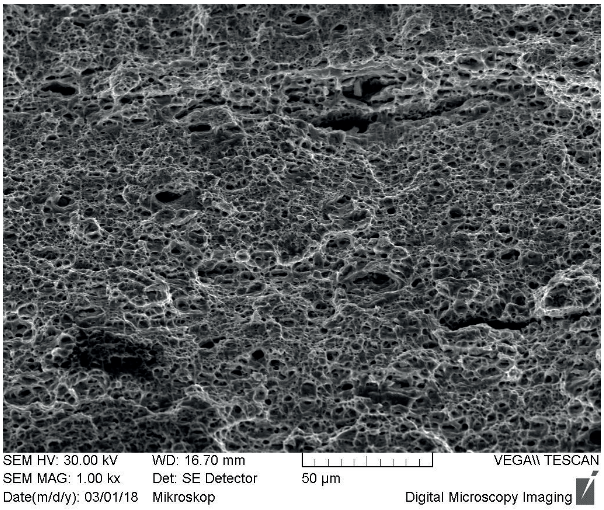


Figure 8 *The SEM image of the fractured surface after the dynamic test*

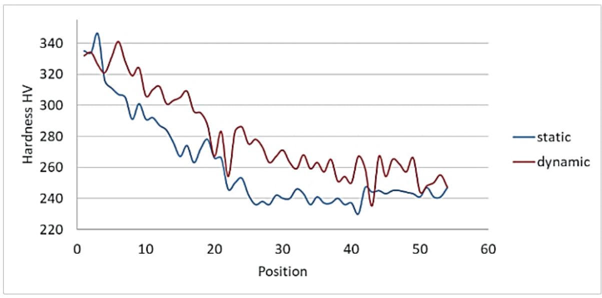


Figure 9 *Hardness distribution from fractured end to unaffected end*

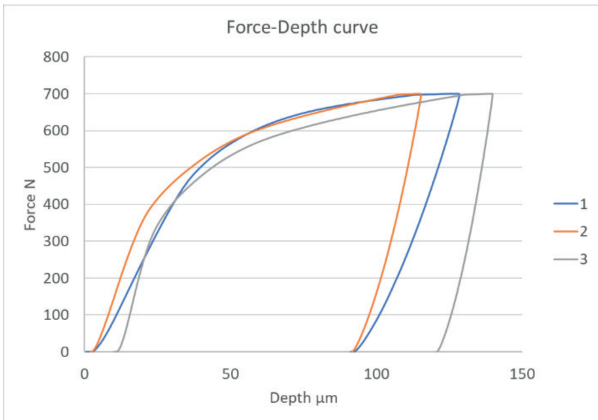


Figure 10 *The force-depth curve for the static sample from the fractured end*

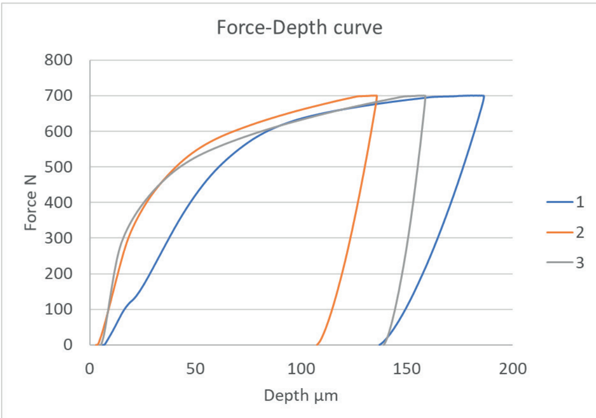


Figure 11 *Force -Depth curve for the dynamic sample from the fractured end*

3.3 Hardness values

Figure 9 shows the hardness values measured in hardness testing machine using the Vickers indenter. The graph is constructed based on the hardness values from fractured end to the unaffected end for both static and dynamic samples. The high hardness values are being recorded near the fractured end and decrease as it moves towards the unaffected end. Plastic deformation is not the same for the static and dynamic conditions, which can be identified using the hardness values. In the case of the static sample, the spread of the plastic deformation is large and comparatively low hardness values are recorded. The reasons for the large plastic deformation in static conditions are the availability of sufficient time and low strain rate during the static tensile test.

In the case of dynamic samples, the spread of the plastic deformation is limited only close to the fractured end and large portion of the sample is unaffected by the plastic deformation, which is concluded by the slow gradual decrease in the hardness values just after the one or two measurements.

Though the relation between hardness and residual strain is slightly complicated by the fact that hardness increases with the increase of the residual strain [10-11],

Table 2 *Local indentation yield strength for static and dynamic samples*

Position	1	2	3	Unaffected area Avg.
Static	891.98	634.30	505.46	614.48
Dynamic	832.52	675.92	595.56	614.48

hardness is still a suitable measure of the local residual strain distribution.

3.4 Macro-indentation results for the local yield strength

The force-depth graph of the unaffected area is obtained from the indentation using the 0.5 mm cylindrical indenter for the static sample. From the force-depth graph, the transition of the curve from elastic to plastic region is almost identical and follows the same pattern. The average value of force from elastic to plastic deviation is about 310 N. Figure 10 shows the force-depth graph near the fractured end obtained from the indentation test using the 0.5 mm cylindrical indenter. From the force-depth graph it clear that the transition from elastic to plastic behaviour is not the same for all the curves. The reason for the different curve response is attributed to the varying plastic deformation during the static tensile test. The values of force from elastic to plastic deformation are about 450 N, 320 N and 255 N, respectively from the fractured end. Using the Hencky theory for the plane strain indentation slips it is possible to calculate the approximate yield strength of the sample. Values of the yield strength are shown in Table 2 [12-14].

Figure 11 shows the force-depth graph near the fractured end obtained from the indentation test after dynamic impact test. Comparison to results of the static sample, these dynamic sample results are considerably different. Force values from elastic to plastic transition are 420 N, 341 N and 300 N, respectively. The sudden drop of the elastic-plastic transition force value from 420 N to 341 N indicates the shorter spread of the plastic deformation during the dynamic impact test. The local yield strength is calculated using the Hencky theory for the plane strain indentation and shown in Table 2. Determination of local yield strength is helpful in further confirmation of the area of plastic strain after the static and dynamic tests. Higher yield strength near the fractured area indicates the higher strain hardening effect. Just like hardness, the yield strength is the indicative parameter for the spread of plastic strain, as well.

As stated above, the obtained results have shown the significant influence of strain rate on the capability of tested steel to spread the plasticity. The mentioned process has a crucial effect on energy consumption. The strengthening process, together with the residual stress level is substantially influenced by the local stress-strain state. This means, that in all the outcomes, the material versus sampledimensions influence should be distinguished. Due to that, the performed analyses must be considered as comparative. Obtained data about the spread of plasticity presents useful information about the influence of the real sample shape and dimensions. Even though in full accordance with valid standards, there is some plastic flow outside the measured area. In the case of restricted part for testing the mentioned effect is not negligible.

4 Conclusion

Comparative analyses of the dual phase steel after loading in static and dynamic conditions were performed. Standard hardness measurement, followed by the indentation tests and evaluation through the Hencky plane strain theory, showed significant sensitivity to strain rate. Observation of the fractured sample in the Scanning Electron Microscopy for the type of fracture response proved the stabile fracture mode. Following conclusions are made based on the above observation:

1. The dynamic strengthening of the experimental dual phase steel at an average strain rate $1060 s^{-1}$ is about 43% higher than in the static conditions.
2. Spread of the plastic deformation is considerably different in static and dynamic conditions, large plastic strain spread can be observed in the static test.
3. The spread of the plastic deformation is also confirmed using the Vickers hardness and shows a high value near the fractured end, decreasing gradually towards the unaffected end.
4. Both in the static and dynamic fracture, the mode of fracture are ductile. Which means even at higher loading the material has maintained the ductile fracture mode.
5. The local indentation yield strength helps in further identifying the spread of the plastic deformation and values show the difference in the hardening effect. An optimized methodology using different positioning of the measured points is necessary for a detailed evaluation of discussed processes by used methodology.

Acknowledgement

This study has been accomplished by support of the Grant No: SGS-2018-023.

Reference

[1] MAZINANI, M. *Deformation and fracture behaviour of a low-carbon dual-phase steel* [online]. Doctoral dissertation. Vancouver: University of British Columbia, 2006. Available from: https://doi.org/10.14288/1.0302172

[2] HWANG, B.-C., CAO, T.-Y., SHIN, S. Y., KIM, S.-H., LEE, S.-H., KIM, S.-J. Effects of ferrite grain size and martensite volume fraction on dynamic deformation behaviour of 0.15C-2.0Mn-0.2Si dual phase steels. *Materials Science and Technology* [online]. 2005, **21**(8), p. 967-975. ISSN 0267-0836. Available from: https://doi.org/10.1179/174328405X47609

[3] BEYNON, N. D., OLIVER, S., JONES, T. B., FOURLARIS, G. Tensile and work hardening properties of low carbon dual phase strip steels at high strain rates. *Materials Science and Technology* [online]. 2005, **21**(7), p. 771-778. ISSN 0267-0836. Available from: https://doi.org/10.1179/174328405X41038

[4] HUANG, T. T., GOU, R. B., DAN, W. J., ZHANG, W. G. Train-hardening behaviours of dual phase steels with microstructure features. *Materials Science and Engineering* [online]. 2016, **672**, p. 88-97. ISSN 0921-5093. Available from: https://doi.org/10.1016/j.msea.2016.06.066

[5] GHASSEMI-ARMAKI, H., MAAß, R., BHAT, S. P., SRIRAM, S., GREER, J. R., KUMARA, K. S. Deformation response of ferrite and martensite in a dual-phase steel. *Acta Materialia* [online]. 2014, **62**, p. 197-211. ISSN 1359-6454. Available from: https://doi.org/10.1016/j.actamat.2013.10.001

[6] HANUS, P., SCHMIDOVA, E., SCHMID, M. The possibilities of evaluating the yield strength in the heat affected zones of a weld through indentation. *Defect and Diffusion Forum* [online]. 2015, **368**, p. 20-24. ISSN 1662-9507. Available from: https://doi.org/10.4028/www.scientific.net/DDF.368.20

[7] OLIVER, W. C., PHARR, G. M. An improved technique for determining hardness and elastic modulus using load and displacement sensing indentation experiments. *Journal of material research.* Volume 7, Issue 6 June 1992, p 1564-1583. 1992. [accessed 2018-12-12]. Available from: https://doi.org/10.1557/JMR.1992.1564

[8] BOWMAN, K. *Mechanical behaviour of materials*. New Jersey, USA: John Wiley and sons., 2004. ISBN 978-0471241980.

[9] ONDRACEK, P. *Study of dynamic strength of dual phase steel for car body*. Diploma thesis. Pardubice: University of Pardubice, Jan Perner Transport Faculty, 2018.

[10] TOSHA, K. Influence of residual stresses on the hardness number in the affected layer produced by shot peening. 2nd Asia-Pacific Forum on Precision Surface Finishing and Deburring Technology : proceedings [online]. 2002, p. 48-54. Available from: https://www.shotpeener.com/library/pdf/2005015.pdf

[11] ZHANG, P., LI, S. X., ZHANG, Z. F. General relationship between strength and hardness. *Materials Science and Engineering* [online]. 2011, **529**, p. 62-73. ISSN 0921-5093. Available from: https://doi.org/10.1016/j.msea.2011.08.061

[12] LUO, J., LIN, J. A study on the determination of plastic properties of metals by instrumented indentation using two sharp indenters. *International Journal of Solids and Structures* [online]. 2007, **44**(18-19), p. 5803-5817. ISSN 0020-7683. Available from: https://doi.org/10.1016/j.ijsolstr.2007.01.029

[13] LUO, J., LIN, J., DEAN, T. A. A study on the determination of mechanical properties of a power law material by its indentation force-depth curve. *Philosophical magazine* [online]. 2006, **86**(19), p. 2881-2905. ISSN 1478-6435, eISSN 1478-6443. Available from: https://doi.org/10.1080/14786430600640528

[14] ENNIS, B. L., BOS, C., AARNTS, M. P., LEEB, P. D., JIMENEZ-MELERO, E. Work hardening behaviour in banded dual phase steel structures with improved formability. *Materials Science and Engineering A* [online]. 2018, **713**, p. 278-286. ISSN 0921-5093. Available from: https://doi.org/10.1016/j.msea.2017.12.078

Ahmad Abadleh

WI-FI RSS-BASED APPROACH FOR LOCATING THE POSITION OF INDOOR WI-FI ACCESS POINT

This paper presents an approach to automatically detect the position of the Wi-Fi access points. It uses Wi-Fi received signal strength as well as some characteristics of the buildings such as the height of the building and the movement direction of the user to detect the position of the access points. This approach comprised of two phases: in phase one, a dynamic threshold is computed for each detected access point using the highest received signal strength. Then the threshold is used to detect a small area surrounding the access point. In phase two, it detects the position of the access point by monitoring the angle between the user and the access point, if the angle is in a certain range, then the position of the access point is detected. The experiments results show a high accuracy achieved by the proposed approach. Moreover, the results show that the proposed approach is promising.

Keywords: *localization, highest received signal strength, access point, distance estimation, path loss*

1 Introduction

The importance of the indoor localization has been increased during the last decade due to the need of practical indoor localization system that meets the requirements of the people. The pervasiveness of the Wi-Fi in the public buildings such as Airports, shopping malls, etc., and the easiness of getting the Wi-Fi signals have enabled the researchers to employ Wi-Fi technology in indoor localization techniques.

Many applications need an accurate indoor localization system to offer localization services to the people, who spend most of their time in indoor environments [1-2]. Providing the user's position in Airports, shopping malls, and hospitals are considered as location-based services. In addition, tracking the children and elder people are critical issues these days.

Many approaches have been proposed to solve the problem of indoor localization, such as fingerprinting, which is the most popular one [3-5]. Some other approaches use trilateration [6]. In trilateration approach, the distance between the access point and the user is computed based on the received signal strength between the access point and the user [7-8]. To estimate the 2D position of the users based on trilateration approach, at least three different signals are required.

Fingerprinting approach is one of the most popular indoor localization techniques. It consists of two phases, in phase one, which is the training phase, the system collects Received Signal Strength (RSS) and store them in a database. Phase two, which is the online phase, the online RSS measurement values are used to detect the position of the user by comparing the online RSS with the stored ones in the database [3-4].

The pervasiveness of smartphones, which are equipped with several sensors, such as accelerometer, gyroscope, and others, allows the researchers to use the Smartphones in indoor localization and tracking users. Moreover, The Wi-Fi access points, which are available in most public buildings are utilized by the researchers to provide the localization services. Furthermore, using the Wi-Fi access points in indoor localization requires no additional cost, which means that Wi-Fi is the most appropriate solution for indoor localization.

Locating the Wi-Fi access points in indoor environments has become a real obstacle to produce a practical indoor localization system. Most of the indoor localization systems assume a predefined position of the access points inside the buildings. However, public buildings environments are frequently exposed to be changed, and then access points positions may be changed, for instance, changing the position to get better coverage, installing new access point, or shutting down one.

In this paper, an approach for locating the access points' positions is proposed. It relies on the fact that when the user passes a nearby access point, he/she will be perpendicular to that access point. Once the user passes a nearby access point, the position of the access point is detected. The main idea behind this approach is to monitor the angle between the user and the access point, once it becomes 90 degrees, it means that the user is just left under that access point. The highest received signal strength value is used to detect the distance between the user and the access point as well as the real building height. Our approach works under the assumption that the height of the building is known, this assumption is valid since the height of the building is fixed and unable to be changed.

The specific contributions of this paper are:

Ahmad Abadleh
CS Department, Faculty of Information Technology, Mutah University, Karak, Jordan
E-mail: ahmad_a@mutah.edu.jo

- Detecting accurate access point positions.
- Providing a practical idea on how the RSS values change while the user is moving.

2 Related work

Many techniques have been proposed in the field of indoor localization. The proposed approach in [1] uses reference points in order to detect the position of the user as well as calibrating the user position each time he/she encounters a reference point. Some approaches exploit fingerprinting techniques for indoor localization [3-4, 9-10]. In these approaches, two phases are used to detect the position. In the first phase, the system collects the signals such as Wi-Fi signals, Bluetooth, FM, and others. The collected signals create the fingerprint database, which is called radio map. In phase two, the position of the user is estimated, the system measures the signals and compares them with the ones in the radio map. Some machine learning algorithms are needed to retrieve the best match. Although these approaches provide a good accuracy level, but the effort needed for building the radio map is the big challenge for the fingerprinting-based approaches. Trilateration-based approaches in [11-12] need to measure the distance from at least three different sources of signals. The position then is considered as the intersection point between the three circles that are formed by the three distances.

Some approaches try to solve the problem of using the signals, for instance, the multipath problem is one of the biggest problems that affect the accuracy of the indoor localization approaches. The approach in [13], reduces the effect of the multipath problem by adding a special field in the beacon frame to detect the direct path between the transmitter and the receiver.

Nowadays, Smartphone has become the most popular cellular device carried by the people. It equipped with several sensors that can be utilized in indoor localization. For instance, accelerometer sensor can be used to detect the steps of the users and gyroscope is used to detect the direction of the users [13-16]. Some approaches exploit the users' profiles when they visit a building to store some data such as the acceleration, the direction, and the Wi-Fi signals [10, 17]. These data used to detect the position of the users using some machine learning algorithms. Channel State Information (CSI) provides more stable information than RSS values [18]. It can be used for providing a knowledge about the direct path of the signal that leads to more accurate distance estimation. However, not all access points share the CSI, therefore; the need for special access points represents a drawback of such approaches.

One of the requirements of the indoor localization approaches is the floor plan. Some approaches assume that the floor plan is already given. Others, such as the one in [1] builds the floor plan automatically via monitoring the movements of the users in an environment. The dynamic floor plan construction is an important issue in indoor localization. Most of these approaches that construct the floor plan rely on the crowdsourcing technique. Crowdsourcing technique works by equipping the users' Smartphones by an application to gather some data to construct the floor plan [1]. Distance estimation is also a critical issue, the smartphone sensors such as accelerometer can be utilized to compute the distance [19]. The distance estimation via the accelerometer is computed as the number of walking steps. The author in [19] presents a dynamic distance estimation by computing accurate walking steps and then multiplying the detected steps by a dynamic step length.

To sum up, most of the indoor localization approaches need the Wi-Fi access points. Therefore; knowing the position of the access points will increase the accuracy of the indoor localization approaches. Our approach tackles this problem by providing an accurate position of the access points. In general, our approach differs from the existing approaches in terms of detecting the positions of the access points, which is based on the changing angle due to the user movements. Moreover, the proposed approach does not need much efforts to build a database. The only parameters needed are the physical height of the building as well as an average height of the Smartphone from the ground.

3 Proposed approach

Access points act as reference points for indoor localization, therefore; detecting the accurate position of the access point is crucial in our work. RSS values can be used to detect the accurate position of the access point when the user passes by an access point. Our approach measures the average of RSS values for a time window (e.g., 2 seconds) because the values of RSS suffer from various problems such as multipath and scattering. Relying on individual RSS values will lead to a severe error. The main idea of the proposed approach is to use the highest average of the RSS to indicate if the user is close to an access point. We rely on the fact that when the user is under an access point, the average of the RSS values for that access point will be the highest [8].

The proposed approach consists of two phases. In phase one, the user surveys the building and the proposed approach computes the average of the RSS values for each time window. Next, the system computes the threshold of each access point according to the highest average of the RSS values. Equation 1 shows how to compute the threshold:

$$RSS\_Thre\ (x) = \frac{\sum_{i=n-w}^{n+w} RSS\_AVG(x)_i}{2 * w + 1}, \qquad (1)$$

where:
$RSS\_Thre(x)$ is the threshold of the access point x,
$RSS\_AVG(x)i$ represents the average RSS value for access point x at time window i,
n is the time when the maximum average RSS value is detected, and w is the window size (e.g., 2 times).

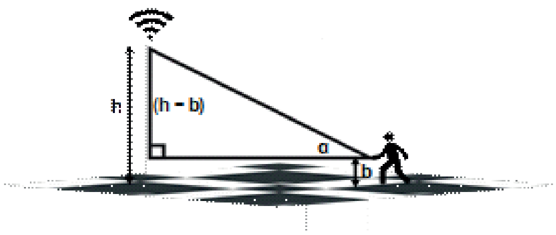


***Figure 1** The scenario when a user is approaching an access point*

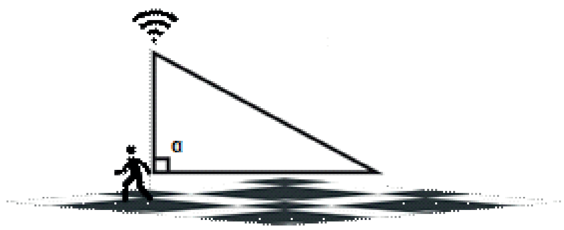


***Figure 2** The scenario when the user is just left the access point*

Equation 1 presents the threshold by calculating the average RSS from the maximum $(2\times w+1)$ RSS average values.

RSS_Thre represents the RSS value when a user is close to an access point. Using RSS_Thre, the system decides that the user is close to an access point. Therefore; Equation 1 limits the search and decides which access point the user is close to.

In phase 2, Equation 1 detects and limits the area of the access point; however, determining the position of the access point within this area is challenge. Figures 1 and 2 demonstrate the scenario for detecting the position of the access point. When the user enters the area of an access point, which is determined by the threshold, the system calculates the angle between the user and the access point using right triangle technique. If the angle is close to 90°, then the system considers this place as the position of the access point. As can be seen from Figure 1, which represents the user approaching an access point where the angle is increasing. Figure 2 represents the scenario when the user has just left the access point and the angle α is about 90°.

As shown in Figures 1 and 2, d represents the distance between the user and the access point, h is the height of the floor, and b is the distance between the user's smartphone and the ground. When a user is approaching the access point, the angle α increases until it becomes close to 90° under the access point or when d is equal to $(h - b)$, which means that the user is exactly under the access point and the triangle becomes a line. If the access point is not attached to the ceiling and instead attached to the wall, the angle α is close to 45° and the user is at the same line of the access point, and then the angle gets decreased as the RSS values decreased. Therefore, our approach recognizes the access point when one or more of the following three conditions is met: a) if angle α is close to 45° then decreases; b) if angle α is close to 90° then decreases; or c) if the distance is equal to the height of the building ($d=h$).

To compute the angle α, we need a prior knowledge of the floor height and b values. To find the distance, d, we use path loss model as follows:

$$RSS = initial_{RSS} - 10\,\lambda \log (d), \tag{2}$$

Where:
$initial_{RSS}$ is the RSS at 1 m from the access point,
RSS is the received RSS value, λ is the path loss exponent,
d is the distance between the receiver and the access point.

Note that λ is a critical factor, it represents the environmental stability. If the indoor environment is stable and clear, then λ is close to 2, and if the indoor environment is unstable and unclear, then λ is close to 4 [14].

Equation 2 suffers from various factors, such as multipath, signal attenuation, and scattering. To reduce the influences of these factors, we use Equation 2 when the user enters the area of an access point, which is detected using the threshold. The detected area that surrounds the access point is small, which means that the area is close to the access point; therefore, the signals are in a line of sight. Furthermore, the existence of the access points in the corridors, which have usually lesser furniture and obstacles than the rooms, makes the RSS signals clear and have less scattering. Distance, d, can be computed based on Equation 3.

$$d = 10^{\frac{(initial_{RSS} - RSS_{AVG})}{10\lambda}}. \tag{3}$$

We use the maximum average RSS value to represent the $initial_{RSS}$, since the maximum average represents the RSS value at the nearest point from an access point. RSS_{AVG} is represented by the RSS average during a time window.

According to the law of sines of the right triangle:

$$sin\ (\alpha) = (h - b) / d. \tag{4}$$

From Equation 4, the angle α can be derived as follows:

$$\alpha = sin^{-1}\ (h - b) / d. \tag{5}$$

To sum up, the proposed approach detects the position of the access points based on two phases, the first phase is to detect the area where the access point is located using the highest average of RSS values based on Equation 1. Then at the next phase, the system uses the distance and the physical information of the floor such as the height of the building to improve the accuracy of the positioning estimation using Equation 2 and Equation 5.

4 Evaluation

4.1 Experimental setup

The proposed approach was evaluated in the building of computer science department at Mutah University. Three

Table 1 Comparisons between proposed approach and existing approaches

Approach	Advantages	Disadvantages	Accuracy
Proposed	No need for calibration of the database	Need building height	< 2 m
Fingerprinting-Based [9, 10, 17, 20]	Able to automatic calibrate	Need surveying radio in a building	(1 - 3) m
Trilateration-Based [11]	No need for calibrations, accuracy is more than 3 m	Need at least three access points	> 3m
I am the antenna [21]	No need for calibration of the database	The user must rotate to detect the blocking sector	Small distance

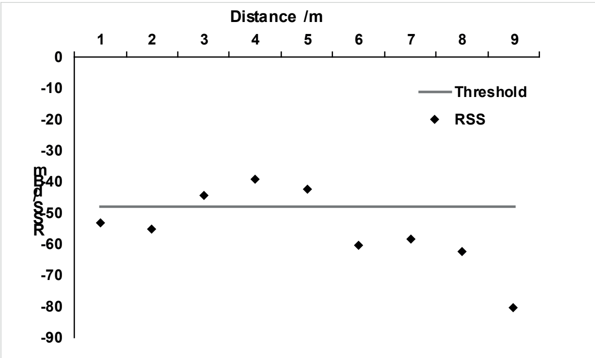


Figure 3 *Area where an access point is located based on Equation 1*

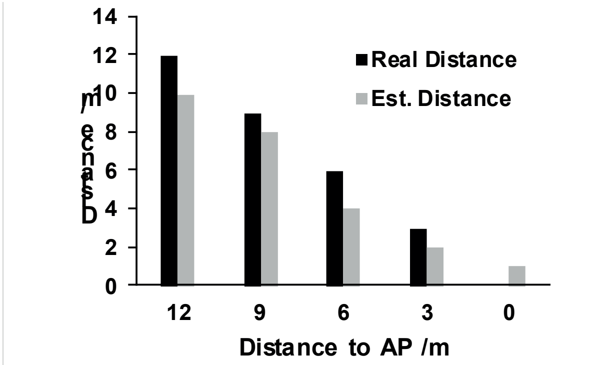


Figure 4 *Path loss model-based distance estimation*

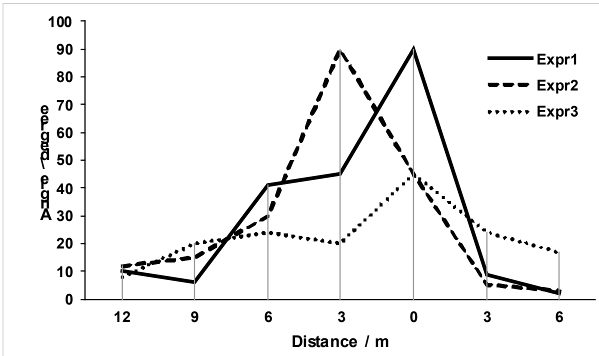


Figure 5 *Angle detection while the user is approaching an access point*

access points are installed in the building. Two of them are attached to the ceiling while the other one is attached to the wall of the building. The experiments have been done using Android based Smartphone. The experiment was conducted when the user reaches the area where the threshold for an access point is detected. The walks inside the building holding his/her Smartphone and passes by the access points.

4.2 Experimental result

4.2.1 Impact of the threshold to detect the area where the access point is located

In this section, the threshold, which is computed using Equation 1 is tested in the environment to detect the area where the access point is located. Figure 3 shows the results.

As can be seen from Figure 3, the threshold restricts and limits the search for the position of an access point to a small area surrounding the access point. The dots above the line represent the RSS values when the user is in the vicinity of an access point. As can be seen from Figure 3, the values are on the range of distance of 2 m to 6 m, which means that the access point is far about 4 m from the user. These results can restrict the search process; however, it is not enough to say that the position of the access point is recognized due to the problem of the signals. Therefore; we applied path loss model to enhance position estimation.

4.2.2 Path loss model-based distance estimation

In this section, we show the results of distance estimation based on the path loss model shown in Equation 2. Figure 4 shows that there are some errors in distance estimation even if the real distance between the user and the access point is not long.

To avoid the multipath and attenuation problems that may affect the results of distance estimation using path loss model, the path loss model should be used where the signal is in a line of sight. Therefore, in the proposed approach, the dynamic threshold which is computed by Equation 1 is performed to decide whether the user is close to an access point or not. If yes, then the proposed approach computes the distance based on the path loss model as the signals are in the line of sight.

4.2.3 Detecting the position of the reference points

After determining the area where the access point is placed, which is a small area surrounding the access point, the next step is how to accurately detect the position of the access point within this area. In this section, we present the result of the proposed approach. Figure 5 illustrates the detection of the angle based on Equations 2 and 4, which is used to detect the position of the access point.

Figure 5 shows the results of the three different experiments. Experiment one and two, the user was 12 m far from the access point when the threshold is detected, he/she walked towards the access point until he/she passed under the access point and left it. In these experiments, there were few people in the environments; therefore, the signals were in a line of sight. Experiment three was conducted when there were a lot of people in the environment.

As can be seen from Figure 5, the angle reached 90° when the user is almost passed under the access point for the experiment one. We can notice here that the angle dropped significantly after it reached 90°, which is an indicator that the user is going further from the access point because the signals become in non-line of sight as the user's body blocks the signal. For experiment two, the angle reached 90° when the user is about 3 m from the access point. Experiment three aimed at testing noisy environment when there is a lot of people in the environment. Based on Figure 5, it is clearly pointed out that the angle between the user and the access point when the user passed near the access point dropped even after reaching 45°. The average error of the proposed approach was 1.6 m, which shows a high accuracy level to be applied.

4.3 Discussion and comparison

Our approach provides the position of the access points which can be used for detecting the users' positions. One of the disadvantages of the trilateration-based approaches, is how to get a line of sight signals from three different sources of signals. Our approach helps to determine the optimum access points to be used for trilateration by excluding the undesirable access points. For instance, if there were four signals come from four different access points, the system can choose the access points that are in the same vicinity of an object and exclude others, which are far from that vicinity. Moreover, detecting the position of the concerned access points help in improving the accuracy of the fingerprinting-based approaches by excluding the signals from the access points that are not close to each other.

Our approach outperforms the existing approaches in terms of accuracy and the effort needed to run the system. For instance, our approach requires only the physical characteristics of the building, such as the height of the building which is fixed and unchangeable. This feature makes our approach one of the few approaches that do not rely mainly on the radio signals which are unreliable. Moreover, relying only on the access points that are attached to the ceiling or to the wall of the building makes the received signals clear and in line of sight which leads to accurate distance estimation. Table 1 summarizes the differences between the proposed approach and some of the existing approaches.

5 Conclusion

Most of the indoor localization techniques need to involve the building map as well as the position of the access points. In this paper, we proposed an approach to dynamically detect the position of the access points via two phases. In phase one, a small area surrounding the access point is detected using a dynamic threshold. Then in phase two, the system monitors the angle between the user who is approaching an access point and the target access point. The angle will increase until it reaches 90 when the user leaves the access point, at this time, the system considers this position as the position of the access point. The results of the experiments showed a promising result in terms of indoor localization accuracy.

References

[1] WU, D., ZHANG, D., XU, C., WANG, Y., WANG, H. WiDir: walking direction estimation using wireless signals. ACM International Joint Conference on Pervasive and Ubiquitous Computing UbiComp '16 : proceedings [online]. ACM New York, NY, USA, 2016. ISBN 978-1-4503-4461-6, p. 351-362. Available from: https://doi.org/10.1145/2971648.2971658

[2] SEN, S., LEE, J., KIM, K., CONGDON, P. Avoiding multipath to revive inbuilding WiFi localization. 11th Annual International Conference on Mobile Systems, Applications, and Services MobiSys´12 : proceedings [online]. ACM New York, NY, USA, 2013. ISBN 978-1-4503-1672-9, p. 249-262. Available from: https://doi.org/10.1145/2462456.2464463

[3] HE, W., SOUVIK, S., AHMED, E., MOUSTAFA, F., MOUSTAFA, Y., CHOUDHURY, R. R. No need to war-drive: unsupervised indoor localization. 10th International Conference on Mobile Systems, Applications, and Services MobiSys : proceedings [online]. ACM New York, NY, USA, 2012. ISBN 978-1-4503-1301-8, p. 197-210. Available from: https://doi.org/10.1145/2307636.2307655

[4] CHINTALAPUDI, K., PADMANABHA IYER, A., PADMANABHAN, V. N. Indoor localization without the pain. 16th Annual International Conference on Mobile Computing and Networking MobiCom´10 : proceedings [online]. ACM New York, NY, USA, 2010. ISBN 978-1-4503-0181-7, p. 173-184. Available from: https://doi.org/10.1145/1859995.1860016

[5] CHON, Y., CHA, H. LifeMap: smartphone-based context provider for location-based services. *IEEE Pervasive Computing* [online]. 2011, **10**(2), p. 58-67. ISSN 1536-1268, eISSN 1558-2590. Available from: https://doi.org/10.1109/MPRV.2011.13

[6] ROY, N., WANG, H., CHOUDHURY, R. R. I am a smartphone and i can tell my user's walking direction. 12th Annual International Conference on Mobile Systems, Applications, and Services : proceedings [online]. ACM New York, NY, USA, 2014. ISBN 978-1-4503-2793-0, p. 329-342. Available from: https://doi.org/10.1145/2594368.2594392

[7] ABADLEH, A., HAN, S., HYUN, S. J., LEE, B., KIM, M. Construction of indoor floor plan and localization. *Wireless Networks* [online]. 2016, **22**(1), p. 175-191. ISSN 1022-0038, eISSN 1572-8196. Available from: https://doi.org/10.1007/s11276-015-0964-6

[8] COLERI ERGEN, S., TETIKOL, H. S., KONTIK, M., SEVLIAN, R., RAJAGOPAL, R., VARAIYA, P. RSSI-fingerprinting-based mobile phone localization with route constraints. *IEEE Transactions on Vehicular Technology* [online]. 2014, **63**(1), p. 423-428. ISSN 0018-9545, eISSN 1939-9359. Available from: https://doi.org/10.1109/TVT.2013.2274646

[9] WANG, X., GAO, L., MAO, S., PANDEY, S. CSI-based fingerprinting for indoor localization: a deep learning approach. *IEEE Transactions on Vehicular Technology* [online]. 2017, **66**(1), p. 763-776. ISSN 0018-9545, eISSN 1939-9359. Available from: https://doi.org/10.1109/TVT.2016.2545523

[10] CHON, Y., CHA, H. LifeMap: smartphone-based context provider for location-based services. *IEEE Pervasive Computing* [online]. 2011, **10**(2), p. 58-67. ISSN 1536-1268, eISSN 1558-2590. Available from: https://doi.org/10.1109/MPRV.2011.13

[11] MURUGAN, R. A., ROSHINI, M. G., RUBHINI, P. S. P. Localization-based user tracking using RSSI. International Conference on Innovations in Engineering and Technology ICIET'16 : proceedings. IJIRSET, 2016.

[12] ZAFARI, F., GKELIAS, A., LEUNG, K. K. A Survey of indoor localization systems and technologies. *IEEE Communications Surveys & Tutorials* [online]. 2017, **PP**(99), p. 1-26. ISSN 1553-877X. Available from: https://doi.org/10.1109/COMST.2019.2911558

[13] ZHOU, Z., CHEN, T., XU, L. An improved dead reckoning algorithm for indoor positioning based on inertial sensors. 2015 International Conference of Electrical, Automation, and Mechanical Engineering : proceedings [online]. Advances in Engineering Research. 2015. ISBN 978-94-62520-71-4, p. 369-371. Available from: https://doi.org/10.2991/eame-15.2015.102

[14] YANG, Z., LIU, Y. Quality of trilateration: confidence-based iterative localization. *IEEE Transactions on Parallel and Distributed Systems* [online]. 2010, **21**(5), p. 631-640. ISSN 1045-9219, eISSN 1558-2183. Available from: https://doi.org/10.1109/TPDS.2009.90

[15] ABADLEH, A., AL-HAWARI, E., ALKAFAWEEN, E., AL-SAWALQAH, H. Step detection algorithm for accurate distance estimation using dynamic step length. 18th IEEE International Conference on Mobile Data Management MDM : proceedings [online]. IEEE, 2017. eISSN 2375-0324, p. 324-327. Available from: https://doi.org/10.1109/MDM.2017.52

[16] DOIPHODE, S., BAKAL, J. W., GEDAM, M. Survey of indoor positioning measurements, methods, and techniques. *International Journal of Computer Applications* [online]. 2016, **140**(7), p. 1-4. eISSN 0975-8887. Available from: https://doi.org/10.5120/ijca2016909361

[17] ZHANG, X., TADROUS, J., EVERETT, E., XUE, F., SABHARWAL, A. Angle-of-arrival based beamforming for FDD massive MIMO. 49th Asilomar Conference on Signals, Systems and Computers : proceedings [online]. IEEE, 2015. eISSN 1058-6393, p. 704-708. Available from: https://doi.org/10.1109/ACSSC.2015.7421224

[18] LIU, H., DARABI, H., BANERJEE, P., LIU, J. Survey of wireless indoor positioning techniques and systems. *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)* [online]. 2007, **37**(6), p. 1067-1080. ISSN 1094-6977, eISSN 1558-2442. Available from: https://doi.org/10.1109/TSMCC.2007.905750

[19] YASMINE, R., PEI, L. Indoor fingerprinting algorithm for room level accuracy with dynamic database. 4th International Conference on Ubiquitous Positioning, Indoor Navigation and Location Based Services (UPINLBS) : proceedings. IEEE, 2016, p. 113-121.

[20] KHALIFEH, J. J., KASSAS, Z. M., SAAB, S. S. Indoor localization based on floor plans and power maps. ION GNSS Conference : proceedings. Red Hook, NY: Curran Associates, Inc., 2015, ISBN 978-1-5108-1725-8, p. 2291-2300.

[21] ZHANG, Z., ZHOU, X., ZHANG, W., ZHANG, Y., WANG, G., ZHAO, B. Y., ZHENG, H. I am the antenna: accurate outdoor AP location using smartphones. 17th Annual International Conference on Mobile Computing and Networking MobiCom '11 : proceedings [online]. ACM, New York, NY, USA, 2011. ISBN 978-1-4503-0492-4, p. 109-120. Available from: https://doi.org/10.1145/2030613.2030626

Vladimir Kindl - Tomas Kavalir - Jiri Sika - Michal Krizek

CORRECTION OF OBLIQUE-ANGLE OSCILLATION FOR LASER DOPPLER VIBROMETRY

The paper proposes a correction method of the oblique-angle vibration for laser doppler vibrometry. It briefly discusses the key mathematical approach considering the surface of the analysed object to be a reference plane and gives a practical example of the method proper application. The proposed correction method is practically verified by laboratory measurement of natural frequencies and mode shapes for vibrations of high voltage transformer housing. The results are further compared to equivalent accelerometer measurement.

Keywords: *laser, doppler, vibrometry, measurement, prototype, oblique-angle, correction*

1 Introduction

Laser Doppler Vibrometry (LDV) has been primarily used in medicine [1-3] but offers a wide range of technical capabilities also in engineering applications involving contactless vibration measurement [4-8]. It has been introduced as a very sensitive method applicable for measurements that assess movements of high-dynamic components. This method is particularly important for applications where physical contact with analyzed device is not technically possible, typically rotating machines in operation, measurement of hot surfaces or surfaces under high voltage.

Commercially available LDV are typically constructed with a single beam to measure radial and axial vibrations or with parallel beams to measure pitch and torsional vibrations. Therefore, they can only collect data at one point at a time. In such a case, performing a complex modal analysis to obtain an operational deformation shape is usually a relatively long process. This problem is even more difficult for larger structures or for low natural frequency structures, such as aircraft, space structures or civil structures [9-16].

As stated in [17], the market offers several types of laser-scanning vibrometers allowing multiple points to be measured simultaneously, but they are usually very expensive and complicated. The authors of the same work [17] presented their own design of a three-dimensional measuring system visible on Figure 1 and consisting of a single point vibrometer that can redirect the laser beam using computer-controlled mirrors. The only disadvantage of the proposed system was the lack of an observation angle correction algorithm when measuring large surface from one position.

This study extends the authors' original work [17] with presenting a simple method of correcting observation angles that can be used generally for any other similar application.

2 Oblique-angle correction

In engineering, most projects require vibration measurements of relatively large technical surfaces, such as a transformer housing, building walls or similar structures. Often, there is insufficient space to install the measuring system at a suitable distance. Therefore, the laser beam senses the vibrations at the specific measuring point under a large angle. This angle changes according to measured point coordinates and the consequent correction is not an easy task.

A practical example is shown in Figure 2. The aim is to investigate natural frequencies and mode shapes for vibrations of high voltage transformer housing. The matrix of investigated points is marked with red dots. The position of the laser vibrometer is considered to be at coordinates [$x0$, $y0$, $z0$]. The arms $r1$ - $r4$ represent the distances measured (with a laser) between the vibrometer lens and all of the transformer housing corners.

As obvious, the oscillations scanned at different positions must be accordingly recalculated prior the final evaluation. The triangle seen in Figure 3 proposes the method to determinate necessary correction coefficient for any evaluated point.

Considering the surface of the transformer housing to be the reference plane, it is possible to determine the observing position by solving the set of Equations (1).

Vladimir Kindl[1,*], Tomas Kavalir[2], Jiri Sika[2], Michal Krizek[2]
[1]Regional Innovation Centre for Electrical Engineering, Faculty of Electrical Engineering, University of West Bohemia, Pilsen, Czech Republic
[2]Regional Technological Institute, Faculty of Mechanical Engineering, University of West Bohemia, Pilsen, Czech Republic
*E-mail of corresponding author: vkindl@kev.zcu.cz

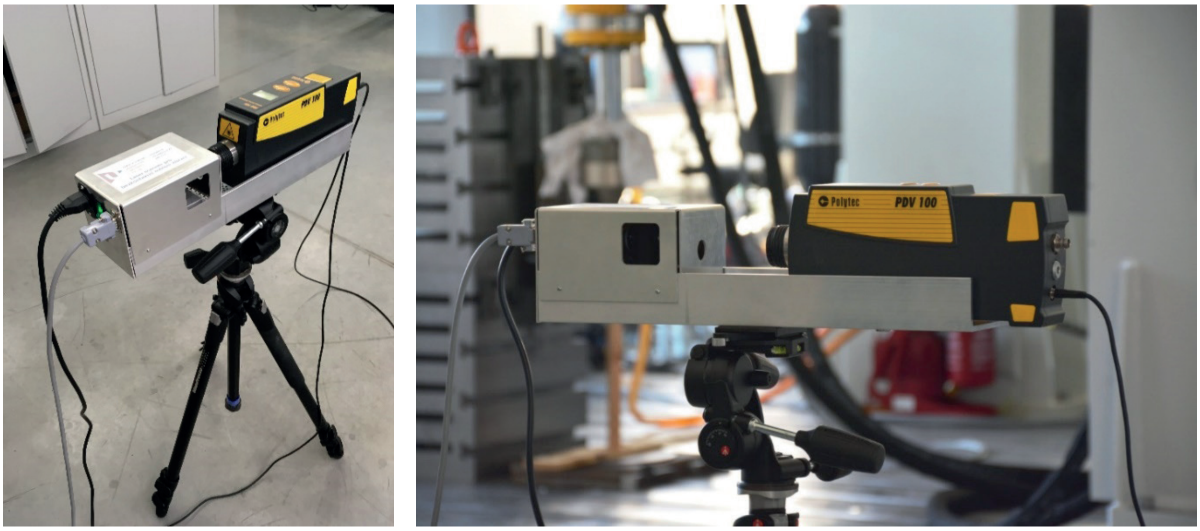


Figure 1 *LDV with XY scan head [17]*

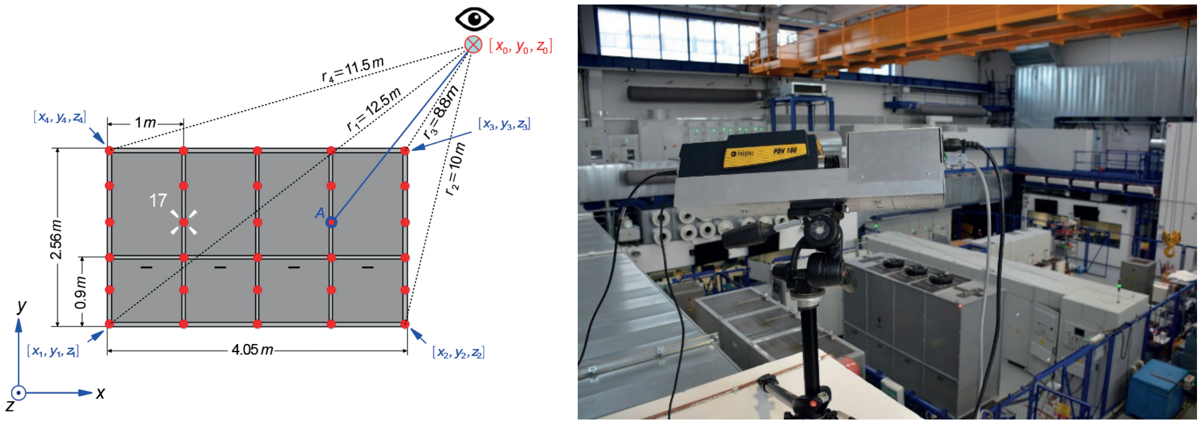


Figure 2 *Practical example for the method application*

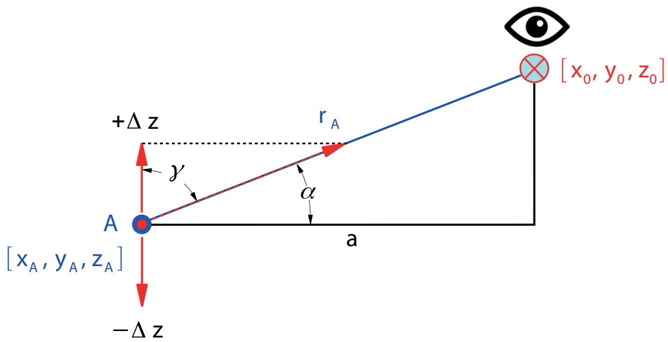


Figure 3 *Correction factor determination*

$$\begin{aligned}(x_0 - x_1)^2 + (y_0 - y_1)^2 + (z_0 - z_1)^2 - r_1^2 = 0\\(x_0 - x_2)^2 + (y_0 - y_2)^2 + (z_0 - z_2)^2 - r_2^2 = 0\\(x_0 - x_3)^2 + (y_0 - y_3)^2 + (z_0 - z_3)^2 - r_3^2 = 0\end{aligned} \tag{1}$$

In this case, Equation (1) can be rewritten according to Figure 2 into a simpler Equation (2).

$$\begin{aligned}x_0^2 + y_0^2 + z_0^2 - r_1^2 = 0\\(x_0 - x_2)^2 + y_0^2 + z_0^2 - r_2^2 = 0\\(x_0 - x_3)^2 + (y_0 - y_3)^2 + z_0^2 - r_3^2 = 0\end{aligned} \tag{2}$$

Assuming x_2=x_3, Equation (2) changes into Equation (3).

$$\begin{aligned}x_0^2 + y_0^2 + z_0^2 - r_1^2 = 0\\(x_0 - x_2)^2 + y_0^2 + z_0^2 - r_2^2 = 0\\(x_0 - x_2)^2 + (y_0 - y_3)^2 + z_0^2 - r_3^2 = 0\end{aligned} \tag{3}$$

By solving the Equation (3) we get the coordinates (4)-(6).

$$x_0 = \frac{x_2^2 + r_1^2 - r_2^2}{2x_2} \tag{4}$$

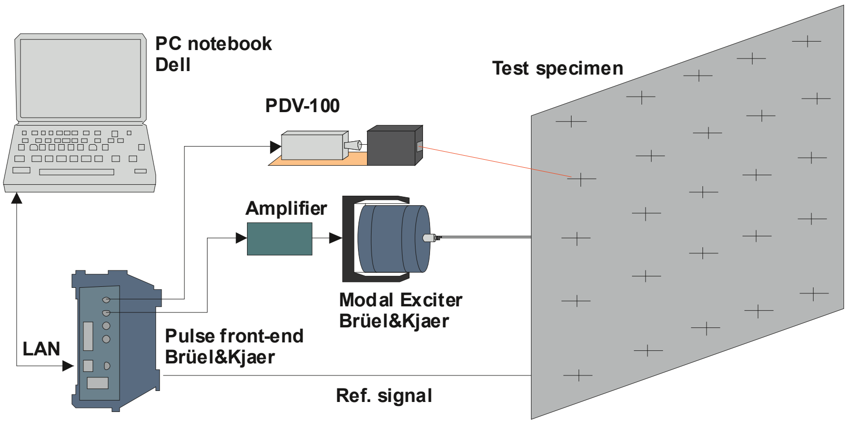


Figure 4 *Block diagram of the experimental setup*

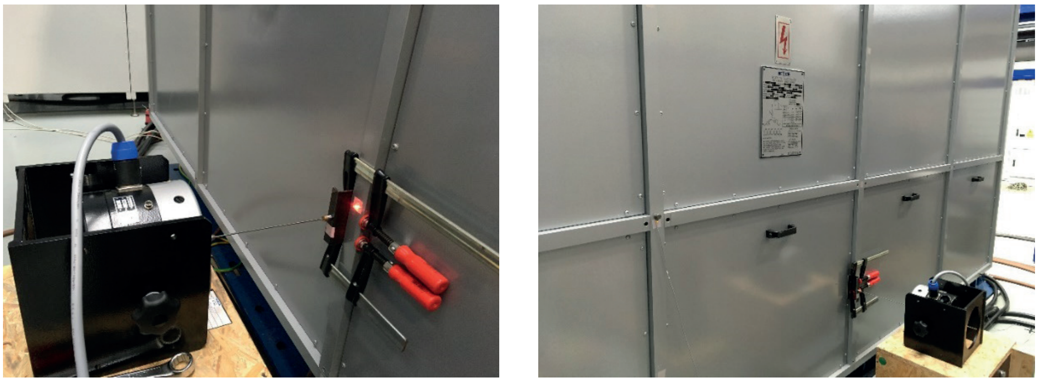


Figure 5 *Vibration generator (left), position of excitation point on transformer housing (right)*

$$y_0 = \frac{y_3^2 + r_2^2 - r_3^2}{2y_3} \tag{5}$$

$$\begin{aligned} z_{01} &= \frac{\sqrt{-x_2^4 y_2^3 - y_2^3(r_1^2 - r_2^2)^2 - x_2^2\left[y_3^4 + (r_2^2 - r_3^2)^2 - 2y_3^2(r_1^2 + r_3^2)\right]}}{2x_2 y_3} \\ z_{02} &= \frac{\sqrt{-x_2^4 y_2^3 - y_2^3(r_1^2 - r_2^2)^2 - x_2^2\left[y_3^4 + (r_2^2 - r_3^2)^2 - 2y_3^2(r_1^2 + r_3^2)\right]}}{2x_2 y_3} \end{aligned} \tag{6}$$

The position of the observation point is then $[x_0, y_0, z_{01}]$. Further, if the length a seen in Figure 3 is calculated as Equation (7)

$$a = \sqrt{(x_0 - x_A)^2 + (y_0 - y_A)^2}\,, \tag{7}$$

then the angle α is given by Equation (8) and the angle γ is obtained from Equation (9).

$$\alpha = \operatorname{atan}\left(z_{01}/a\right) \tag{8}$$

$$\gamma = \pi/2 - \alpha \tag{9}$$

Finally, the correction factor is according to Equation (10).

$$k_r = \cos\gamma \tag{10}$$

The method can be used for any complex shape by dividing the whole surface of the analyzed object into smaller but simpler regions and applying it repeatedly. It is similar to application of the finite element method.

3 Experimental Measurement

The validity of the proposed correction method is practically demonstrated by laboratory measurement of natural frequencies and mode shapes for vibrations of high voltage transformer housing shown in Figure 2 right. A block diagram of the measurement system is shown in Figure 4.

During the experiment, the transformer housing was mechanically excited by the dynamic vibration generator (Type 4824) in the frequency sweep mode (1-100 Hz). It is a lightweight modal exciter capable of exciting oscillations

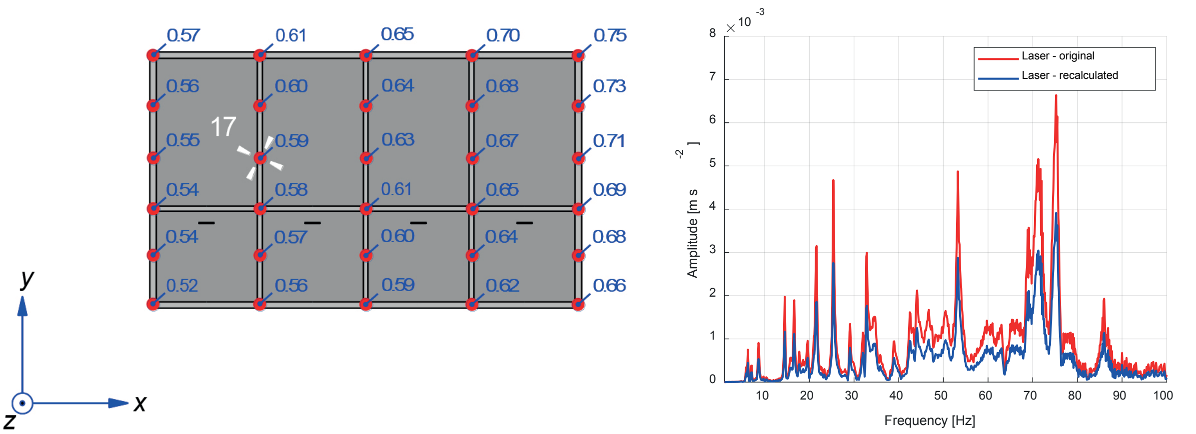


Figure 6 *The correction factors calculated for evaluated measuring points (left), the measured vibration spectrum valid for the measured point "17" (right)*

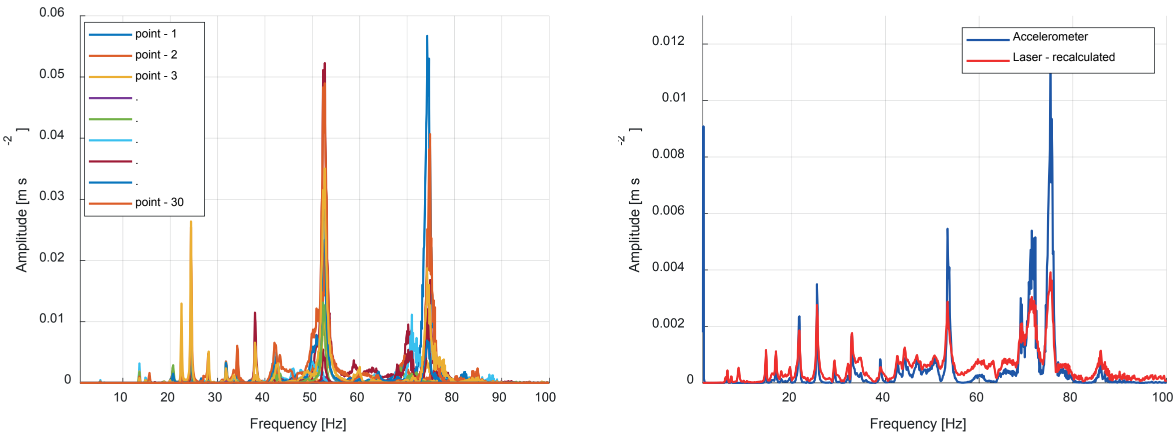


Figure 7 *Vibration spectrum measured with accelerometer at all tested points (left), comparison between LDV and accelerometer measurement performed at point "17" (right)*

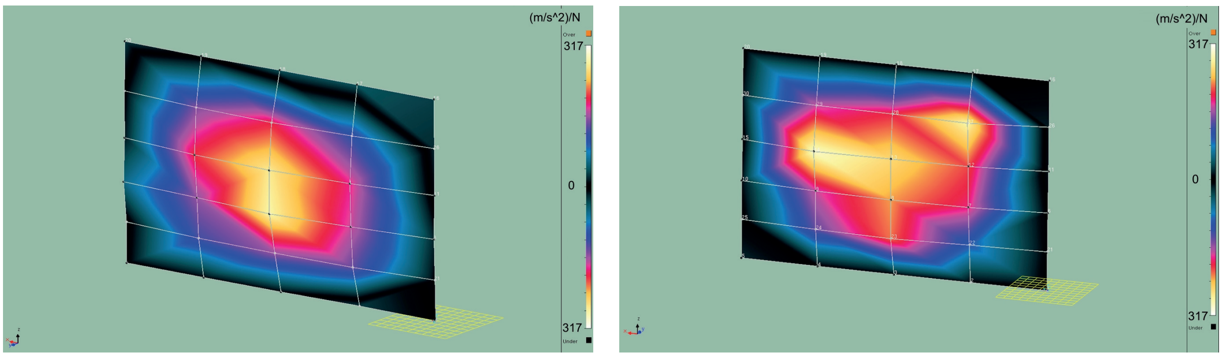


Figure 8 *Mode shape of the transformer housing at first significant frequency 5.25 Hz; accelerometer (left), laser vibrometer (right)*

with a force of 100 N. Figure 5 shows the location of the exciter along with the transformer housing being analyzed.

Measurements were repeated four times in a sequence and subsequently averaged. The transformer housing from the viewpoint of the laser vibrometer (laser targeting to the upper right corner) is shown in Figure 2.

The resulting correction factors calculated using Equations (1)-(10) are listed in the left side of Figure 6. The vibration spectrum measured at the measuring point "17" can be seen in the right side of the same figure.

An additional equivalent accelerometer measurement was performed to validate the presented results as this method is usually considered to be a reference in a given scientific field. Comparison between LDV and accelerometer measurement is shown in Figure 7. For this purpose, a constant current line drive accelerometer (4533-B) was a perfect choice due to high sensitivity, wide frequency range and low noise.

Minor inaccuracies in the frequency domain are caused by the non-linear response of the transformer housing, whose frame is manufactured from a set of aluminum structural beams interconnected with a plastic clutch assembly. Another slight difference manifested mainly at higher frequencies may be caused by the accelerometer mass. This additional weight can cause slight distortion in both amplitude and spectral regions by shifting individual antinodes.

The qualitative comparison between transformer housing mode shapes derived from results of accelerometer measurement and the LDV measurement is shown in Figure 8.

4 Conclusion

The paper has given a brief discussion on the technical background and the most important benefits of using laser Doppler vibrometry. It has proposed a correction method of the oblique-angle vibration for a vibration measurement with a laser beam. The study has brought a simple mathematical description of the analyzed geometrical problem and has shown a practical example of its proper usage. Moreover, it could be used for any complex shape by dividing the whole surface of the analyzed object into smaller but geometrically simpler regions and applying it repeatedly.

The method has been verified by a laboratory measurement performed on the high voltage transformer housing. The results have shown very good agreement between corrected LDV and the equivalent accelerometer measurement. Therefore, the proposed correction method should be considered as valid.

Acknowledgment

This research has been supported by the Ministry of Education, Youth and Sports of the Czech Republic under the project OP VVV Electrical Engineering Technologies with High-Level of Embedded Intelligence CZ.02.1.01/0.0/0.0/18_069/0009855 and by funding program of the University of West Bohemia number SGS-2018-009. Also, the research has been supported by project LO1502 “Development of the Regional Technological Institute” under the auspices of the National Sustainability Programme I of the Ministry of Education of the Czech Republic aimed to support research, experimental development and innovation.

References

[1] CHEN, M., O’SULLIVAN, J. A., SINGLA, N., SIREVAAG, E. J., KRISTJANSSON, D., LAI, P., KAPLAN A. D., ROHRBAUGH J. W. Laser Doppler vibrometry measures of physiological function: evaluation of biometric capabilities. *IEEE Transactions on Information Forensics and Security* [online]. 2010, **5**(3), p. 449-460. ISSN 1556-6021. Available from: https://doi.org/10.1109/TIFS.2010.2051542

[2] SCALISE, L., ERCOLI, I., MARCHIONNI, P., TOMASINI, E. P. Measurement of respiration rate in preterm infants by laser Doppler vibrometry. IEEE International Symposium on Medical Measurements and Applications : proceedings [online]. IEEE, 2011. ISBN 978-1-4244-9338-8, p. 657-661. Available from: https://doi.org/10.1109/MeMeA.2011.5966740

[3] KAPLAN A. D., ORSULLIVAN, J. A., SIREVAAG E., J., LAI P., ROHRBAUGH, J. W. Hidden state models for noncontact measurements of the carotid pulse using a laser Doppler vibrometer. *IEEE Transactions on Biomedical Engineering* [online]. 2012, **59**(3), p. 744-753. ISSN 0018-9294, eISSN 1558-2531. Available from: https://doi.org/10.1109/TBME.2011.2179297

[4] AMBROZINSKI, L., SPYTEK, J., DZIEDZIECH, K., PIECZONKA, L., STASZEWSKI W. J. Damage detection in plate-like structures based on mode-conversion sensing with 3D laser vibrometer. IEEE International Ultrasonics Symposium IUS : proceedings [online]. IEEE, 2017. ISSN 2076-3417, p. 1-4. Available from: https://doi.org/10.1109/ULTSYM.2017.8092957

[5] LI, R., WANG, T., ZHU, Z.; XIAO, W. Vibration characteristics of various surfaces using an ldv for long-range voice acquisition. *IEEE Sensors Journal* [online]. 2011, **11**(6), p. 1415-1422. ISSN 1530-437X. Available from: https://doi.org/10.1109/JSEN.2010.2093125

[6] SPANIK, P., SEDO, J., DRGONA, P., FRIVALDSKY, M. Real time harmonic analysis of recuperative current through utilization of digital measuring equipment. *Elektronika IR Elektrotechnika* [online]. 2013, **19**(5), p. 33-38. ISSN 1392-1215, eISSN 2029-5731. Available from: https://doi.org/10.5755/j01.eee.19.5.4364

[7] GAO, Ch., WANG, Q., WIE, G., LONG, X. A highly accurate calibration method for terrestrial laser Doppler velocimeter. *IEEE Transactions on Instrumentation and Measurement* [online]. 2017, **66**(8), p. 1994-2003. ISSN 0018-9456, eISSN 1557-9662. Available from: https://doi.org/10.1109/TIM.2017.2685078

[8] BERNAT, P. KACOR, P. Utilisation of stray electromagnetic field for no-contact operational diagnostic of asynchronous machine. 10th International Conference ELEKTRO 2014 : proceedings [online]. University of Zilina, Faculty of Electrical Engineering, 2014. ISBN 978-1-4799-3721-9, p. 256-261. Available from: https://doi.org/10.1109/ELEKTRO.2014.6848898

[9] KIM, D., SONG, H., KHALIL, H.; J. LEE, L., WANG, S., PARK, K. 3-D Vibration measurement using a single laser scanning vibrometer by moving to three different locations. *IEEE Transactions on Instrumentation and Measurement* [online]. 2014, **63**(8), p. 2028-2033. ISSN 0018-9456, eISSN 1557-9662. Available from: https://doi.org/10.1109/TIM.2014.2302244

[10] KIM, M. G., JO, K., KWON, H. S., JANG, W., PARK, Y., Z., LEE J. Fiber-optic laser doppler vibrometer to dynamically measure MEMS actuator with in-plane motion. *Journal of Microelectromechanical Systems* [online]. 2009, **18**(6), p. 1365-1370. ISSN 1057-7157, eISSN 1941-0158. Available from: https://doi.org/10.1109/JMEMS.2009.2031698

[11] PHENGPOM, T.; KAMADA, Y., MAEDA, T., MURATA J., KAGISAKI, Y., NISHIMURA, S. Experimental study on sectional performance of horizontal axis wind turbine at optimum operation by using LDV system. International Conference and Utility Exhibition on Green Energy for Sustainable Development (ICUE) : proceedings. IEEE, 2014. ISBN 978-1-4799-2627-5, p. 1-6.

[12] PAGAN, L., LAKE, K. Modal analysis: a comparison between finite element analysis (FEA) and practical laser Doppler vibrometer (LDV) Testing. 19th International Conference on Computer Modelling & Simulation UKSim-AMSS : proceedings [online]. IEEE, 2017. ISBN 978-1-5386-2736-5, p. 75-80. Available from: https://doi.org/10.1109/UKSim.2017.27

[13] REITEN, M. T., WRIGHT, R. G. Laser Doppler vibrometry use in detecting faulty printed circuit boards. IEEE Autotestcon : proceedings. 2008, p. 33-36.

[14] SUN, H., LIU, J., KENNEL, R,. Improving the accuracy of laser self-mixing interferometry for velocity measurement. IEEE International Instrumentation and Measurement Technology Conference (I2MTC) : proceedings [online]. IEEE, 2017. ISBN 978-1-5090-3596-0, p. 1-5. Available from: https://doi.org/10.1109/I2MTC.2017.7969922

[15] OUAHABI, A., DEPOLLIER, E., SIMON, L., KOUME, D. Spectrum estimation from randomly sampled velocity data [LDV]. *IEEE Transactions on Instrumentation and Measurement* [online]. 1998, **47**(4), p. 1005-1012. ISSN 0018-9456, eISSN 1557-9662. Available from: https://doi.org/10.1109/19.744659

[16] KWAPISZ, L., JAKUBOWSKI, P., RADZIENSKI, M. Problems with vibroacoustic LDV measurements for Windows. Joint Conference - Acoustics : proceedings [online]. 2018. ISBN 978-1-5386-7115-3, p. 1-4. Available from: https://doi.org/10.1109/ACOUSTICS.2018.8502350

[17] KAVALIR, T., KRIZEK, M., SIKA, J., KINDL, V. Upgrading of the single point laser vibrometer into a laser scanning vibrometer. *Communications - Scientific Letters of the University of Zilina* [online]. 2018, **20**(1), p. 61-66. ISSN 1335-4205, eISSN 2585-7878. Available from: http://komunikacie.uniza.sk/index.php/communications/article/view/47

Jan Celko - Matus Kovac - Kristina Huszarova

INFLUENCE OF SELECTED VEHICLE MANEUVERS ON REDUCTION OF THE URBAN ROADS CAPACITY

Capacity assessment of urban roads according to Slovak standard does not sufficiently take into account the influence of vehicle maneuvers on road section performance between the two intersections. This research analyzed turning relations on selected urban road intersections and the influence of right turn and left turn on major stream speed changes. For the purpose of determining the influence of the right turn on decrease in capacity, measurements were carried out at 7 uncontrolled intersections with curve radius ranging from 6 to 30 m. To determine the influence of the left turn on the capacity of urban road a critical gap was evaluated, using the Raff's, method, based on the analysis of accepted and rejected gaps in the major traffic stream, which was one of the main inputs for simulations. The findings were used to determine the influence of selected maneuvers on the road capacity, which led to a proposal for reduction coefficients based on computational analysis performed using simulations in PTV VISSIM.

Keywords: *traffic, urban roads, capacity, traffic flow, simulation*

1 Introduction

Influence of the turning maneuvers at simple intersections and parking spaces on the reduction of the capacity of urban roads has not received much attention. Focus has predominantly been directed at signal intersections, e.g. Kim [1].

Several models and analyses were created for unsignalized intersections, which consider turning relations [2-6].

Authors of [7] dealt with an analysis and modelling of turning relations and their influence on the intersection capacity in urban intersections in China. They generally focused on two types of crossing behaviors. The first type is called the single-vehicle-crossing (SVC) and usually appears when the traffic flow is not saturated. The second type is known as vehicle-stream crossing (VSC) and refers to situations when one or more vehicles have to seek for the right gap to move across another vehicle stream. More attention from researchers is devoted to describing this type of crossing behavior.

Research has also focused on the capacity analysis of turning maneuvers on the U-turn intersections and their influence on the capacity of the intersections. This topic was addressed in [8] where analysis applied the values of the base critical gaps $t_{c,base}$, as well as the base follow-up time $t_{f,base}$.

The critical gap was determined to be about 6.4 s, the follow-up time 2.5 s. In the case of U-turns, accommodated at median openings with narrow median nose width of 6.4 m, the critical gap was about 6.9 s and the follow-up time 3.1 s. Difference in capacity was up to 286 pc/h for making the U turns at median openings with narrow medians (median nose width 6.4 m).

The turning relations are often simulated by software tools. In recent years, VISSIM of PTV VISION packet has been used most frequently.

Researchers in [9] simulated the turning relations using the VISSIM. Although their analysis of turning was predominantly based on the Harder´s model, they also determined the base critical gaps for different types of movement on unsignalized intersections (Table 1). Apart from presenting important data, the model confirms the suitability of the VISSIM program for similar purposes.

Delay during the turning relations on intersections is also analyzed in the Highway Capacity Manual [10]. The HCM analyzes the problem of calculation of delay during the turning on intersections separately for the left and right turns. The delay during the right turn is solely a result of deceleration of turning vehicles and the adaptation to the speed of previous vehicles. The delay during the left turn is a result of waiting for the previous vehicle to complete their turning maneuver. Generally, the typical values of delay given in Table 2 may be used.

The values are only valid for 10% of turning vehicles and must be reduced in the case of the remaining vehicles. Predictions of speed changes on the right turning lanes on urban streets are offered in [11].

The parking manoeuvers significantly contribute to reduction of the capacity of urban streets. Results of [12], which describe the number of lanes and the number of parking manoeuvers per hour as the variables for the capacity reduction, were adopted in the HCM 2000 [10]. Likewise, Valleley in [13] focuses on relation between

Jan Celko[1,*], Matus Kovac[1], Kristina Huszarova[2]
[1]Department of Highway Engineering. Faculty of Civil Engineering, University of Zilina, Slovakia
[2]Freelance researcher, Zemianske Kostolany, Slovakia
*E-mail of corresponding author: jan.celko@fstav.uniza.sk

__Table 1__ Critical Headway and Follow-Up Time for Different Turning Movements, [9]

Vehicle movement	Base critical, tc,base (s)	Base follow-up time, tf,base (s)
Left turn from major (four-lane)	4.1	2.2
U-turn (six-lane)	5.6	2.3
U-turn (four-lane, wide median)	6.4	2.5
U-turn (four-lane, narrow median)	6.9	3.1
Through traffic on minor (four-lane)	6.5	4.0
Left turn from minor (four-lane)	7.5	3.5

__Table 2__ Typical values of delay by HCM [10]

Midsegment Volume (veh/h/ln)	Through Vehicle Delay (s/veh/pt) by Number of Through Lanes		
	1 Lane	2 Lanes	3 Lanes
200	0.04	0.04	0.05
300	0.08	0.08	0.09
400	0.12	0.15	0.15
500	0.18	0.25	0.15
600	0.27	0.41	0.15
700	0.39	0.72	0.15

the number of parking maneuvers and the reduction of urban road capacity. Yousif and Purnawan [14] analyze the difference in time delays between the parallel and angle on-street parking.

Authors of [15] analyze the influence of these changes on the travel-time delays. The parking maneuvers affect car and bike lanes. They also increase the delay of traffic and reduce the capacity of the adjacent travel lane. Along with that, on-street parking also increases the number of traffic accidents. They conclude that on-street parking could reduce capacity and cause congestion. Their model is designed to predict delay in the travel time during the parking maneuvers under various conditions.

The methodology of collection, selection and analysis of data regarding the characteristics of traffic flow and observations of actual intersections in the city of Zilina were performed as a part of research activities conducted at the author´s institution. The aim of this part was to determinate the influence of selected maneuvers on urban road capacity. The analysis included the effect of turning vehicles to the capacity of the intersection without the influence of next effects, e.g. impact of pedestrians, in the sense of Slovak Standard for the simple intersections. Only the analysis of regular intersections was selected for presentation in the paper.

The results were compared to the currently effective methodology stated in Slovak standard, which only takes into consideration the influence of maneuvers that is based on their minimum numbers. To verify the theoretical calculations, measurements were used as input into a simulation model which was used to further specify obtained results.

2 The influence of turning vehicles on the capacity of urban roads

2.1 Right turns

Measuring spots were selected based on the previous research findings related to the characteristics of traffic and road network, in a way that would represent maximum range of radius sizes for turns from the main road, a sufficient number of turns with respect to traffic intensity and the angle of intersection of approx. 90°. Altogether, 7 uncontrolled level intersections with curve radius ranging from 6 to 30 m were tested. Measurements were carried out at individual spots in duration of 4 hours in order to record the traffic flow during the peak hour, as well as in lower volumes.

Instantaneous vehicle speed during the right turn was measured using a hand-held radar. Measured and analyzed were factors, as well as deceleration of vehicles, prior to turning with respect to the curve radius.

In order to determine a generally valid dependency, the data were selected at two levels and the resulting sample was used to determine the level of influence of the right-turn maneuver on the urban road capacity. To assure objectivity of both selections, the data were processed according to the standards of mathematical statistics and the speed dependency on turn and radius size was determined, as illustrated in Figure 1.

Results show quite a wide range of speeds on turns. While the speed on a turn of R = 6 m is in the range of 20.59±2.89 km/h the speed on a turn of R = 30 m is in the range of 33.28±3.43 km/h, which means the speed is higher by 61.63%. From the resulting dependency formula, it

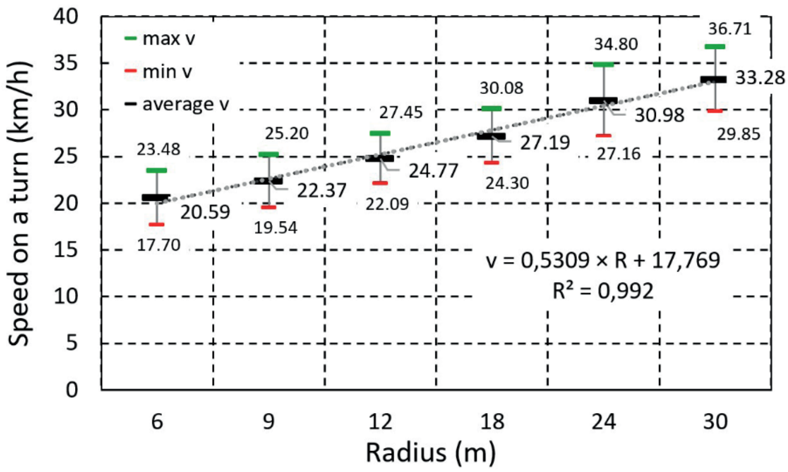


Figure 1 *Influence of the right turn radius size on the speed on a turn*

Table 3 *Through vehicle speed (km/h) with respect to the right turns for a = 3.4 m/s*$^{-2}$

R (m)	Number of right turns			Percentage of right turns				
	25	50	100	10%	20%	30%	40%	50%
6	49.033	48.729	48.096	47.318	44.459	41.754	38.245	37.128
9	49.069	48.992	48.3	47.717	46.644	44.456	42.405	38.565
12	49.106	49.091	48.64	48.143	47.168	46.427	45.236	43.392
18	49.135	49.176	48.903	48.37	48.145	47.594	47.073	45.856
24	49.184	49.261	49.159	49.093	49.175	48.92	48.708	48.402
30	49.194	49.281	49.235	49.291	49.402	49.425	49.246	48.985

Table 4 *Reduction coefficient of capacity with respect to the right turns for a = 3.4 m/s*$^{-2}$

R (m)	Number of right turns			Percentage of right turns				
	25	50	100	10%	20%	30%	40%	50%
6	1.00	1.00	1.00	1.00	0.99	0.98	0.96	0.94
9	1.00	1.00	1.00	1.00	1.00	0.99	0.97	0.96
12	1.00	1.00	1.00	1.00	1.00	0.99	0.98	0.98
18	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99
24	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
30	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

follows that increasing the turn radius size by 1 m increases the speed by 0.9 km/h.

This confirms the assumption that regulations should not quantify all the right turns by one common value because their influence on the vehicle speed might be entirely different.

To determine the influence of selected vehicle maneuvers on decreasing the capacity of collector urban road, a simulation model was developed using the simulation software PTV VISSIM. From geometrical perspective, this was a simple model. To calibrate the model, the final speed values and other characteristics of vehicle movement in traffic flow were used in order to determine the influence of the radius size of the right turns on the capacity of urban road. The microsimulation allows evaluate the traffic flow characteristics second by second based on the new design elements. Software PTV VISSIM could log several indicators (e.g. speed, density and volumes) from the lane segments. The data reflect changes of the traffic flow characteristics depending on design, [16].

Six simulation series were carried out using the model, each one corresponding to a particular radius size and a corresponding speed on a turn (of maximum and minimum size). Thus calibrated, the model was assigned a lane with varying numbers of vehicles going straight and turning right. The alteration of values was carried out 8 times for each series, with the following ratios: 1775:25, 1750:50, 1700:100 vehicles per hour and with the following ratios expressed in percentage: 90:10, 80:20, 70:30, 60:40 and 50:50. The purpose of this variation in ratios of the direction of traffic was to create various situations to determine the influence of the right turn maneuver on the decrease in the capacity of a collector urban road with respect to the number of turning vehicles. The first three ratios corresponded to

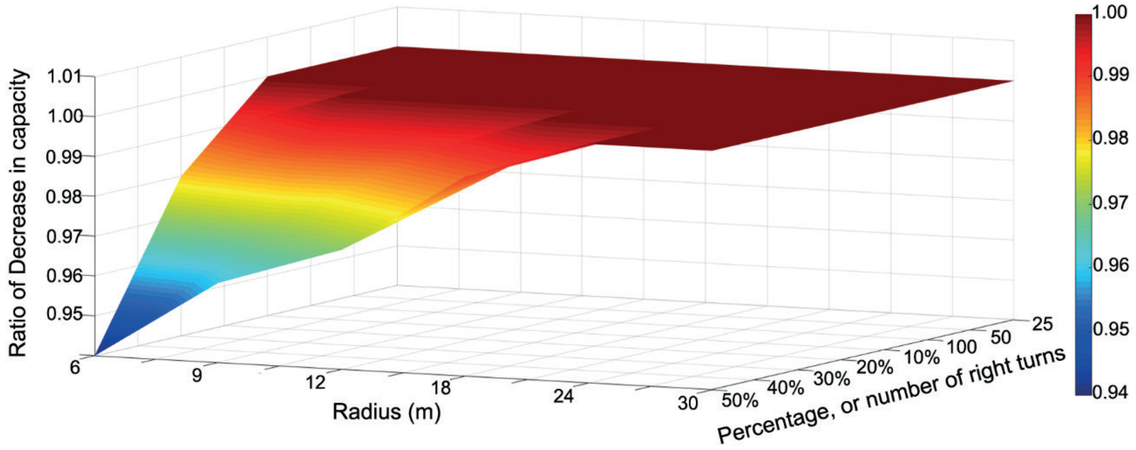


Figure 2 *Dependency of decrease of capacity on the number (percentage) of turning vehicles and curve radius size (a = 3.4 m/s⁻²)*

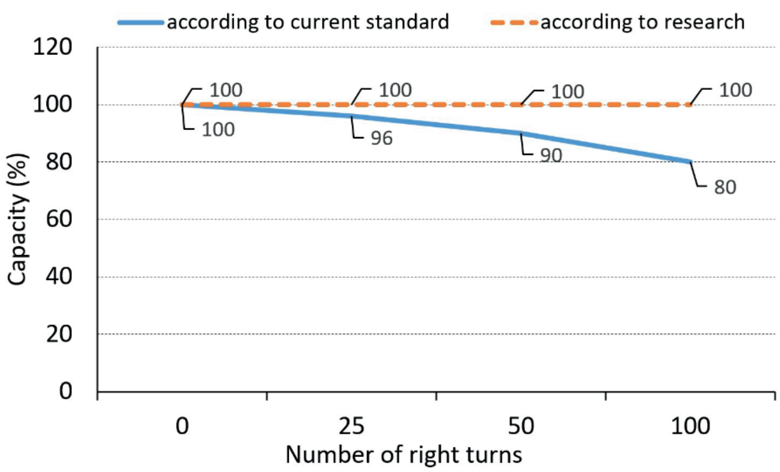


Figure 3 *Decrease in capacity with respect to number of the right turns according to the research and according to Slovak standard*

the number of turns from the continuous straight lane in direction to the right as they are considered by STN 73 6110 [17] i.e. 25, 50, 100 maneuvers per hour, respectively. The series were simulated twice, for the value of deceleration of a vehicle of a = 2.0 m/s^{-2} as considered by the simulation software and for the value of deceleration of a vehicle of a = 3.4 m/s^{-2} by AASHTO Green Book [18]. Overall, to determine the influence of the right maneuver on the capacity of the collector urban road, nearly 100 simulations were carried out and evaluated, the required output data being the average speed of the continuous traffic flow and the number of vehicles passing through the model in 1 hour, which was used to determine the decrease of the capacity as a ratio of these vehicles to the number of vehicles equal to the basic capacity, i.e. the basic volume of the collector urban road (reduction coefficient). Examples of results of the simulations are shown in Tables 3 and 4 and Figure 2.

Results show that the decrease in the speed of vehicles in the traffic flow is lower than what was predicted from the absolute values of the speed of vehicles on turn with respect to the radius size. The average decrease in speed of the traffic flow from maximum speed limit was 2.89 km/h at a = 2.0 m/s^{-2} and 2.74 km/h at a = 3.4 m/s^{-2}. Considering the fact that the initial required speed of vehicles in a simulation model oscillates within the range 50±2.0 km/h, the decrease in the speed of the through traffic flow due to the right turn is very low. Maximum decrease in speed is 13 km/h, which corresponds to the minimum radius size and represents 50% of the right turns.

The results show that the deceleration of vehicles prior to turning (i.e. the distance from the edge of the intersection at the moment when deceleration began) does not have a significant influence on the traffic flow as a whole and the corresponding average decrease in speed and urban road capacity.

From these findings follows that influence of the right turn on the decrease in the capacity of urban road is not significant. Decrease in capacity takes place when the ratio of turning vehicles is high (30% and more), provided that the radius size is lower than 12 m. Table 4 illustrate that maximum decrease of capacity according to the reduction coefficient determined from the ratio of vehicles released by the simulation model to the initial number of vehicles, is approximately 6%, at minimum radius size and 50% of right turns.

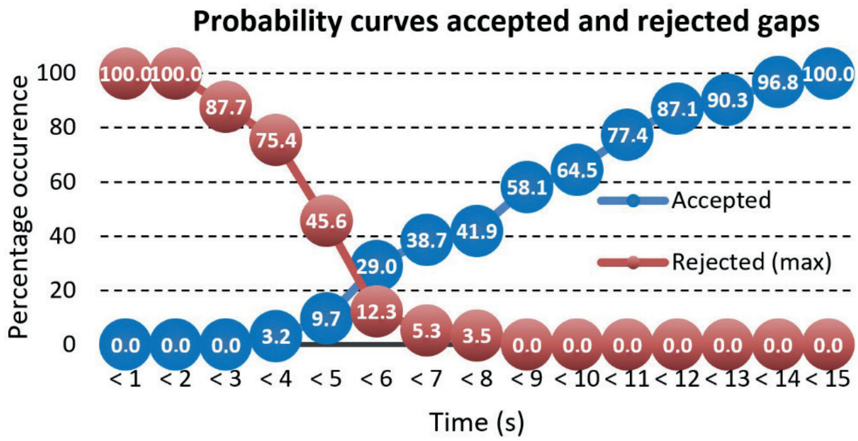


Figure 4 *Results of t_g based on the Raff's method for one of the selected intersections*

Based on the findings, it is possible to determine functional levels for the quality assessment of the collector urban roads according to speed.

Comparison to the methods of assessment of the right turns according to Slovak standard [17] shows that when the number of turns is 25, the capacity of the section decreases by 4%; with the number of turns being 50, there will be a 10% decrease; and with 100 turns, the expected decrease is 20%. Research results for such a number of turning vehicles did not shown any decrease in capacity (Figure 3).

2.2 Left turns

The effect of the left turns to the decreasing of the capacity of simple intersections is determined in the Slovak Standard without the influence of opposite traffic flow intensity. For the purpose of determining the influence of the left turn on decrease in capacity, measurements were carried out at 5 uncontrolled intersections in the city of Zilina. Measurements were performed at individual spots in duration of 4 hours in order to record the traffic flow during the peak hour, as well as in lower volumes.

To determine the influence of the left turn on the capacity of urban road it was necessary to first determine the critical gap. For this purpose, the Raff's method was used, which draws values of the critical time gap from the intersection of sum lines of accepted and rejected gaps (Figure 4). The sum line for accepted gaps (the rising curve) is a line, whose every point states the percentage of all the accepted gaps that are lower than the given gap. The sum line for rejected gaps (the declining curve) is a line, whose every point state what percentage of all the rejected gaps is greater than the given gap. For every vehicle, only its maximum rejected gap was considered for the sum line (a vehicle may reject more gaps for turns on the superior counter flow in the traffic flow). For the evaluation purpose, were considered only gaps of those drivers who, prior to accepting a gap in the superior traffic flow to make a left turn, had rejected at least one gap and at the same time, did not accept a gap that was lower than the one they had rejected before.

The outcome of the measurements, processed videos from individual intersections and subsequently obtained accepted and maximum rejected gaps, was an estimation of critical time gaps. They were determined for individual intersections, which were observed by four selected methods of assessment:

1. estimate of t_g based on the gaps that were accepted and rejected by drivers turning left, and which occurred between the two vehicles driving only straight in a superior traffic flow during the peak-hour intensity - label (PHI without RT)
2. estimate of t_g based on all the gaps that were accepted and created by drivers turning left, which occurred in a superior traffic flow during the peak-hour intensity - label (PHI)
3. estimate of t_g based on the gaps that were accepted and rejected by drivers turning left, and occurred between the two vehicles driving only straight in a superior traffic flow during the time of measurements - label (all measurements, without RT)
4. estimate of t_g based on the gaps that were accepted and rejected by drivers turning left, and which occurred in a superior traffic flow during the time of measurements - label (all measurements).

The results of these evaluations are presented in Table 5.

The results show a relatively broad span in t_g, which is dependent on the type and quantity of data it was estimated from. The t_g based on measurements taken during the peak hour has a larger span than t_g based on all the measurements, taken during the entire observation. The maximum span of t_g reaching 2.0 seconds resulted from evaluation of gaps between the two vehicles driving straight in the superior traffic, which drivers turning left accepted or rejected during the peak hour. The dependency of the critical time gaps t_g on the intensity of superior streams is illustrated by Figure 5.

Table 5 *Span of the critical time gaps t_g obtained from evaluations of accepted and maximum rejected gaps*

t_g (s)			
University of Zilina Research (PHI)	5.0	-	6.0
University of Zilina Research (PHI, without Right Turns)	4.0	-	6.0
University of Zilina Research (all measurements)	5.1	-	5.7
University of Zilina Research (all measurements, without Right Turns)	5.1	-	5.7

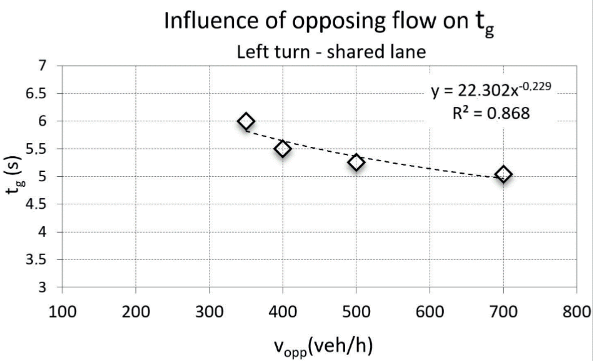


Figure 5 *Dependency of t_g on the intensity of the superior traffic stream*

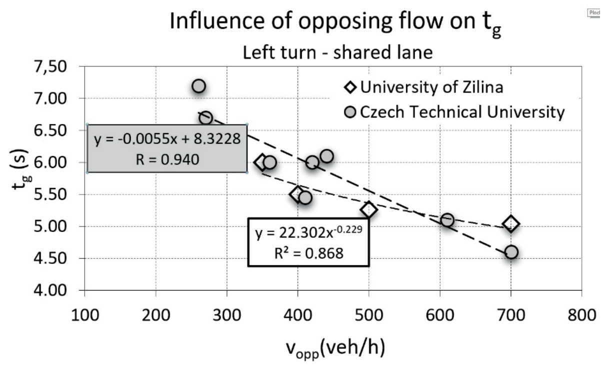


Figure 6 *Dependency of t_g on the intensity of superior traffic stream - comparison of author´s study (trend described by exponential function) and the CVUT study, [21]*

Analyzed measurements confirm the dependency of the critical time gaps t_g on the intensity of vehicles in the superior traffic flow. With rising intensity, drivers turning left accept shorter gaps between vehicles. This phenomenon has been confirmed by the results of research done in [19], [20], [21]. Figure 6 presents the results of studies of Czech Technical University [21] and University of Zilina. The comparison was chosen on the dependence of very similar traffic conditions in Czech and Slovak republic.

The speed of decrease of t_g (the steepness of the curve) is lower in the case of results obtained by authors than in the case of dependency discovered by the study by Czech Technical University (CVUT). This may result from factors such as the speed of the superior traffic flow as well as the mentality of drivers. While the dependency obtained from the CVUT study is represented by a linear function, the dependency obtained from authors is represented by an exponential function, which better describes the trend in data (the authors–expect that with rising intensity of superior streams the value of t_g will be stable, i.e. it will never equal to zero). The results have been confirmed also by [22], where the observed t_g value was 5.8-6.04 s. In order to determine the influence of the left turn maneuvers of vehicles on capacity of the collector urban road, 4 series of simulations were carried out in a simulation model. In each series, different value of the critical time gap (4.0 s - minimum; 5.3 s - average; 5.5 s - stated in the Slovak Technical Condition TP 102 [23]); 6.0 s - maximum) was entered for the link, from which vehicles turned left from the main road to a side street. Direction of the traffic varied at the point of entry into this link, from entry in the straight direction and to the left in a similar fashion as in the case of the right turn in various ratios. Three ratios corresponded to the number of the left turns from the continuous traffic flow to the left in a way that is considered by Slovak standard [17]). Since it is expected that the capacity of a section of a collector urban road in the case of the left turns is largely influenced by the density of the superior traffic flow, the entry intensity values for the superior stream in the simulation model varied from 100 to 1800. Overall, to determine the influence of the left maneuver on decrease in the capacity of the collector urban road, 576 simulations were carried out and evaluated leading to 576 reduction coefficients. An example of the simulation results is presented by Figures 7 and 8.

From the findings follows that with increasing critical time gap t_g increases the influence of left turn, which causes a significant decrease in the capacity of a section. With the maximum number of turns (100 = 33 left turns), which is considered by Slovak Standard [17], the decrease in capacity may be as much as 39% (entry volume 1800 pc/h with the number of vehicles in the superior traffic flow 1800 pc/h), or 43% (entry volume 1233 pc/h with the number of vehicles in the superior traffic flow 1800 pc/h).

With the maximum number of turning vehicles, as it is considered by the standard, and with the volume upon entry at 1800 pc/h, the capacity does not decrease until the number of turning vehicles in the superior traffic flow reaches 1500 pc/h at t_g = 4 s. With other t_g the decrease does not manifest until the intensity of the superior traffic flow is equal to 1233 pc/h.

Increase in the number of turning vehicles causes increase in the influence of the left turn, which results in a significant decrease in the capacity of a section. At the ratio of the left turning vehicles of 10%, the capacity decreases as soon as the volume of the superior traffic stream is 700 pc/h, with t_g = 4 s leading to a decrease by 6%, and with t_g = 6 s up to 14% (at the intensity upon entry at 1800 pc/h) (Figure 9).

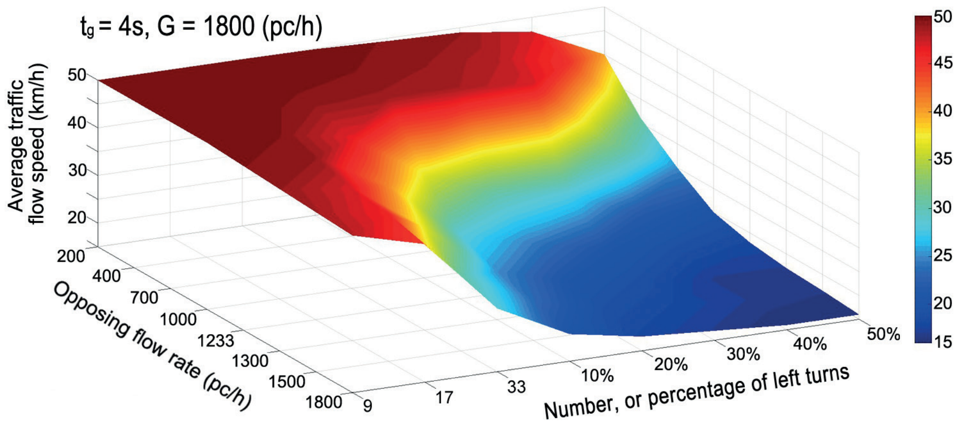


Figure 7 *Dependency of average speed of the traffic stream on the number (percentage) of turning vehicles and the intensity of counter-stream DP*

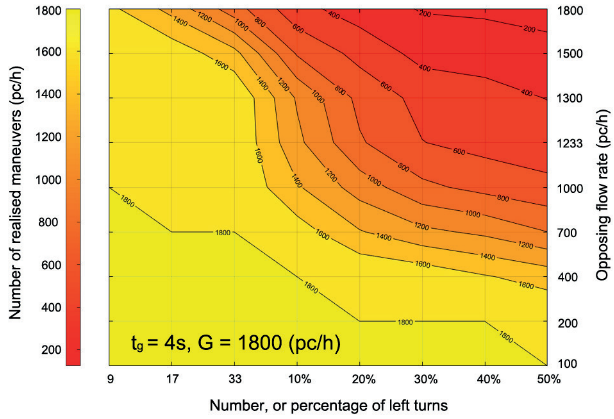


Figure 8 *Dependency of number of realized maneuvers on the number (percentage) of turning vehicles and the opposing flow rate*

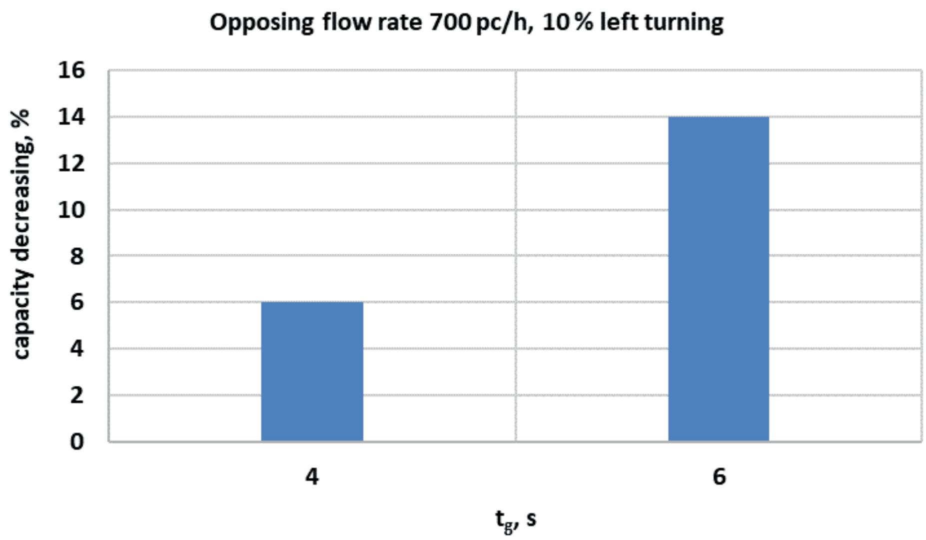


Figure 9 *Dependency of capacity decreasing on the t_g value*

Given the same volume upon entry and the ratio of turning vehicles being 50%, the capacity decreases as soon as the intensity of the superior traffic stream is at 400 pc/h, at t_g = 4 or 200 pc/h for other t_g.

For 33 left turns, the standard considers flat decrease in the capacity by 20% with no regard to the intensity of the superior traffic flow and the critical time gap. The research findings show that decrease in the capacity spans between 0-28% for t_g = 4.0 s; 0-53% for t_g = 5.3 s; 0-71% for t_g = 5.5

s and 6.0 s. From that follows that the capacity of a section should not be determined solely by the number of the left turns because of the broad span of the rate of influence of this maneuver in relation to the intensity of the superior traffic flow. In the extreme case, a higher ratio of the left turns may decrease the capacity by as much as 90%.

3 Conclusion

The analysis of results shows that the right turn *per se* does not significantly influence the decrease in the capacity of urban road as it is considered by the Slovak standard [17]. The decrease in the capacity only occurs at a high ratio of turning vehicles (min. 30%) and at the radius size not being larger than 12 m. From that follows that in order to assess the capacity of urban road, it would be more objective to use a combination of the two methods - to determine Level of Service (LOS) based on the speed of the continuous traffic flow and decrease in the capacity based on the reduction coefficient.

In the case of the left turn, the results show clear dependency of the capacity of urban road and the speed of traffic flow on the combination of the intensity, i.e. the ratio of turning vehicles and volume of the superior traffic flow.

All the obtained dependencies could provide guidelines for the assessment of collector roads not based on the decreasing their capacity but based on determination of functional levels with respect to the average speed of vehicles in traffic flow, as well. It has clearly been shown that besides the number of turning vehicles, it is necessary to take into account other characteristics of the traffic flow, such as the intensity of the superior traffic stream and the critical time gap. The presented results objectify and expand the scale of values required for the determination of the maneuvering coefficient.

Furthermore, in order to determine the decrease in the capacity of uncontrolled intersections in the urban areas [24], it is necessary to pay attention to impact of pedestrians on the turning maneuvers and also the effect of intersections with the unconventional arrangement of superior traffic flows. In this respect, research activities at the university are already being implemented and are directed towards adjusting the Slovak standards and technical regulations.

References

[1] KIM, J-T. Estimation of uniform delay of permitted left turns from exclusive turn lanes. *Journal of Transportation Engineering* [online]. 2006, **132**(9), p. 708-714. ISSN 0733-947X, eISSN 1943-5436. Available from: https://doi.org/10.1061/(ASCE)0733-947X(2006)132:9(708)

[2] TROUTBECK, R. J., BRILON, W. *Unsignalized intersections theory* [online]. 1997. Available from: https://www.fhwa.dot.gov/publications/research/operations/tft/chap8.pdf

[3] KIM, J., ELEFTERIADOU, L. Estimation of capacity of two-lane two-way highways using simulation model. *Journal of Transportation Engineering* [online]. 2010, **136**(1), p. 61-66. ISSN 0733-947X, eISSN 1943-5436. Available from: https://doi.org/10.1061/(ASCE)0733-947X(2010)136:1(61)

[4] CHANDRA, S., AGRAWAL, A., RAJAMMA, A. Microscopic analysis of service delay at uncontrolled intersections in mixed traffic conditions. *Journal of Transportation Engineering* [online]. 2009, **135**(6), p. 323-329. ISSN 0733-947X, eISSN 1943-5436. Available from: https://doi.org/10.1061/(ASCE)0733-947X(2009)135:6(323)

[5] HUBBARD, S. M. L., BULLOCK, D. M., MANNERING, F. L. Right turns on green and pedestrian level of service: statistical assessment. *Journal of Transportation Engineering* [online]. 2009, **135**(4), p. 153-159. ISSN 0733-947X, eISSN 1943-5436. Available from: https://doi.org/10.1061/(ASCE)0733-947X(2009)135:4(153)

[6] OGALLO, H. O., JHA, M. K. Methodology for critical-gap analysis at intersections with unprotected opposing left-turn movements. *Journal of Transportation Engineering* [online]. 2014, **140**(9), p. 1-7. ISSN 1757-8981, eISSN 1757-899X. Available from: https://doi.org/10.1061/(ASCE)TE.1943-5436.0000691

[7] XIAO, Y., RAN, Q., YANG, J., WANG, Z. Analysis and Modeling of Crossing Behavior at Urban Intersections in China. *Journal of Transportation Engineering* [online]. 2011, **137**(2), p. 121-127. ISSN 1757-8981, eISSN 1757-899X. Available from: https://doi.org/10.1061/(ASCE)TE.1943-5436.0000201

[8] LIU, P., LU, J. J., HU, F., SOKOLOW, G. Capacity of U-turn movement at median openings on multilane highways. *Journal of Transportation Engineering* [online]. 2008, **134**(4), p. 147-154. ISSN 0733-947X, eISSN 1943-5436. Available from: https://doi.org/10.1061/(ASCE)0733-947X(2008)134:4(147)

[9] LIU, P., QU, X., YU, H., WANG, W., CAO, B. Development of a VISSIM simulation model for U-turns at unsignalized intersections. *Journal of Transportation Engineering* [online]. 2012, **138**(11), p. 1333-1339. ISSN 1757-8981, eISSN 1757-899X. Available from: https://doi.org/10.1061/(ASCE)TE.1943-5436.0000438

[10] TRB Transportation Research Board of the National Academies. *HCM2010 - Highway Capacity Manual*. Vol. 3: Interrupted flow. USA: National Academy of Sciences, 2010. ISBN 0-309-06681-6.

[11] FITZPATRICK, K., SCHNEIDER IV., W. H., PARK, E. S. Predicting speeds in an urban right-turn lane. *Journal of Transportation Engineering* [online]. 2006, **132**(3), p. 199-204. ISSN 0733-947X, eISSN 1943-5436. Available from: https://doi.org/10.1061/(ASCE)0733-947X(2006)132:3(199)

[12] CHICK, C. *On-street parking - A guide to practice*. London: Landor Publishing, 1996. ISBN 1899650-01-6.

[13] VALLELEY, M. *Parking perspectives: A source book for the development of parking policy*. London: Landor Publishing, 1997. ISBN 1-899650-06-7.

[14] YOUSIF, S., PURNAWAN, S. On-street parking: Effects on traffic congestion. *Traffic Engineering & Control*. 1999, **40**(9), p. 424-427. ISSN 0041-0683.

[15] GUO, H., GAO, Z., YANG, X., ZHAO, X., WANG, W. Modeling travel time under the influence of on-street parking. *Journal of Transportation Engineering* [online]. 2012, **138**(2), p. 229-235. ISSN 0733-947X, eISSN 1943-5436. Available from: https://doi.org/10.1061/(ASCE)TE.1943-5436.0000319

[16] KOCIANOVA, A, DRLICIAK, M., PITLOVA, E. Influence of roundabout capacity enhancement on emission production. *IOP Conference Series: Materials Science and Engineering* [online]. 2017, 236, art. no. 012035. ISSN 1757-8981, eISSN 1757-899X. Available from: https://doi.org/10.1088/1757-899X/236/1/012035

[17] STN 736110 *Projektovanie miestnych komunikacii / Design of the urban streets* (in Slovak). Slovak Technical Standard. Bratislava: SUTN, 2004.

[18] AASHTO Green Book. *A policy on geometric design of highways and streets*. Washington, DC: American Association of State Highway & Transport, 2001. ISBN 1560511567.

[19] AKCELIK, R. A review of gap-acceptance capacity models. 29th Conference of Australian Institutes of Transport Research CAITR 2007: proceedings. 2007.

[20] GUO, R. J., WANG, X. J., WANG, W. X. Estimation of critical gap based on Raff's definition. *Comput Intell Neurosci* [online]. 2014, 236072. ISSN 1687-5265, eISSN 1687-5273. Available from: https://doi.org/10.1155/2014/236072

[21] SLABY, P. Faktory ovlivnujici kapacitu nerizene krizovatky /Factors determinated of the unsignalised intersection capacity (in Czech). *Silnicni obzor*. 2007, **1**, p. 16-17. ISSN 0322-7154.

[22] GAVULOVA, A. Use of statistical techniques for critical gaps estimation. 12th International Conference RelStat´12: proceedings. CD ISBN 978-9984-818-49-8, p. 20-26.

[23] TP 102. *Vypocet kapacit pozemnych komunikacii / Capacity analysis of the roads*. Slovak Technical Condition. Ministry of Transport, Construction and Regional Development of Slovak Republic 2015 (in Slovak).

[24] HUSZAROVA, K. *Kapacitne vypocty miestnych komunikacii / Capacity analysis of the urban streets* (in Slovak). Ph.D. thesis. Zilina: University of Zilina, 2012.

Oleksandr Pshinko - Andrii Shcherbak - Dmytro Rudenko

RESEARCH OF OPERATIONAL PROPERTIES OF MODIFIED SPECIALIZED CONCRETE FOR TRANSPORT CONSTRUCTIONS

It was established that the polymeric component of the organomineral modifying complex changes the nature of the super-molecular structures in the activated cement system - at optimal filling, globules decrease in size preventing the phase surface diffusion, which contributes to increase of the waterproofness of modified concrete. When introducing a modified cement system into the concrete mixture, the reduction of the open porosity to 3-5%, depending on the composition, has been achieved. Conducted tests for water resistance and frost resistance of the repair layer of concrete showed that the modified concrete corresponds to the mark on water resistance W14 and the brand on the frost resistance F300. The developed technology of physico-chemical activation of the cement system allows the use of conventional cement for obtaining durable concrete of special purpose, which allows to reduce the cost of such concrete by 27-34%.

Keywords: *modified concrete, cement system, sulphate resistance, frost resistance, durability*

1 Purpose

Investigation of the operational properties of modified concrete of special purpose with determination of the possibility of use of the ordinary Portland cement for construction of structures operating under aggressive sulphate environment.

2 Methods

The research of operational properties of modified concrete with use of the infrared spectroscopy, X-ray diffraction, microscopic, differential-thermal and chemical methods has been carried out.

3 Scientific novelty

It was established that the polymeric component of the organomineral modifying complex changes the nature of the super-molecular structures in the activated cement system - at optimal filling, globules decrease in size preventing the phase surface diffusion, which contributes to increase of the waterproofness of modified concrete; it was established that at temperatures of 20-40 °C the polymer particles of the organomineral modifying complex with their functional groups interact with the surface organic substances of fine silica, which increases the activity of calcium silicates and hydrosilicate new formations, contributing to increase of the strength of the cement matrix by activating the curing process in a binding system.

4 Practical significance

When introducing a modified cement system into the concrete mixture, the reduction of the open porosity to 3-5%, depending on the composition, has been achieved. Conducted tests for water resistance and frost resistance of the repair layer of concrete revealed that the modified concrete corresponds to the mark on water resistance W14 and the brand on the frost resistance F 300. The developed technology of physico-chemical activation of the cement system allows the use of conventional cement for obtaining durable concrete of special purpose, which allows to reduce the cost of such concrete by 27-34%.

5 Introduction

The durability of concrete and reinforced concrete depends on a large number of factors, the main of which are the conditions of operation, the type and composition of concrete, as well as the degree of aggressiveness of groundwater, the impact of which is under construction structures.

As it is known [1-2], the main reason for destruction of the bulk concrete in the contact zone with groundwater is the corrosion of the cement matrix of concrete. The reason for this is formation of calcium hydrosulphoaluminate,

Oleksandr Pshinko[1], Andrii Shcherbak[2], Dmytro Rudenko[3,*]
[1]Dnipropetrovsk National University of Railway Transport named after Academician V. Lazaryan, Dnipro, Ukraine
[2]Department of Graphics, Faculty of Bridges and Tunnels, Dnipropetrovsk National University of Railway Transport named after Academician V. Lazaryan, Dnipro, Ukraine
[3]Department of Project Management, Building and Building Materials, Faculty of Industrial and Civil Construction, Dnipropetrovsk National University of Railway Transport named after Academician V. Lazaryan, Dnipro, Ukraine
*E-mail of corresponding author: veberc@ukr.net

the interaction of lime with magnesium salts, as well as direct leakage of lime from concrete. The most destructive effect on concrete is exhibited by the sulphate corrosion, regardless of the composition and structure of concrete, the type of structures, the nature and magnitude of operating load and conditions of service. For current presentations of salts that are part of the aggressive medium, sulphates of various nature and concentration are the most dangerous for the cement stone. Destruction of the cement matrix of concrete in sulphate media is accompanied by formation of the three-sulphate crystals of calcium hydrosulphoaluminate. Crystallization of the calcium hydrosulphoaluminates causes destruction of the cement matrix due to a significant increase in the volume of the solid phase. According to Lee [3], this fact itself is enough to explain destruction of the cement stone.

Formation and destruction of calcium hydrosulphoaluminate is an important chemical process. The study of the mineralogical composition of the cement stone samples stored in a sulphate medium showed that a significant amount of SO_4^{2-} ions bind to cement stone, [4-6]. The more of the three-calcium aluminate (C_3A) is in the cement, the more of SO_4^{2-} ions binding, that is, absorption is sulphoaluminate.

In connection with the main destructive factors of the sulphate corrosion, methods for increasing the durability of concrete under the sulphate aggression have been developed. These include use of the sulphate-resistant cement, Portland cement containing (C_3A) content not more than 5% and a number of special cements; increase in the content of gypsum in the cement with a faster binding of aluminates in the plastic state; increase in the density of concrete; introduction of admixtures in concrete; use of the carbonate fillers [7-8].

Those methods aim to prevent or slow down diffusion of the sulphate ions into concrete, reduce the content of calcium aluminates or their timely reaction with certain components of concrete. Sulphate interaction should become a component part of processes associated with the structure formation of the cement matrix of concrete. It is not as much to protect the structure from penetrating sulphate water into the concrete or to reduce the content of (C_3A) in the cement, as to get the cement matrix in the concrete, where hydrosulphoaluminate will be instead of hydrated aluminate. The authors of [9-10] came to the same conclusion about the positive influence on the sulphate resistance of cement when introducing gypsum.

6 Results

To determine the possibility for increasing durability of the exploited reinforced concrete structures, studies on the weather resistance of modified concrete have been carried out. Modified concrete samples are characterized by a slight deformation throughout the test period. When modifying the cement system, the mass gain of samples is insignificant compared to the normal concrete. Modified concrete in specific conditions of operation is guaranteed a fairly high atmospheric resistance. This is also confirmed by the stable values of material strength during the test. The mathematical model of processes of the corrosion resistance of concrete was obtained, for which the method of the experiment factor planning was used. The essence of the method is the variation of all the factors that influence the process on a certain plan, representation of the mathematical model in the form of a linear polynomial and the study of the last method of mathematical statistics. The data processing allowed derivation of an equation that relates the sulphate stability of the concrete with parameters of the aggressive medium (the content of sulphate ions) and the characteristics of the concrete itself (the content of C_3A in the cement, the quantitative content of the active complex in the concrete and the $CaCO_3$ in the fine aggregate). Using the mathematical model of the concrete corrosion resistance gives an opportunity to calculate the coefficient of sulphate stability and predict the durability of the reinforced concrete structures that are exploited under conditions of sulfate aggression.

For an estimate of the water influence on the microstructure of the modified cement system, an infrared analysis of the samples was carried out before and after keeping them in water for 6 months. It was established that changes occur in the region of absorption bands of $1380\,cm^{-1}$ and $1450\,cm^{-1}$. Introduction of the polymer component of the organomineral modifying complex (OMMC) into the cement system changes the nature of the super-molecular structures - at optimal filling globules decrease in size. An increase in diameter of the super-molecular structures can lead to development of micro porosity. The presence of micro cracks and defects leads to the fact that, along with activated diffusion, there is a phase surface diffusion, which leads to an increase in permeability [11-13].

The organomineral modifying complex consists of a plasticizer, an active mineral component and a chemical structure-optimizing agent. Amorphized silica with a specific surface area 1100 m^2/kg was chosen as the active mineral component. The peculiarity of the chemical optimizer of structure formation is its ability to stabilize the crystal formation of the cement matrix, being a structural and chemical analogue of the mass of the crystalline hydrates. Surfactant OMMC changes the relaxation processes, promotes creation of the less stressed and defective structures and prevents appearance of the phase diffusion. In addition, creation of a monolayer SAA on the surface of a mineral modifier in the form of a microfiber leads to emergence of the “surfactant-mineral microfiber” in contact with mobile (less rigid), easy to regenerate bonds, which positively affects adhesion of the polymeric component to the surface of a mineral modifier.

During the operation of special structures, their surface is exposed to stretching and compressing stress [7, 14]. To determine the possibility of increasing durability of used reinforced concrete structures, studies of atmospheric

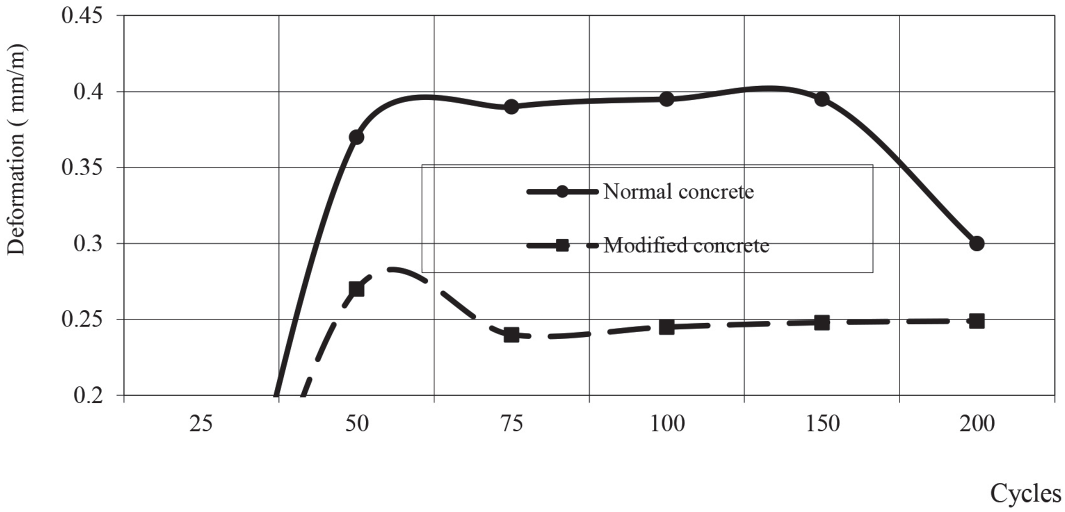


Figure 1 *Change of linear deformations of concrete at alternating water saturation and drying (Portland cement PCI-400-P-H)*

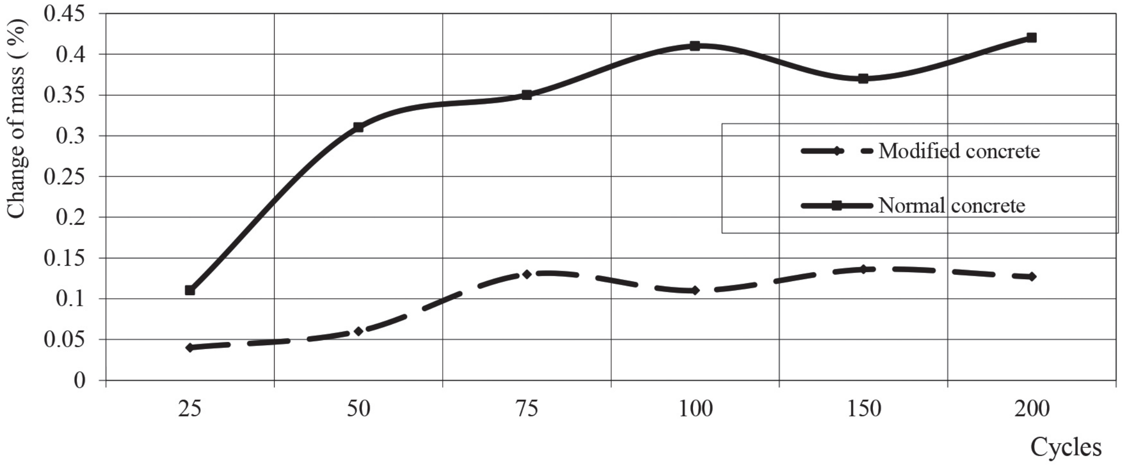


Figure 2 *Change of mass of concrete samples at alternating water saturation and drying (Portland cement PCI-400PH)*

stability of the modified concrete samples have been carried out using the following procedure.

Samples of the fine-aggregate concrete of size $4 \times 4 \times 16\,cm$ with $W/C = 0.5$ were made. After 28 days of hardening, three samples of each batch were dried at a temperature of 80 °C to constant weight, after that they were tested for bending and their halves were compressed. In the end, faces of other samples of all batches strictly centered rappers based on epoxy were fixed. The samples were then placed in a thermostat and dried at 80 °C for 15 *h*. Subsequently, after 1 hour of natural cooling the samples were weighed and with the help of engineers' dial gauge with a price of $0.0001\,mm$ their initial length was measured. After that, the samples were immersed in fresh water for 7 hours at a temperature of 20 °C, they were taken out from water, wiped with a damp cloth, weighed and their length was measured. Samples were tested up to 200 cycles of water saturation and drying. After each 50 cycles testing, the three samples were taken, dried to a constant mass and tested for bending and their halves were compressed. The expending values in *mm/m* were determined in comparison to the length of samples of the same cycle after their drying.

The results of research on the influence of alternating water saturation and drying of concrete samples are shown in Figures 1 and 2. Experiments revealed that linear changes in samples depend on the composition of concrete. Modified concrete samples are characterized by the low deformability throughout the test period (see Figure 1). Similar character of the weather resistance of modified concrete was also observed with respect to change in the mass of the test samples. It should be noted that when modifying the cement the weight gain of the samples is insignificant in comparison to the normal concrete (see Figure 2). The mass increase of samples of the normal concrete is accompanied by an increase of irreversible deformations, apparently due to water absorption in the presence of open porosity.

The mass loss of samples with alternating water saturation and drying is observed for all the samples; however, for the modified concrete this process is not extreme. Obviously, this can be explained by the more dense structure of the modified cement matrix of concrete.

As it follows from the results of experiments (see Figures 1, 2), a fairly high atmospheric resistance is

***Table 1** The strength of modified concrete after alternating water saturation and drying (Portland cement PC-I-400P-H)*

Type of concrete	Strength (MPa) after alternating water saturation and drying (cycles)							
	50		100		150		200	
	Compression	Bending	Compression	Bending	Compression	Bending	Compression	Bending
Normal	32.4	4.6	27.6	4.1	-	-	-	-
Modified	67.3	8.7	67.4	8.4	66.1	7.6	64.6	7.1

guaranteed for the modified concrete in specific conditions of operation. This is also confirmed by the stable values of material strength during the test. For the normal concrete there is a decrease in strength both during compression and bending. Standard samples began to collapse after 127 cycles of alternating water saturation and drying, while samples of modified concrete were in satisfactory state up to almost 200 cycles, after which the tests were stopped. Results of determining the strength of concrete throughout the duration of experiments alternating water saturation and drying are given in Table 1.

When the water content of the concrete is lower than the boundary, determined in each case by the peculiarities of the materials and the state of the cement matrix, the material becomes permeable. On the other hand, the waterproofness of concrete with permanent composition decreases with increasing its water content. In this case there is no explanation for the reasons for reducing the waterproofness of the concrete. According to [8], with an increase in *W/C* from 0.45 to 0.8, the permeability of concrete increases by 100 times. The authors of [2, 7] found that when using the Portland cement, the coefficient of filtration of the cement stone increases by 10-20 times with an increase in W/C from 0.4 to 0.8. It is also argued that the main reason for reducing the waterproofness of concrete is the increase of its initial water content. A number of experts explain this by influence of reducing the cement content [7, 9, 15].

Considering the significant influence on formation of the structure of waterproof concrete by contraction processes, as well as considering solidifying concrete as a single system, it is most likely to assume that the primary effect on the waterproofness of concrete is the value of the cement paste *W/C*. It is known that with increase of the W/C the quality of the cement paste decreases, destructive processes intensify in it, as a result of which a powerful system of pores and capillary channels is created in the material [6].

When modifying the cement system, the reduction of the open porosity of concrete to 3-5%, depending on the composition is acquired. Conducted tests on the waterproofness of concrete established that the modified concrete corresponds to the waterproof mark W 14.

In the aggregate of results of studies on the waterproofness of concrete, it can be concluded that influence of the modified concrete composition on fluctuations of the water resistance is expressed not so sharply, as for normal concrete.

Taking into account the operation of the elements of concrete and reinforced concrete structures in conditions of variable water level, they are subjected to alternate freezing and thawing under conditions of capillary suction. Therefore, concrete, designed for building and restoration of special structures, should have the high frost resistance.

Modern ideas about causes and mechanism of destruction of the concrete under the influence of moisture and frost come to the following, [16-17]: concrete is considered as a capillary-porous body, the structure of which is defined both by its components and technological parameters - conditions of preparation, placing, compaction, hardening and storage. The distribution of moisture and its total amount in concrete depends on both the nature of its structure and the environmental conditions.

Under the influence of negative temperature on a capillary-porous material containing moisture, there are its own temperature deformations, which are imposed by deformation of ice, formed from the water frozen in the pores. The magnitude and sign of the resulting deformation, which determine the state of the system, are variable quantities and depend on the conditions of the external environment and the nature of the concrete structure.

Alongside with studies of the frost resistance, the X-ray diffraction and differential-thermal analysis of the cement matrix of concrete have been carried out. As follows from defectograms, the composition of new formations in the cement stone of normal concrete is somewhat different from the same composition of modified concrete. In conventional concrete, the three-sulfate form of calcium hydrosulphoaluminate $(d = 9.73; 5.61; 3.85 \cdot 10^{-10} m)$, C_3AH_6 $(d = 4.45; 2.30; 1.572 \cdot 10^{-10} m)$ $(CaOH)_2$ $(d = 4.91; 2.61; 1.79 \cdot 10^{-10} m)$, hydrosilicates of calcium areof increased basic capacity $(d = 4.91; 2.61; 1.79 \cdot 10^{-10} m)$. As part of the new formations of modified concrete the formation of four-calcium hydroaluminate $(d = 7.8; 3.85; 2.43; 1.67 \cdot 10^{-10} m)$ was marked, as well as recrystallization into a mono-sulphate form of calcium hydrosulphoaluminate $(d = 8.92; 4.96; 3.99; 2.25 \cdot 10^{-10} m)$, which obviously contributes to increasing the frost resistance of the modified concrete.

The data of the differential-thermal analysis confirm the results obtained during the radiographic studies. The endo-effect with a maximum of 132 °C on a thermogram of the cement stone of normal concrete, subjected to a frost resistance test, corresponds to dehydration of the three-sulphate form of calcium hydrosulphoaluminate and calcium hydrosilicates. Temperatures of 440 to 445 °C correspond to the decomposition of $(CaOH)_2$, while the effect for the modified cement matrix is less noticeable. At temperatures 586, 698, 716 °C, the low-basic hydrosilicates of calcium type $CSH(B), C_2SH_2$ are dehydrated. The endo-effects at temperatures of 690 and 710 °C for conventional cement are also responsible for expansion of $CaCO_3$, although calcium carbonate is released in small amounts.

Thus, the composition of cement and the structure of additives determine the nature of the interaction with the aluminate and silicate components of cement. The ability to preferentially localize on the surface of the aluminate components has additives that do not react with Ca^{2+}, but contain functional groups that give complexes with Al^{3+}, as well as insoluble products of the interaction of polyelectrolytes with Ca^{2+}, if they contain free polar active groups, which are fixed on hydroxylate surface of hydroaluminates and calcium hydrosulphoaluminates.

Formation of hydrosulphoaluminates during the precipitation on the lime quickly fades due to the surface shielding by hydrated films. The generated coagulation structures do not compact much in the first stages of hydration. The high adsorption capacity of the polymeric component of the OMMC containing amido groups in relation to the products of hydration of Portland cement clinker, and especially to calcium hydroaluminates, results in the rapid formation of loose moisture coagulation structures in the modified cement system, which causes avalanche growth of initial strength.

The high-molecular SAA change the conditions for formation of the phase contacts in the emerging structure. When localized in the contact zone, aliphatic macromolecular SAA increase and aromatic reduce the bond strength of hydrate-hydrate and hydrate-carrier or hydrate-hydrate, which affects the integral strength of the structure [5].

Speaking about selective adsorption of the SAA on clinker minerals and hydrated phases, one cannot but note that many researchers, characterizing and assessing the effectiveness of the SAA, assign great importance to the value of the ξ-potential on the surface of solid-phase particles [18]. For cements of different mineralogical composition, the ξ-potential values are different and this should be reflected in plasticization of suspensions.

The study of processes of the corrosive destruction of concrete proceeding under the influence of aggressive groundwater containing sulphate ions allowed to consider and determine the nature and degree of destruction of the reinforced concrete structures, depending on various parameters of the aggressive medium, properties of the concrete itself and the conditions of its testing.

The influence of the type of cement, the quantitative and qualitative content of the organomineral modifying complex and the concentration of sulphate ions in the environment on the stability of concrete were studied under conditions of one-sided and comprehensive influence of the aggressive medium on the samples. Based on the experimental data array a statistical mathematical model of the investigated process was constructed.

To obtain a mathematical model of processes of the corrosion resistance of concrete, the method of factor planning of the experiment was used, the essence of which consists in variation of all the factors influencing the process according to a certain plan, the representation of the mathematical model in the form of a linear polynomial and the study the latter by the method of mathematical statistics.

The general form of the statistical mathematical model, in this case, is expressed by a linear polynomial

$$Y = b_0 + b_1 x_1 + \ldots + b_n x_n, \tag{1}$$

where:

b_0 is a constant term,

b_1 is a linear effects $(s = 1, 2, \ldots, n)$,

n is a number of factors.

Y The coefficient of sulphate stability is chosen as the outcome variable Y. According to the results of previous studies the following factors have the most significant effect on concrete corrosion:

x_1 is C_{3A} content in Portland cement,

x_2 is a content of sulphate ions in the aggressive environment,

x_3 is as content of particles of $CaCO_3$ in the sand,

x_4 is a quantitative content of the active complex.

Application area of these factors, taking into account the data of previous experiments, is determined by the following limits: $5 = x_1 = 8$; $2 = x_3 = 10$; $1 = x_2 = 20$; $10 = x_4 = 50$.

For convenience, the parameters that correspond to each value of the experimental data were chosen. The principle of correspondence between the experimental data and parameters is as follows: the increasing value of the experimental data must correspond to the greater value of the parameter. Moreover, if the experimental data are in a clearly defined group of specific data, then this source code corresponds to the group code. By increasing or decreasing the value of the parameter, it is possible to determine how the value of the experimental data increases or decreases and how it affects the sulphate stability coefficient K_C.

The data processing allowed to derive an equation that relates the sulphate stability of the concrete with the parameters of the aggressive medium (the content of sulphate ions) and the characteristics of the concrete itself (the content of C_3A in the cement, the quantitative content of the active complex in the concrete and the $CaCO_3$ in the fine aggregate):

$$\begin{aligned} Y = 0.9552 - 0.3438 \cdot 0.1x_1 + 0.6292 \cdot 0.1x_2 - \\ - 0.1709 \cdot 0.1x_3 + 0.71x_4 \end{aligned} \tag{2}$$

The test for adequacy has shown the good convergence of model results. Deviation of the calculated value of from the experimental one, does not exceed $\Delta K_C = \pm 0.1$ in the whole range of test conditions. Translated into physical scale, equation (2) takes the form:

$$K_C = 0.9552 - 0.3438C_3A + 0.6292CaCO_3 - \\ - 0.1709SO_4 + 0.71AK. \quad (3)$$

The active influence on the sulphate stability coefficient of concrete samples is made by the active complex (x_4); the following influence, by value, is the content of $CaCO_3$ in the fine aggregate. The minus sign indicates the reversal of the dependence of sulphate resistance on the content of C_3A in the cement.

Using the mathematical model of the concrete corrosion resistance gives an opportunity to calculate the coefficient of sulphate stability and predict the durability of reinforced concrete structures that are exploited under conditions of sulphate aggression.

7 Conclusions

A. When maturing samples of concrete in a sulphate medium for 360 days, the reduction of strength of the modified concrete is 3-6% (reduction of the strength of normal concrete is 12-23 %), the coefficient of sulphate resistance K_C is within 0.91-0.93. Stabilization of the strength of modified concrete with time indicates the prevailing of constructive processes over destructive.

B. The mathematical model of corrosion resistance processes is obtained. The processing of the data allowed to derive an equation that relates the sulphate stability of the concrete with the parameters of the aggressive medium (the content of sulphate ions) and the characteristics of the concrete (content of C_3A, cement, $CaCO_3$ in the fine aggregate, degree of modification of the cement system). The test for adequacy has shown the good convergence of the model results. Deviation of the calculated value of K_C from the experimental one, does not exceed $\Delta K_C = \pm 0.1$ in the whole range of test conditions.

References

[1] ADAMSON, A. W. *Physical chemistry of surfaces* (in Russian). Moscow: Mir Publ., 1999. ISBN 0471148733.

[2] RUDENKO, D. Properties of the phase components of the modified cement system. *Teka Komisji Motoryzacji i Energetyki Rolnictwa*. 2013, 13(4), p. 218-224. ISSN 1641-7739.

[3] LEA, F. M. *Chemistry of cement and concrete*. 3. ed. Chemical Publishing Book, 1971. ISBN 9780820602127.

[4] LEE, C. Y., LEE, H. K., LEE, K. M. Strength and microstructural characteristics of chemically activated fly ash-cement systems. *Cement and Concrete Research* [online]. 2003, 33(3), p. 425-431. ISSN 0008-8846, eISSN 1873-3948. Available from: https://doi.org/10.1016/S0008-8846(02)00973-0

[5] KORPA, A., KOWALD, T., TRETTIN, R. Hydration behaviour, structure and morphology of hydration phases in advances cement-based systems containing micro and nanoscale pozzolanic additives. *Cement and Concrete Research* [online]. 2008, 38(7), p. 955-962. ISSN 0008-8846, eISSN 1873-3948. Available from: https://doi.org/10.1016/j.cemconres.2008.02.010

[6] LIU, C.-I., HUANG, J.-S. Highly flowable reactive powder mortar as a repair material. *Construction and Building Materials* [online]. 2008, 22(6), p. 1043-1050. ISSN 0950-0618, eISSN 1879-0526. Available from: http://dx.doi.org/10.1016/j.conbuildmat.2007.03.009

[7] DVORKIN, L., DVORKIN, O. Basics of concrete science (in Russian). St-Petersburg: Stroi-Beton, 2006. ISBN 590319702-7.

[8] LEE, M. G., WANG, Y.-CH., CHIU, CH.-T. A preliminary study of reactive powder concrete as a new repair material. *Construction and Building Materials* [online]. 2007, 21(1), p. 182-189. ISSN 0950-0618, eISSN 1879-0526. Available from: https://doi.org/10.1016/j.conbuildmat.2005.06.024

[9] RUDENKO, N. Technology of shotcreting based on activated binder. *Teka Komisji Motoryzacji i Energetyki Rolnictwa*. 2014, 14(1), p. 222-228. ISSN 1730-8658.

[10] RUDENKO, D. V. Physico-chemical modification of the cement system of monolithic concrete (in Ukrainian). *Science and Progress of Transport* [online]. 2015, 60(6), p. 174-182. ISSN 2307-3489, eISSN 2307-6666. Available from: https://doi.org/10.15802/stp2015/57103

[11] HEWLETT, P. C. *Lea's chemistry of cement and concrete*. 4. ed. Michigan: Arnold, 1998. ISBN 9780340565896.

[12] SHISHKIN, A., NETESA, N., SCHERBA, V. Effect of the iron-containing filler on the strength of concrete. *Eastern-European Journal of Enterprise Technologies* [online]. 2017, **5**(6)(89), p. 11-16. ISSN 1729-3774, eISSN 1729-4061. Available from: https://doi.org/10.15587/1729-4061.2017.109977

[13] URMASHEV, B. A., ISSAKHOV, A. Numerical modeling of disperse materials process in a continuous-flow plasma reactor. *Eurasian Chemico-Technological Journal* [online]. 2018, 20, p. 73-79. ISSN 1562-3920, eISSN 2522-4867. Available from: https://doi.org/10.18321/ectj710

[14] WANG, D., SHI, C., WU, Z., XIAO, J., HUANG, Z., FANG, Z. A review on ultra high performance concrete: Part II. Hydration, microstructure and properties. *Construction and Building Materials* [online]. 2015, 96, p. 368-377. ISSN 0950-0618, eISSN 1879-0526. Available from: http://dx.doi.org/10.1016/j.conbuildmat.2015.08.095

[15] SANCHEZ, F., SOBOLEV, K. Nanotechnology in concrete - a review. *Construction and Building Materials* [online]. 2010, 24, p. 2060-2071. ISSN 0950-0618, eISSN 1879-0526. Available from: http://dx.doi.org/10.1016/j.conbuildmat.2010.03.014

[16] COLLEPARDI, M. *The new concrete*. Villorba, Loc Castrette, Treviso: Grafiche Tintoretto, 2006. ISBN 889014694X9788890146947.

[17] KOCAB, D., KUCHARCZYKOVA, B., DANEK, P., VYMAZAL, T., HANUS, P., HALAMOVA, R. Destructive and non-destructive assessment of the frost resistance of concrete with different aggregate. *IOP Conference Series: Materials Science and Engineering* [online]. 2018, **379**(1), 012022. ISSN 1757-8981, eISSN 1757-899X. Available from: https://doi.org/10.1088/1757-899X/379/1/012022

[18] PLANK, J., HIRSCH, C. Impact of zeta potential of early cement hydration phases on super-plasticizer adsorption. *Cement and Concrete Research* [online]. 2007, 37(4), p. 537-542. ISSN 0950-0618, eISSN 1879-0526. Available from: http://dx.doi.org/10.1016/j.cemconres.2007.01.007

Maria Hudakova - Jan Dvorsky

ANALYSIS OF THE MARKET RISK SOURCES IN THE SMALL AND MEDIUM-SIZED ENTERPRISES OF TRANSPORT

The aim of this paper was to define the important market risk sources in the transport small and medium-sized enterprises segment. A part of this aim is to find out how entrepreneurs evaluate these sources, and quantify the differences in their evaluation based on the entrepreneur's characteristics, such as nationality, age, gender and others. The questionnaire was completed by 122 enterprises from Slovakia, Poland, the Czech Republic and Serbia. Statistical tools such as pivot tables, percentages and goodness-of-fit tests were applied to verify the formulated hypotheses. The most important source of market risk is a strong competition in the line of business. The obtained education of entrepreneurs is statistically significant characteristics for the evaluation of the market risk sources in selected transport enterprises. The findings are important for state institutions and their support systems in the transport SMEs segment.

Keywords: *market risk, small and medium-sized enterprise, transport, losing the customers, stagnation of the market*

1 Introduction

Enterprises are facing constant changes in the business environment and the way to deal with these changes also depends on the ability of the enterprise to adapt and accept the variability of everyday life [1]. The issues of market risk management in small and medium-sized enterprises (SMEs) have been analyzed and discussed for a long time [2]. The enterprise (also transport enterprise), is facing constant changes in the business environment at the national level and the way to deal with these changes also depends on the ability of the enterprise to adapt and accept the new actualities [3-4].

The paper contains a detailed analysis of the following market risk sources: losing the customers; a strong competition in the line of business; stagnation of the market; unreliability of the suppliers. The case study presents the answers from 122 transport enterprises in Slovakia, the Czech Republic, Poland and Serbia.

The structure of the paper is as follows: The first part presents current findings in the small and medium-sized enterprises of the transport segment. The second part defines the aim of the paper, the research methodology, research methods and the data collection. The section of Results presents the evaluation of the empirical research of market risk sources. In the discussion, there is a comparison to other research results presented. The conclusion offers a final summary of own research, its limits and future.

2 Short literature background

The risk management is a global process and a driver for business process innovation. Its deployment needs to be supported by a knowledge base associated with a decision support system [5]. In both developed and emerging economies, capital markets have become more important as a means of allocating resources. As a result, both banks and non-financial firms have realized that the number, type and extent of their exposures have increased significantly. Finally, a spate of volatile financial innovations are simultaneously a source of risk and a means to mitigate it [6].

To an economist, risk is defined as the existence of uncertainty about future outcomes [7]. Risk is a key factor in economic life because people and firms make irrevocable investments in research and product development, plant and equipment, inventory and human capital, without knowing whether the future cash flows from these investments will be sufficient to compensate both debt and equity holders [8-9].

Global surveys show that even though the risk management of the company is not a new discipline, current models of risk management are not flexible enough to be able to take into account the dynamics of the market [10].

According to Dvorsky et al. and Costa and Fernandes [11-12], the market risk related sources that exert the most negative influence on enterprise success are an increased competition, limited market size, low demand, inefficient marketing, poor understanding of competitors, poor

Maria Hudakova[1], Jan Dvorsky[2,*]
[1]Department of Crisis Management, Faculty of Security Engineering, University of Zilina, Slovakia
[2]Department of Business Administration, Faculty of Management and Economics, Tomas Bata University in Zlin, Czech Republic
*E-mail of corresponding author: j1dvorsky@utb.cz

understanding of location and markets and the inability to identify the target market [13-14].

The authors in general think that to successfully manage or control any transport activity, it is necessary to determine the degree and extent of risk. They define the terms “risk”, “risk management” and other relevant concepts in this field as being that risk management is one of the modern working methods that are important not only for transport companies but also for other organizations and other companies. The outcome of their research analysis is the essential risk reduction according to implementation of the Lean System and adaptation of the Outsourcing system with a transport company. Those methods are important for the risk analysis in a transport company [15-16].

3 Data, methodology and methods

The aim of the paper is to define important market risk sources in the transport SME segment and to find out how entrepreneurs evaluate these sources and quantify the differences in their evaluation based on the entrepreneur’s characteristics (nationality, age, gender, obtained education and how long the entrepreneurs have been doing business) and the enterprises’ number of employees.

The data collection was carried out in 2017 and 2018. The sample consisted of 1,689 enterprises in Slovakia, the Czech Republic, Poland and Serbia. The structure of the sample represents small and medium-sized enterprises in the four countries studied. The data was collected through a standard questionnaire via an online survey. The answers given by the respondents were recorded online in the four countries by means of questionnaire. With regard to the content and form of the questionnaire used during the survey, great attempts were made to ensure that the questions were comprehensible and to completely filter out any ambiguity, even in terms of the order of the questions.

The entrepreneurs were selected using ‘the random selection method’ (using the ‘Randbetween’ function) from specialized databases of entrepreneurs for each country (Slovakia - Cribis database, Czech Republic - Albertina database, Poland - Central Registration and Information on Business (CEIDG), Serbia - Statistical Office of the Republic of Serbia (OP3C)). With this method, randomness was ensured. Of the 1,689 small and medium-sized enterprises analyzed, Slovakia provided 487 respondents (28.8 %), Poland 474 (28.1 %), the Czech Republic 408 (24.2%) and Serbia 320 (18.9 %).

The entrepreneurs could give their opinion to the risk sources, which affect the enterprise intensively - a very low intensity of the risk source (A1); a low intensity of the risk source (A2); a medium intensity of the risk source (A3); a high intensity of the risk source (A4) and a very high intensity of the risk source (A5). The explanation: the attitudes of entrepreneurs are: low intensity (A1+A2); medium intensity (A3) and high intensity (A4+A5) (three point Likert scale in Tables 1-6).

The authors used questionnaire who contained sources for the market risk, economic, financial, operational, personnel, security and legal risks. Each risk was created from four sources of risk (the sources of risk were created by authors). The sources of the market risk (MR): losing the customers (MR1); strong competition in the line of business (MR2); stagnation of the market (MR3); unreliability of the suppliers (MR4). The following hypotheses were made in order to achieve the main aim of the study:

H: Within the defined (H1: nationality; H2: gender; H3: age; H4: obtained education; H5: number of employees and H6: how long the entrepreneurs have been doing business) groups of entrepreneurs, there are statistically significant differences in the evaluation of market risk sources.

To evaluate the formulated hypotheses and thus meet the primary goal of the paper, the tools of descriptive statistics such as tables and descriptive characteristics (frequency, percentages, sum). Then, the relationship between qualitative answers of entrepreneurs (using Pivot Table) and contingency intensity was used (using the Pearson’s coefficient of contingency, which is based on the Chi-square). The Pearson’s coefficient was calculated and then interpreted because of the decision about the statistical significance of differences between selected groups of the entrepreneurs. For assessment of the level of significance (limit of acceptance or rejection of hypothesis) the level of p-value 0.05 was used. Calculations were made using the analytical software SPSS Statistics.

The transport entrepreneurs were chosen based on demographic characteristics (gender, age, education, nationality) and the companies based on selected criteria (number of employees, how many years they have been doing business). The structure of the transport entrepreneurs´ characteristics who filled in the questionnaire was as follows: the nationality: Slovak entrepreneurs - 31 (25.4 %); Czech entrepreneurs - 20 (16.4 %); Polish entrepreneurs - 51 (41.8%) and Serbian entrepreneurs - 20 (16.4 %); the gender: male - 96 (79 %); female - 26 (21 %); the age - up to 30 years - 38 (31.2 %); from 31 to 50 years - 62 (50.8 %); over 50 years - 22 (18.0 %); the obtained education - secondary school without the school-leaving exam - 19 (15.6 %); secondary school with the school-leaving exam - 58 (47.5 %); university graduates - 45 (36.9 %). The selected characteristics of the companies: the number of employees - micro-enterprises (to 10 employees) - 69 (56.6 %); a small company (to 50 employees) - 43 (35.2 %); a medium-sized company (to 250 employees) - 10 (8.2 %); how long the entrepreneurs have been doing business: more than 10 years - 53 (43.4 %), from 5 to 10 years - 32 (26.2 %), from 1 to 5 years - 37 (30.3 %).

4 Results and discussion

The following Tables 1-6 summarise the results of the assessment of the market risk´ sources (MR1, MR2, MR3, MR4) of entrepreneurs according to the selected characteristics. The structure of the market risk´ sources according to transport entrepreneurs was (n = 122): MR1

***Table 1** The evaluation of sources of market risk according to nationality*

MR1	SR	PL	CR	SRB	MR2	SR	PL	CR	SRB
Low intensity:	8	9	5	5	Low intensity:	6	5	5	5
19.7%	26%	18%	25%	25%	11.5%	19%	10%	25%	25%
Medium intensity:	11	14	6	5	Medium intensity:	8	14	8	5
26.2%	35%	27%	30%	25%	29.5%	26%	27%	40%	25%
High intensity:	12	28	9	10	High intensity:	17	32	7	10
54.1%	39%	55%	45%	50%	59.0%	55%	63%	35%	50%
MR3	SR	PL	CR	SRB	MR4	SR	PL	CR	SRB
Low intensity:	7	11	8	6	Low intensity:	15	13	8	9
26.2%	23%	22%	40%	30%	37.7%	48%	25%	40%	45%
Medium intensity:	19	23	7	7	Medium intensity:	9	20	7	5
45.9%	61%	45%	35%	35%	33.6%	29%	39%	35%	25%
High intensity:	5	17	5	7	High intensity:	7	18	5	6
27.9%	16%	33%	25%	35%	28.7%	23%	35%	25%	30%

Note: SR - Slovakia; PL - Poland; SRB - Serbia, CR - Czech Republic. Source: own data collection.

***Table 2** The evaluation of sources of market risk according to gender of entrepreneurs*

MR1	Male	Female	MR2	Male	Female
Low intensity:	21	5	Low intensity:	12	5
19.7%	22%	19%	11.5%	13%	19%
Medium intensity:	31	5	Medium intensity:	32	6
26.2%	32%	19%	29.5%	33%	23%
High intensity:	44	16	High intensity:	52	15
54.1%	46%	62%	59.0%	54%	58%
MR3	Male	Female	MR4	Male	Female
Low intensity:	25	7	Low intensity:	36	10
26.2%	26%	27%	37.7%	38%	38%
Medium intensity:	45	11	Medium intensity:	34	7
45.9%	47%	42%	33.6%	35%	27%
High intensity:	26	8	High intensity:	26	9
27.9%	27%	31%	28.7%	27%	35%

Source: own data collection.

- low intensity (A1+A2) 24 (19.7 %); medium intensity (A3) 32 (26.2 %); high intensity (A4+A5) 66 (54.1 %); MR2 - low intensity (A1+A2) 14 (11.5 %); medium intensity (A3) 36 (29.5 %); high intensity (A4+A5) 72 (59.0 %); MR3 - low intensity (A1+A2) 32 (26.2 %); medium intensity (A3) 56 (45.9 %); high intensity (A4+A5) 34 (27.9 %); MR4 - low intensity (A1+A2) 46 (37.7 %); medium intensity (A3) 41 (33.6 %); high intensity (A4+A5) 35 (28.7 %).

The nationality of entrepreneurs is not a statistically significant characteristics of evaluating the market source: losing the customers (p - value = 0.324); strong competition in the line of business (p - value = 0.118); stagnation of the market (p - value = 0.295); unreliability of the suppliers (p - value = 0.217). Hypothesis H1 is rejected.

The gender of entrepreneurs is not a statistically significant characteristics of evaluating the market source: "losing the customers" (p - value = 0.718); strong competition in the line of business (p - value = 0.108); stagnation of the market (p - value = 0.905); unreliability of the suppliers (p - value = 0.144). Hypothesis H2 is rejected.

The age of entrepreneurs is not a statistically significant characteristics of evaluating the market source: "losing the customers" (p - value = 0.238); strong competition in the line of business (p - value = 0.314); stagnation of the market (p - value = 0.148); unreliability of the suppliers (p - value = 0.273). Hypothesis H3 is rejected.

The obtained education of entrepreneurs is a statistically significant characteristics of evaluating the market source: "losing the customers" (p - value = 0.045); strong competition in the line of business (p - value = 0.004); stagnation of the market (p - value = 0.047); unreliability of the suppliers (p - value = 0.033). Hypothesis H4 is accepted.

Table 3 *The evaluation of sources of market risk according to age of entrepreneurs*

MR1	>30	30-50	50<	MR2	>30	30-50	50<
Low intensity:	7	14	5	Low intensity:	6	5	5
19.7%	18%	23%	23%	11.5%	16%	8%	23%
Medium intensity:	8	14	10	Medium intensity:	8	21	6
26.2%	21%	23%	45%	29.5%	21%	34%	27%
High intensity:	23	34	7	High intensity:	24	36	11
54.1%	61%	55%	32%	59.0%	63%	58%	50%
MR3	>30	30-50	50<	MR4	>30	30-50	50<
Low intensity:	8	18	6	Low intensity:	11	27	8
26.2%	21%	29%	27%	37.7%	29%	44%	36%
Medium intensity:	15	33	8	Medium intensity:	14	22	5
45.9%	39%	53%	36%	33.6%	37%	35%	23%
High intensity:	15	11	8	High intensity:	13	13	9
27.9%	39%	18%	36%	28.7%	34%	21%	41%

Note: The age up to 30 years (>30); the age from 31 to 50 years (30-50); the age over 50 years (50<). Source: own data collection.

Table 4 *The evaluation of sources of market risk according to obtained education of entrepreneurs*

MR1	SS	SSw	UG	MR2	SS	SSw	UG
Low intensity:	5	14	5	Low intensity:	5	5	8
19.7%	26%	24%	11%	11.5%	26%	9%	18%
Medium intensity:	6	18	8	Medium intensity:	7	20	6
26.2%	32%	31%	18%	29.5%	37%	34%	13%
High intensity:	8	26	32	High intensity:	7	33	31
54.1%	42%	45%	71%	59.0%	37%	57%	69%
MR3	SS	SSw	UG	MR4	SS	SSw	UG
Low intensity:	5	13	15	Low intensity:	6	22	17
26.2%	26%	22%	33%	37.7%	32%	38%	38%
Medium intensity:	9	32	13	Medium intensity:	8	15	15
45.9%	47%	55%	29%	33.6%	42%	26%	33%
High intensity:	5	13	17	High intensity:	5	21	13
27.9%	26%	22%	38%	28.7%	26%	36%	29%

Note: The obtained education - secondary school without the school-leaving exam (SS); secondary school with the school-leaving exam (SSw) and university graduates (UG). Source: own data collection.

The number of employees of enterprises is not a statistically significant characteristics of evaluating the market source: strong competition in the line of business (p - value = 0.914); stagnation of the market (p - value = 0.946); unreliability of the suppliers (p - value = 0.575). The number of employees of enterprises is the statistical significant of evaluating the market source: “losing the customers” (p - value = 0.042). Hypothesis H5 is rejected.

The age of enterprises is not a statistically significant characteristics of evaluating the market source: “losing the customers” (p - value = 0.612); strong competition in the line of business (p - value = 0.984); stagnation of the market (p - value = 0.748); unreliability of the suppliers (p - value = 0.186). Hypothesis H6 is rejected.

The most important source of market risk is “a strong competition in the line of business” (59% of all entrepreneurs). The second most important source of market risk is “losing the customers” (54.1% of all entrepreneurs). Then, it is sources “unreliability of the suppliers” (28.7% of all entrepreneurs) and “stagnation of the market” (27.9% of all entrepreneurs).

Own research results show that within the defined obtained education groups of the entrepreneurs, there are significant differences in the evaluation of the market risk sources (p-value of Chi-square tests are lower than the level of significance).

The biggest barriers that prevent the transport enterprises from an effective control of the market risks relate to the problems regarding the availability of information, no matter if internal or external data. Such information is necessary for evaluation and risk management, or their integration into the decision

***Table 5** The evaluation of sources of market risk according to number of employees*

MR1	MIE	SE + ME	MR2	MIE	SE + ME
Low intensity:	17	7	Low intensity:	9	5
19.7%	25%	13%	11.5%	13%	9%
Medium intensity:	23	9	Medium intensity:	21	15
26.2%	33%	17%	29.5%	30%	28%
High intensity:	29	37	High intensity:	39	33
54.1%	42%	70%	59.0%	57%	62%
MR3	MIE	SE	MR4	MIE	SE
Low intensity:	17	15	Low intensity:	29	17
26.2%	25%	28%	37.7%	42%	32%
Medium intensity:	33	23	Medium intensity:	24	17
45.9%	48%	43%	33.6%	35%	32%
High intensity:	19	15	High intensity:	16	19
27.9%	28%	28%	28.7%	23%	36%

Note: MIE - micro-enterprise (to 10 employees); SE - small enterprise (to 50 employees); ME - medium enterprise (to 250 employees). Source: own data collection.

***Table 6** The evaluation of sources of market risk according to how long the entrepreneurs have been doing business*

MR1	1-5	5-10	10+	MR2	1-5	5-10	10+
Low intensity:	10	5	9	Low intensity:	5	5	6
19.7%	27%	16%	17%	11.5%	14%	16%	11%
Medium intensity:	10	7	15	Medium intensity:	10	10	16
26.2%	27%	22%	28%	29.5%	27%	31%	30%
High intensity:	17	20	29	High intensity:	22	17	31
54.1%	46%	63%	55%	59.0%	59%	53%	58%
MR3	1-5	5-10	10+	MR4	1-5	5-10	10+
Low intensity:	8	11	13	Low intensity:	15	7	24
26.2%	22%	34%	25%	37.7%	41%	22%	45%
Medium intensity:	19	12	25	Medium intensity:	10	13	18
45.9%	51%	38%	47%	33.6%	27%	41%	34%
High intensity:	10	9	15	High intensity:	12	12	11
27.9%	27%	28%	28%	28.7%	32%	38%	21%

Note: How long the entrepreneurs have been doing business: from 1 to 5 years (1-5); from 5 to 10 years (5-10) and more than 10 years (10+). Source: own data collection.

making process [17-18]. However, Hritzuk states that the information is not the most important aspect, but knowledge of transport managers is [19].

In this context, the authors remark that the innovation is too costly and SMEs are too weak in peripheral regions. Therefore, there is a great need for reasonable and flexible institutional support systems [20-22].

5 Conclusions

The paper aimed at defining important market risk sources in the transport SME segment. A part of this aim was a comparison of defined market risk sources of transport enterprises based on number of employees, nationality, age, gender, the obtained education and how long the entrepreneurs have been doing business.

The obtained education of entrepreneurs is a statistically significant characteristics to evaluate the market risk sources in selected transport enterprises. The transport managers, which had the university education, evaluated the market risk sources of the higher intensity. The nationality, age, gender and how long the entrepreneurs have been doing business are not statistically significant for evaluation of the market risk sources in the selected transport enterprises.

The authors are aware of the research limits (e. g. a regional character of the study - central European countries and Serbia, the sample size - only 122 transport enterprises of four countries, basic statistical methods as the goodness-of-fit tests). The authors believe that the paper has brought several interesting findings and new incentives for further research and discussion regarding the evaluation of the market risks and their sources. The market risk is the most important risk, which negatively influences the business performance of transport enterprises.

It is worth concentrating the future research on a comparison of other risks and their sources: the economic risk, financial risk, operational risk, safety risk, legal risk, human resources risk according to entrepreneurs´ characteristics (nationality, age, the obtained education, and so on). Authors believe that the entrepreneurs´ attitudes to other risks and their sources are different in the transport segment.

The results of this paper are interesting for small and medium sized enterprises of the transport segment, entrepreneurship support organisations, as well as for the Ministries of Transport in the selected countries. It is important that the managers of transport company's discussion with ministry of transport and others competent institution in the different forms: conference events, education events organized of Ministry of Transport, workshops with topic risk management inside transport companies, and so on. Improving awareness and knowledge of the market risk and its resources is important for the profit of transport companies.

Acknowledgment

Publication of this paper was supported by: The Scientific Grant Agency - project KEGA No. 030ZU-4/2018 Research of Risk Management in Enterprises in Slovakia to create a new study program Risk Management for the FBI University of Zilina and the Internal Grant Agency No. IGA/FAME2019/001 Key Factors Determining the Business Performance of Small and Medium-Sized Enterprises.

References

[1] KAMPF, R., LORINCOVA, S., KAPUSTINA, L. M., LIZBETINOVA, L. Motivation level and its comparison between senior managers and blue-collar workers in small and medium-sized transport enterprises. *Communications - Scientific Letters of the University of Zilina* [online]. 2017, **19**(4), p. 43-49. ISSN 1335-4205, eISSN 2585-7878. Available from: http://komunikacie.uniza.sk/index.php/communications/article/view/269

[2] HUDAKOVA, M., MASAR, M., LUSKOVA, M., PATAK, M. R. The dependence of perceived business risks on the size of SMEs. *Journal of Competitiveness* [online]. 2018, **10**(4), p. 54-69. ISSN 1804-171X, eISSN 1804-1728. Available from: https://doi.org/10.7441/joc.2018.04.04

[3] BELAS, J., SOPKOVA, G. Significant determinants of the competitive environment for SMEs in the context of financial and credit risks. *Journal of International Studies* [online]. 2016, **9**(2), p. 139-149. ISSN 2071-8330, eISSN 2306-3483. Available from: https://doi.org/10.14254/2071-8330.2016/9-2/10

[4] CEPEL, M., STASIUKYNAS, A., KOTASKOVA, A., DVORSKY, J. Business environment quality index in the SME segment. *Journal of Competitiveness* [online]. 2018, **10**(2), p. 21-40. ISSN 1804-171X, eISSN 1804-1728. Available from: https://doi.org/10.7441/joc.2018.02.02

[5] ALQUIER, A. M. B., TIGNOL, M. H. L. Risk management in small- and medium-sized enterprises. *Production Planning and Control* [online]. 2006, **17**(3), p. 273-282. ISSN 0953-7287, eISSN 1366-5871. Available from: https://doi.org/10.1080/09537280500285334

[6] AVILOVA, T. V., VOYTOLOVSKIY, N. V., DIKAREVA, V. A., CHERNYSHEVA, A. M. Efficiency of applying risks management systems at industrial enterprises under market conditions. *Journal of Applied Economic Sciences*. 2017, **12**(3), p. 766-771. ISSN 1843-6110.

[7] KIMBALL, R. C. Failures in risk management. Boston: New England Economic Review, Federal Reserve Bank of Boston, 2000, p. 3-12.

[8] BUGANOVA, K., MORICOVA, V. Innovation of education in risk and crisis management. *Turkish Online Journal of Educational Technology*. 2017, November Special Issue INTE, p. 177-182. ISSN 1303-6521.

[9] LUSKOVA, M., BUGANOVA, K. Practical problems of university students' learning and performance assessment. *Turkish Online Journal of Educational Technology.* 2015, p. 436-441. ISSN 1303-6521.

[10] HUDAKOVA, M., SCHONFELD, J., DVORSKY, J., LUSKOVA, M. The market risk analysis and methodology of its more effective management in SMEs in the Slovak republic. *Montenegrin Journal of Economics* [online]. 2017, **13**(2), p. 151-161. ISSN 1800-5845, eISSN 1800-6698. Available from: https://doi.org/10.14254/1800-5845/2017.13-2.10

[11] DVORSKY, J., POPP, J., VIRGLEROVA, Z., KOVACS, S. Assessing the Importance of Market Risk and its Sources in SMEs of the Visegrad Group and Serbia. *Advances in Decision Sciences* [online]. 2018, **22**(A), p. 1-26. ISSN 2090-3359, eISSN 2090-3367. Available from: http://journal.asia.edu.tw/ADS/wp-content/uploads/papers/2018/ADS-Market-Risk_Final-version.pdf

[12] COSTA, A., FERNANDES, R. Urban public transport in Europe: technology diffusion and market organization. *Transportation Research Part A: Policy and Practice* [online]. 2012, **46**(2), p. 269-284. ISSN 0965-8564, eISSN 1879-2375. Available from: https://doi.org/10.1016/j.tra.2011.09.002

[13] TUBIS, A. Route risk assessment for road transport companies. In: *Contemporary complex systems and their dependability* [online]. ZAMOJSKI W., MAZURKIEWICZ J., SUGIER J., WALKOWIAK T., KACPRZYK J. (eds.). Advances in Intelligent Systems and Computing DepCoS-RELCOMEX 2018 : proceedings. Vol 761. Cham : Springer, 2018. ISBN 978-3-319-91445-9, eISBN 978-3-319-91446-6. Available from: https://doi.org/10.1007/978-3-319-91446-6_46

[14] OLIVEIRA CRUZ, C., MIRANDA SARMENTO, J. Institutional "tetris" in infrastructure regulation: harmonizing governance, regulation and policy-making in the transport sector. *Case Studies on Transport Policy* [online]. 2019, **7**(1), p. 22-27. ISSN 2213-624X. Available from: https://doi.org/10.1016/j.cstp.2018.11.003

[15] JARASUNIENE, A., BATARLIENE, N., CIZIUNIENE, K. Business risk management at transport companies: Lithuanian study case. 22nd International Conference Transport Means : proceedings. 2018. ISSN 1822-296X, eISSN 2351-7034, p. 297-304.

[16] LIN, S., CHEN, R., LV, Z., ZHOU, T., JIN, C. Integrated measurement of liquidity risk and market risk of company bonds based on the optimal Copula model. North American Journal of Economics and Finance [online]. 2019, **50**, 101004. ISSN 1062-9408. Available from: https://doi.org/10.1016/j.najef.2019.101004

[17] NEDELIAKOVA, E., SEKULOVA, J., NEDELIAK, I. Reduction of transport risks at rail level crossings. 19th International Conference Transport Means : proceedings. 2015. ISSN 1822-296X, eISSN 2351-7034, p. 236-239.

[18] HUDAKOVA, M., DVORSKY, J. Assessing the risks and their sources in dependence on the rate of implementing the risk management process in the SMEs. Equilibrium. Quarterly Journal of Economics and Economic Policy [online]. 2018, **13**(3), p. 543-567. ISSN 1689-765X, eISSN 2353-3293. Available from: https://doi.org/10.24136/eq.2018.027

[19] HRITZUK, N. Why companies risk losing customers by not reciprocating on shared data: Rebuilding the data-sharing economy in a consumer-driven world. Journal of Advertising Research [online]. 2018, **58**(4), p. 394-398. ISSN 0021-8499, eISSN 1740-1909. Available from: https://doi.org/10.2501/JAR-2018-047

[20] LEWANDOWSKA, A., STOPA, M. SMEs innovativeness and institutional support system: the local experiences in qualitative perspective. Polish case study. Oeconomia Copernicana [online]. 2018, **9**(2), p. 333-351. ISSN 2083-1277, eISSN 2353-1827. Available from: https://doi.org/10.24136/oc.2018.017

[21] TRESHCHEVSKY, Y. I., SEREBRYAKOVA, N. A., GOLIKOVA, G. V., VOLKOVA, S. A., VOLKOVA, T. A. The system of state support for small and medium entrepreneurship and evaluation of its effectiveness. Espacios [online]. 2018, **39**(12), ISSN 0798-1015. Available from: http://www.revistaespacios.com/a18v39n12/18391212.html

[22] FABUS, M., CSABAY, M. State aid and investment: case of Slovakia. Entrepreneurship and Sustainability Issues [online]. 2018, **6**(2), p. 480-488. eISSN 2345-0282. Available from: https://doi.org/10.9770/jesi.2018.6.2(1)

Yaroslav Martynyshyn - Elena Khlystun - Yelena Kovalenko

THE CROSS-CULTURAL COMMUNICATIONS IN BUSINESS TRIPS: STATISTICAL MEASURES IN COORDINATES OF UKRAINE

The purpose of this study is to find ways to increase the effectiveness of cross-cultural communications from the standpoint of Ukrainian business. The methodology of the research is based on statistical measures; there is quantitative identification of parameters of intercultural business communication processes, their modeling, analysis and forecasting. As a result of the study, the relationship between different types of intercultural communication is determined: the transaction oriented and the relationship, formal and informal, monochrome and polychrome, expressive and restrained. Profiles and classifications of the cross-cultural communications have been constructed. The communication disagreements and corresponding reactions of Ukrainian businessmen in different countries and regions of the world have been determined. Models have been developed that reflect the patterns of the relationship between the success of communication (reaction) and intercultural differences. The obtained results can be used to substantiate the cross-cultural communication strategies of business trips.

Keywords: *profile of cross-cultural communication, type of communication culture, communication disagreement and reaction, communication model, business trip*

1 Introduction

Entering the third millennium, people have become accustomed to the idea that people live in a global world, where border crossings have not created any problems through an effective system of modern communications. In these conditions, the Ukrainian business opens up new opportunities and prospects for realizing its potential in the international arena, which, at the same time, imposes additional requirements on the professional level of businessmen and company managers. Entrepreneurs and managers must be able to operate successfully in a wide range of cultures in order to keep pace with changes taking place in the world and to remain competitive. Airlines compete with each other to provide businessmen with convenient transit and create conditions under which they would arrive at destinations fresh and rested. However, as soon as representatives of companies step into the land of a country, they are left alone with a new culture, different languages and business styles. The ability to adapt and bring one's business style in line with the style of other cultures plays an important role in their successes or failures.

In this regard, the purpose of this study is to find ways to increase the effectiveness of the cross-cultural communications, based on which Ukrainian businessmen, working in international markets could be more successful in communicating with representatives of other cultures, bypassing those sharp corners, which often become a stumbling block in the process of business travel, negotiation and conclusion of profitable contracts.

An effective communication activity of a businessman on an international scale is not a difficult task. Its solution is facilitated by the cross-cultural management, under which it is clear that the art of managing people's behavior and building relationships at the junction of business cultures, the ability to manage different attitudes, culture and habits of people in order to achieve the best business results [1]. The cross-cultural management studies how people and organizations in the global environment take cultural differences into account [2]; cooperation with representatives of another culture, maximum tolerance to differences and recognition of the priorities of foreign partners [3]; behavior of people in organizations around the world and describes organizational behavior in different countries and cultures, compares different models of this behavior and seeks to understand and improve the interaction between employees, customers, suppliers and partners from different countries and cultures [4]. Understanding approaches to doing business in different countries, people can evaluate the potential benefits and problems of cooperation with them and thus make competent decisions on how to work with a particular people and find out if there is any special need for it.

The biggest problem in establishing intercultural communications in the business trip process is cultural disagreement that may lead to misunderstandings and even conflicts. There are the following most common causes of violations of intercultural communication:

Yaroslav Martynyshyn[1,*], Elena Khlystun[1], Yelena Kovalenko[2]
[1]Kiev National University of Culture and Arts, Ukraine
[2]National Academy of Managerial Staff of Culture and Arts, Ukraine
*E-mail of corresponding author: biguss@meta.ua

different perceptions and interpretations of reality by representatives of different cultures [5]; differences in the stereotypes of evaluation of the same phenomena in different cultures [6]; manifestation of a sense of superiority associated with the commitment to the culture of their country [7]; semantic and technical disturbances in communication arising as a result of verbal communication and emotional communication (para verbalism), as well as differences in gestures (non-verbal) [8].

An important tool in identifying cultural differences in international business communication is a typology, which is based on the dismemberment of the communication business culture as a system for individual elements and their grouping using a generalized, idealized type. This tool is based on definition of similarities and differences between the cultural elements and it is aimed at reflecting the structure and features of business culture in different countries and regions of the world. Today, in the cross-cultural management, there are four types of paired opposites of communication behavior in conducting business [9-10]:

1) focus on culture ***agreement*** or ***relationship***. It is believed that if attention is focused on the deal, the participants think mainly about the task and if attention is focused on the relationship, then the participants are more likely to think about people. A lot of representatives of business focused on relationships believe that the focus on the deal is belligerent and aggressive;
2) ***a formal***, elite culture with a hierarchical organization and a strict observance of differences in status and authority, or an ***informal***, egalitarian culture, in which it is considered that all people are equal with a slight difference in status and authority. The informal behavior of some offends the perceptions of high-ranking representatives of elite cultures, just as their concentration on their importance may offend the feelings of representatives of the egalitarian culture;
3) ***monochrome*** culture with a rigid attitude to time and graphs, or ***polychrome*** culture with a flexible relation to time and graphs. Some countries worship the clock and value precision. Others condescendingly refer to time and graphs, they are more focused on the people who surround them. The conflict arises when those belonging to the first group consider the representatives of the other group lazy and undisciplined, whereas they are considered arrogant, bound within mandatory terms;
4) emotionally ***expressive***, or emotionally ***restrained*** (***neutral***) culture. Communication of expressive people is significantly different from the communication of restrained people. This applies both to verbal communication and to non-verbal communication. These differences can lead to misunderstandings that adversely affect negotiation, transaction and management processes.

Doubles of the opposite types in cross-cultural communication are ideal types. They are sufficiently fully described in the scientific literature [11-13], however, in practice, in pure form, are rare. Today, in conditions of globalization of society, communication cultures of different countries mostly combine these cross-cultural opposites with some predominance of elements of a cultural type. However, in scientific sources there is no data on the correlation of these opposites, which makes it impossible to identify differences and build intercultural communication strategies in the process of business travel to different countries of the world:

- correlation definition of different types of intercultural communication and profiles construction and cross-cultural communication classifications of countries and regions of the world and the main communicants of Ukrainian business;
- identification of cross-cultural communication disagreements between representatives of Ukrainian business and business representatives from foreign partner countries;
- measures identification of cross-cultural communication reactions of Ukrainian entrepreneurs and managers on intercultural differences with foreign partners;
- statistical development and mathematical tools for modeling, analyzing and predicting the effectiveness of cross-cultural communications of Ukrainian business, depending on the level of intercultural differences.

2 Methodology

The methodological basis of the research is the dialectical principle of cognition, systematic and cultural approaches, statistical methods of surveying, expert evaluation, analytical grouping, mathematical modeling, analysis and prediction of cross-cultural communication processes, as well as the fundamental provisions of the theory of management in the intercultural environment. Based on the objectives of the study, its main focus is on the construction of the cross-cultural communication profiles, identification of the cultural differences and identification of patterns of their influence on the formation of communication responses, which will serve as the basis for developing the cross-cultural strategies for behavior of representatives of Ukrainian business.

The research methodology includes the following steps.

1. Collection of statistical data about the research object, which involves a survey of representatives of Ukrainian business and the evaluation of the structure of the four duplex opposite types of communication (D and U; F and I; M and P; E and N) in Ukraine and in foreign countries (where the business trips were carried out), as well as evaluation of the success rate of communications are reactions (R) of Ukrainian businessmen to cross-cultural differences.

The structure of the pair of opposing types of cross-cultural communication for each respondent is estimated in units of unit:

D and U - the share of concentration on the transaction and the relationship (D+U =1);

F and I - the proportion of formalities and informality (F+I =1);

M and P - the proportion of monochrome and polychrome (M+P =1);

E and N - the share of expressiveness and restraint, neutrality (E+N =1).

The reaction to cultural differences, or the level of success of cross-cultural communication (R) for each respondent is estimated on a 100-point scale.

The study covers 20 countries and regions and 716 respondents in particular: Baltic - 37; Belarus - 42; Canada - 34; China - 32; Czechia - 38; France - 36; Germany - 35; Hungary - 34; India - 32; Italy - 33; Moldova - 38; Poland - 36; Romania - 35; Russia - 44; Scandinavia - 32; Slovakia - 36; Spain - 33; Turkey - 37; UK - 34; USA - 38.

2. Summarizing statistical data and calculating general indicators of the cross-cultural communication across countries and regions of the world:

a) systematization of statistical data by country and regions;

b) calculation of average values the structure parameters of the pair of communication culture opposing pairs:

$$\begin{aligned}&CD=\Sigma D/Q,\ CU=1-CD,;\\&CF=\Sigma F/Q,\ CI=1-CF,\\&CM=\Sigma M/Q,\ CP=1-CM,\\&CE=\Sigma E/Q,\ CN=1-CE,\end{aligned} \tag{1}$$

where Q - the number of respondents in a particular country or region;

c) calculation of average values of the reaction (success) of the cross-cultural communication (YR) in the studied countries:

$$YR=\Sigma R/Q. \tag{2}$$

3. Construction of profiles and classifications of cross-cultural communication in countries and regions of the world from the standpoint of Ukrainian entrepreneurs and managers. The profile of the country's communication culture consists of the average values of the indicators of the structure of the pair of intercultural communication opposing types:

$$\{CD \text{ and } CU;\ CF \text{ and } CI;\ CM \text{ and } CP;\ CE \text{ and } CN\}. \tag{3}$$

4. Identify cross-cultural communication disagreements across countries and regions. The average values of intercultural communication differences in each pairwise opposite type of the cross-cultural communication (ΔCDU; ΔCFI; ΔCMP; ΔCEN) and in general (ΔC) of one or another country are calculated according to the following formulas:

$$\begin{aligned}&\Delta CDU=|CDo-CDi| \text{ or } |CUo-CUi|,\\&\Delta CFI=|CFo-CFi| \text{ or } |CIo-CIi|,\\&\Delta CMP=|CMo-CMi| \text{ or } |CPo-CPi|,\\&\Delta CEN=|CEo-CEi| \text{ or } |CNo-CNi|,\\&\Delta C=(\Delta CDU+\Delta CFI+\Delta CMP+\Delta CEN)/4,\end{aligned} \tag{4}$$

where o, i - indexes that represent indicators relating respectively to Ukraine and the foreign country.

5. Analytical grouping of countries and regions by the middle level of the cross-cultural communication disagreement (ΔC) and revealing patterns of its influence on the success of communication (YR) of Ukrainian businessmen:

$$\Delta C \rightarrow YR. \tag{5}$$

6. Construction of statistical and mathematical models of communication of the cross-cultural communication reactions across countries and regions of the world depend on the level of intercultural differences:

$$\tilde{R} = k\,(\Delta DU, \Delta FI, \Delta MP, \Delta EN), \tag{6}$$

where R - the effective indicator of the model of a particular country (the success of communication, or the reaction of representatives of the Ukrainian business to the cross-cultural differences), in points;

ΔDU, ΔFI, ΔMP, ΔEN - factor indicators of the model (cross-cultural differences), in parts of unit. They are determined by each respondent according to the following formulas:

$$\begin{aligned}&\Delta DU=|Do-Di| \text{ or } |Uo-Ui|,\\&\Delta FI=|Fo-Fi| \text{ or } |Io-Ii|,\\&\Delta MP=|Mo-Mi| \text{ or } |Po-Pi|,\\&\Delta EN=|Eo-Ei| \text{ or } |No-Ni|.\end{aligned} \tag{7}$$

The construction of models involves the following steps:

A. Verification of consolidated and systematic statistical sample data for their compliance with established requirements for statistical and mathematical modeling and representativeness. The results of such verification have shown that information is sufficient, both in terms of the number of units and the variation of attributes and in harmony of its aggregates with normal distribution, and also whether it is representative of the general population [14].

The test showed that the source information is sufficient, both in the number of observation units ($Q/4 \geq 8$) and in the variation of the resultant and factor characteristics ($V>10\%$), and in the harmony of its aggregates with normal distribution ($\tau < 3\sigma$); it is also representative of the general population, since its actual error, at a given probability level of 0.95, does not exceed the marginal ($\Delta f < \Delta lim$).

***Table 1** Profiles of cross-cultural business communications*

Country, region	Profile							
	CDU		CFI		CMP		CEN	
	CD	CU	CF	CI	CM	CP	CE	CN
Ukraine	0.41	0.59	0.67	0.33	0.56	0.44	0.61	0.39
Baltic	0.83	0.17	0.58	0.42	0.74	0.26	0.45	0.55
Belarus	0.38	0.62	0.71	0.29	0.60	0.40	0.59	0.41
Canada	0.88	0.12	0.05	0.95	0.91	0.09	0.67	0.33
China	0.02	0.98	0.98	0.02	0.96	0.04	0.01	0.99
Czechia	0.66	0.34	0.72	0.28	0.75	0.25	0.62	0.38
France	0.84	0.16	0.83	0.17	0.77	0.23	0.91	0.09
Germany	0.92	0.08	0.90	0.10	0.93	0.07	0.32	0.68
Hungary	0.67	0.33	0.55	0.45	0.64	0.36	0.80	0.20
India	0.01	0.99	0.99	0.01	0,03	0.97	0.00	1.00
Italy	0.87	0.13	0.61	0.39	0.74	0.26	0.96	0.04
Moldova	0.34	0.66	0.84	0.16	0.36	0.64	0.89	0.11
Poland	0.49	0.51	0.57	0.43	0.64	0.36	0.52	0.48
Romania	0.37	0.63	0.88	0.12	0.39	0.61	0.96	0.04
Russia	0.39	0.61	0.73	0.27	0.61	0.39	0.67	0.33
Scandinavia	0.91	0.09	0.41	0.59	0.84	0.16	0.35	0.65
Slovakia	0.51	0.49	0.62	0.38	0.66	0.34	0.56	0.44
Spain	0.76	0.24	0.51	0.49	0.74	0.26	0.87	0.13
Turkey	0.02	0.98	0.98	0.02	0.01	0.99	0.99	0.01
UK	0.93	0.07	0.91	0.09	0.92	0.08	0.28	0.72
USA	0.95	0.05	0.04	0.96	0.94	0.06	0.63	0.37

Therefore, this sample information can be used in modeling the interconnections of cross-cultural communication reactions and intercultural differences with dissemination and interpretation of results for the entire general population of Ukrainian business (error up to 3%).

B. Detection of the form of the cause-and-effect relationship between factor and resultant features carried out by means of grouping and graphing methods and constructing a model in a general symbolic form.

As confirmed by analysis, the relationship between the performance indicator (R) and the factors (ΔDU, ΔFI, ΔMP, ΔEN) is inverse, and the form of communication is close to the linear.

Consequently, the general form of statistical and mathematical models will be the following:

$$\tilde{R} = 100 - a_1\Delta DU - a_2\Delta FI - a_3\Delta MP - a_4\Delta EN, \quad (8)$$

where 100, a_1, a_2, a_3, a_4 - models' options, apart: 100 - free member (maximum value of communication success); $a_1 \ldots a_4$ - coefficients of regression.

C. Modelling in numerical form. This work is carried out on a computer and includes correlation calculations and evaluation of reliability of the communication characteristics: the numerical values of regression coefficients (a_1, a_2, a_3, a_4), multiple and partial correlation coefficients (r, r_1, r_2, r_3, r_4) are determined (d, d_1, d_2, d_3, d_4), the actual values of the Fisher (F) and Student criteria (t_1, t_2, t_3, t_4). With help of the t- and F-criteria one can evaluate the reliability of the regression coefficients and the model as a whole. Based on the correlation coefficients, the binding force is estimated and the determination coefficients are the proportion of the variation of the resultant characteristics, which is determined by influence of the factor characteristics.

7. Statistical and mathematical analysis and forecasting. With help of developed numerical models it is possible to carry out a deep analysis of the effectiveness (success) of cross-cultural communications. In particular, using the regression coefficients (a_1, a_2, a_3, a_4). The degree of influence of the corresponding factor (ΔDU, ΔFI, ΔMP, ΔEN) on the resultant indicator (R) has been determined; in the scores: with the change of the individual factor per unit, the resultant indicator will change to the corresponding factor. Knowing the magnitude of the variation of each factor, the maximum change in the effective index has been found and by the determination coefficients (d, d_1, d_2, d_3, d_4) there is a conclusion on the proportion of its variation due to the influence of all or a particular factor included in the model. On the basis of models, it is also possible to predict cross-cultural communication reactions.

Table 2 Distribution of countries and regions for dual opposite types of communication culture

Predominant type of culture	Specific weight	Country, region	Ctype
Focus on the deal / Orientation on the relationship			
Culture orientated for an agreement	High	USA (0.95), UK (0.93), Germany (0.92), Scandinavia (0.91)	CD=0.93
	Average	Canada (0.88), Italy (0.87), France (0.84), Baltic (0.83)	CD=0.85
	Low	Spain (0.76), Hungary (0.67), Czech (0.66), Slovakia (0.51)	CD=0.65
Culture focused on relationship	High	India (0.99), China (0.99), Turkey (0.98)	CU=0.99
	Low	Moldova (0.66), Romania (0.63), Belarus (0.62), Russia (0.61), Ukraine (0.59), Poland (0.51)	CU=0.60
Formal culture / Informal culture			
Formal culture	High	India (0.99), China (0.98), Turkey (0.98), UK (0.91), Germany (0.90)	CF=0.95
	Average	Romania (0.88), Moldova (0.84), France (0.83), Russia (0.73), Czechia (0.72), Belarus (0.71), Ukraine (0.67)	CF=0.77
	Low	Slovakia (0.62), Italy (0.61), Baltic (0.58), Poland (0.57), Hungary (0.55), Spain (0.51)	CF=0.57
Informal culture	High	USA (0.96), Canada (0.95)	CI=0.96
	Low	Scandinavia (0.59)	CI=0.59
Monochrome Culture / Polychrome Culture			
Monochrome culture	High	China (0.96), USA (0.94), Germany (0.93), UK (0.92), Canada (0.91), Scandinavia (0.84)	CM=0.90
	Average	France (0.77), Czech (0.75), Italy (0.74), Spain (0.74), Baltic (0.74)	CM=0.75
	Low	Slovakia (0.66), Poland (0.64), Hungary (0.64), Russia (0.61), Belarus (0.60), Ukraine (0.56)	CM=0.62
Polychrome culture	High	Turkey (0.99), India (0.97)	CP=0.98
	Low	Moldova (0.64), Romania (0.61)	CP=0.63
Expressive culture / Neutral culture			
Expressive culture	High	Turkey (0.99), Italy (0.96), Romania (0.96), France (0.91)	CE=0.96
	Average	Moldova (0.89), Spain (0.87), Hungary (0.80)	CE=0.85
	Low	Canada (0.67), Russia (0.67), USA (0.63), Czechia (0.62), Ukraine (0.61), Belarus (0.59), Slovakia (0.56), Poland (0.52)	CE=0.61
Neutral culture	High	India (1.00), China (0.99)	CN=1.00
	Low	UK (0.72), Germany (0.68), Scandinavia (0.65), Baltic (0.55)	CN=0.65

Substituting specific values of factor-factors in the model (ΔDU, ΔFI, ΔMP, ΔEN), the expected values of the effective index have been predicted (R).

3 Results and discussion

The basic result of the research, which is based on the following results, is the construction of profiles of the cross-cultural communications of the countries and regions of the world, with which the Ukrainian business interacts. As can be seen from Table 1, profiles by country and region are different. In some countries, they are very high, while in some, on the other hand, are very low, while in others are at an average level. However, this does not in any way mean that some of the crops are better, and some are worse. There is no absolute standard of correctness or perfection that can be applied to assessment of the communication behavior. Cultural differences are neither beautiful nor bad, they are just other; although some cultural behavior may be easier than others to adapt to specific environmental conditions. Ukrainian communication culture is no closer to an ideal than any other culture, although it may be better for Ukrainian entrepreneurs and managers. Thus, ethno-relativism is the assumption that communication cultures can be understood only relative to one another, and specific behavior - only within the context of a cultural context, must be fundamental in understanding of the cross-cultural communications.

However, there are not only differences but also some similarities between the communication cultures of the countries and regions of the world, which allow them to be classified according to cultural types (see Tables 2 and 3).

India and China are representatives of the oldest eastern civilizations, as well as Turkey, a representative of the Muslim world (see Table 3, Classes Nos. 1, 2, 3), the most visible communication cultures, from the totality of the studied countries. Communication cultures of these three countries are as much as possible oriented on interrelations, formality, elitism, strict adherence to

***Table 3** Distribution of countries and regions by combined classes communication culture*

No	Classes of communication culture	Formula of combinations	Country, region	Ccombin
1	Maximally oriented on the relationship, formality, polychrome, neutrality	U+F+P+N	India (0.99; 0.99; 0.97; 1.00)	0.99
2	Maximally oriented on the relationship, formality, monochrome, neutrality	U+F+M+N	China (0.99; 0.98; 0.96; 0.99)	0.98
3	Maximally oriented on the relationship, formality, polychrome, expressiveness	U+F+P+E	Turkey (0.98; 0.98; 0.99; 0.99)	0.99
3a	Moderately oriented on relationships, formality, polychrome; as expressive as possible	U+F+P+E	Romania (0.63; 0.88; 0.61; 0.96) Moldova (0.66; 0.84; 0.64; 0.89)	0.76
4	Maximally focused on the deal, informality, monochrome; moderately expressive	D+I+M+E	USA (0.95; 0.96; 0.94; 0.63) Canada (0.88; 0.95; 0.91; 0.67)	0.86
5	Maximum approximation; moderately informal, monochrome, neutral	D+I+M+N	Scandinavia (0.91; 0.59; 0.84; 0.65)	0.75
6	Maximum focused on the deal, formality, monochrome; moderately neutral	D+F+M+N	UK (0.93; 0.91; 0.92; 0.72) Germany (0.92; 0.90; 0.93; 0.68)	0.86
6a	Moderately focused on the deal, formality, monochrome, neutrality	D+F+M+N	Baltic (0.83; 0.58; 0.74; 0.55)	0.68
7	Moderately oriented on the relationship, formality, monochrome, expressiveness	U+F+M+E	Ukraine (0.59; 0.67; 0.56; 0.61) Belarus (0.62; 0.71; 0.60; 0.59) Russia (0.61; 0.73; 0.61; 0.67) Poland (0.51; 0.57; 0.64; 0.52)	0.61
8	Moderately focused on the deal, formality, monochrome, expressiveness	D+F+M+E	Slovakia (0.51; 0.62; 0.66; 0.56) Czech (0.66; 0.72; 0.75; 0.62) Hungary (0.67; 0.55; 0.64; 0.80)	0.65
8a	Moderately focused on the deal, formality, monochrome; as expressive as possible	D+F+M+E	France (0.84; 0.83; 0.77; 0.91) Italy (0.87; 0.61; 0.74; 0.96) Spain (0.76; 0.51; 0.74; 0.87)	0.78

hierarchy and differences in the status and power of communicants. In addition, India and Turkey have the most polychrome cultures, which do not pay much attention to the time and schedule of work, while China is the bearer of a rigidly monochromatic culture. Still, the communication culture of India and China is as restrained, neutral, while Turkey, on the contrary, is as expressive as possible.

Further, among the studied countries and regions, the United States, Canada, Great Britain and Germany (see Table 3, Classes Nos. 4, 6), which are as much as possible focused on the deal and monochrome, are particularly distinguished. The differences between them are that in the US and Canada, the business communication culture is at most informal, egalitarian and moderately expressive, while in the UK and Germany it is as formalized and moderately neutral.

The cultures of the Scandinavian and Baltic countries are somewhat similar to the communication cultures of the United States, Germany and among themselves (see Table 3, Classes 5, 6a), which are equally moderately neutral. However, Scandinavian countries, compared to the Baltic countries, are much more focused on the deal and monochrome. The main difference between them is that Scandinavian communication culture is moderately informal and similar, on this basis, to the culture of the United States, while the Baltic is moderately formal and more similar to the culture of Germany.

Communication cultures of Romania, Moldova, France, Italy and Spain are characterized by a maximum level of expressiveness (see Table 3, Classes Nos. 3a, 8a), and they are similar to the culture of Turkey. However, in all the other parameters with Turkey's culture, only Romania and Moldova are the most correlated, which are moderately oriented on interrelations, formality and polychrome. France, Italy and Spain, according to their profiles, have the highest resemblance to Slovakia, the Czech Republic and Hungary (see Class No. 8), but, in contrast to the latter, they are characterized by significantly higher indicators of orientation to the agreement, formality, monochrome and expressiveness.

The cultures of business communication in Ukraine, Belarus, Russia and Poland (see Table 3, Grade 7), which are moderately oriented towards interrelations, formalities, monochrome and expressiveness, are very similar to the cultures of Slovakia, the Czech Republic and Hungary. The only significant difference is that the former are more focused on the relationship and the other on the deal.

Nevertheless, despite some similarities in profiles the of communication cultures of countries and regions of the

***Table 4** The cross-cultural communication disagreements and reactions*

Country, region	Differences					Reaction
	ΔCDU	ΔCFI	ΔCMP	ΔCEN	ΔC	YR
Baltic	0.42	0.09	0.18	0.16	0.21	59.8
Belarus	0.03	0.04	0.04	0.02	0.03	92.1
Canada	0.47	0.62	0.35	0.06	0.38	35.5
China	0.39	0.31	0.40	0.60	0.43	23.1
Czechia	0.22	0.05	0.19	0.01	0.12	75.2
France	0.43	0.16	0.21	0.30	0.28	49.8
Germany	0.51	0.23	0.37	0.29	0.35	40.1
Hungary	0.26	0.12	0.08	0.19	0.16	67.1
India	0.40	0.32	0.53	0.61	0.47	18.5
Italy	0.46	0.06	0.18	0.35	0.26	54.0
Moldova	0.07	0.17	0.20	0.28	0.18	66.4
Poland	0.08	0.10	0.08	0.09	0.09	76.7
Romania	0.04	0.21	0.17	0.35	0.19	62.2
Russia	0.02	0.06	0.05	0.06	0.04	86.9
Scandinavia	0.50	0.26	0.28	0.26	0.32	45.3
Slovakia	0.10	0.05	0.10	0.05	0.08	79.8
Spain	0.35	0.16	0.18	0.26	0.24	58.1
Turkey	0.39	0.31	0.55	0.38	0.41	30.2
UK	0.52	0.24	0.36	0.33	0.36	36.7
USA	0.54	0.63	0.38	0.02	0.39	32.3

***Table 5** Grouping of countries and regions at the level of the cross-cultural differences and revealing their influence on communication reactions*

Groups by level of disagreement		Average value	
		differences ΔC	reactions YR
to 0.10	(Belarus, Russia, Slovakia, Poland)	0.06	83.9
0.11-0.20	(Czechia, Hungary, Moldova, Romania)	0.16	67.7
0.21-0.30	(Baltic, Spain, Italy, France)	0.25	55.4
0.31-0.40	(Scandinavia, Germany, UK, Canada, USA)	0.36	38.0
over 0.40	(Turkey, China, India)	0.44	23.9

world, there are still differences between them, which form the corresponding reactions of Ukrainian entrepreneurs and managers in the process of business travel (see Table 4). The greatest discrepancies have been with the cultures of India, China and Turkey and the smallest with Belarus, Russia, Slovakia and Poland.

The analytical grouping of countries and regions according to the level of cross-cultural differences confirms the existence of a logical inverse relationship between the size of disagreements and the success of communications (see Table 5).

More deeply, the patterns of influence of the cross-cultural differences on the reaction of the Ukrainian businessmen can be analyzed and predicted on the basis of developed statistical and mathematical models (see Table 6), which are sufficiently reliable for practical use, since the actual values of the ***t***- and ***F***-criteria have appeared many times more critical values. The multiple correlation coefficients of these models ($\boldsymbol{r}$ = 0.82 ... 0.90) indicate a strong link between the effective (R) and the factor (ΔDU, ΔFI, ΔMP, ΔEN) signs.

With decreasing intercultural communication differences ΔDU, ΔFI, ΔMP, ΔEN by 0.1, the success of communication R in the aggregate of the studied countries and regions will increase on average: due to each factor by: $\Delta R_1 = 0.1 \cdot a_1 = 4.7 \dots 7.9$; $\Delta R_2 = 0.1 \cdot a_2 = 2.8 \dots 7.3$; $\Delta R_3 = 0.1 \cdot a_3 = 3.4 \dots 7.1$; $\Delta R_4 = 0.1 \cdot a_4 = 2.6 \dots 6.2$ points; by all factors at ΔR = 13.5 … 28.5 points. Variation in the success of communication is determined by the complex of these factors, on average, by $\boldsymbol{d}$ = 67 ... 82%, including by some factors: $\boldsymbol{d}_1 = 0.20 \dots 0.25$; $\boldsymbol{d}_2 = 0.11 \dots 0.21$; $\boldsymbol{d}_3 = 0.13 \dots 0.21$; $\boldsymbol{d}_4 = 0.12 \dots 0.19$%.

Only one of the possible combinations of the changing cultural differences across the whole of the studied

Table 6 *Statistical and mathematical models of communications of communication reactions depending on the cross-cultural differences*

Country, region	Model	The coefficients of determination				
		d	d1	d2	d3	d4
Baltic	$\tilde{R}$ = 100 - 55.4ΔDU - 49.4ΔFI - 43.5ΔMP - 29.7ΔEN	0.77	0.22	0.19	0.17	0.19
Belarus	$\tilde{R}$ = 100 - 65.3ΔDU - 62.9ΔFI - 60.5ΔMP - 53.2ΔEN	0.82	0.22	0.21	0.21	0.18
Canada	$\tilde{R}$ = 100 - 48.2ΔDU - 41.8ΔFI - 40.2ΔMP - 30.6ΔEN	0.70	0.21	0.18	0.18	0.13
China	$\tilde{R}$ = 100 - 61.0ΔDU - 37.7ΔFI - 34.1ΔMP - 46.7ΔEN	0.69	0.23	0.14	0.13	0.19
Czechia	$\tilde{R}$ = 100 - 54.9ΔDU - 52.8ΔFI - 50.8ΔMP - 44.7ΔEN	0.79	0.21	0.21	0.20	0.17
France	$\tilde{R}$ = 100 - 49.1ΔDU - 47.3ΔFI - 45.4ΔMP - 40.0ΔEN	0.78	0.21	0.20	0.19	0.18
Germany	$\tilde{R}$ = 100 - 49.9ΔDU - 43.2ΔFI - 41.6ΔMP - 31.6ΔEN	0.71	0.21	0.18	0.18	0.14
Hungary	$\tilde{R}$ = 100 - 63.3ΔDU - 58.8ΔFI - 54.2ΔMP - 27.1ΔEN	0.77	0.22	0.20	0.18	0.17
India	$\tilde{R}$ = 100 - 64.5ΔDU - 27.9ΔFI - 40.1ΔMP - 41.8ΔEN	0.67	0.25	0.11	0.15	0.16
Italy	$\tilde{R}$ = 100 - 49.0ΔDU - 45.5ΔFI - 43.7ΔMP - 36.7ΔEN	0.71	0.20	0.18	0.18	0.15
Moldova	$\tilde{R}$ = 100 - 57.8ΔDU - 53.8ΔFI - 51.8ΔMP - 35.9ΔEN	0.75	0.22	0.20	0.19	0.14
Poland	$\tilde{R}$ = 100 - 74.9ΔDU - 66.9ΔFI - 64.2ΔMP - 61.5ΔEN	0.78	0.22	0.20	0.19	0.17
Romania	$\tilde{R}$ = 100 - 57.7ΔDU - 53.5ΔFI - 49.4ΔMP - 45.3ΔEN	0.74	0.21	0.19	0.18	0.16
Russia	$\tilde{R}$ = 100 - 78.9ΔDU - 73.3ΔFI - 70.5ΔMP - 59.2ΔEN	0.80	0.22	0.21	0.20	0.17
Scandinavia	$\tilde{R}$ = 100 - 47.4ΔDU - 44.1ΔFI - 42.5ΔMP - 29.4ΔEN	0.73	0.21	0.20	0.19	0.13
Slovakia	$\tilde{R}$ = 100 - 71.8ΔDU - 69.2ΔFI - 66.5ΔMP - 58.5ΔEN	0.79	0.21	0.21	0.20	0.17
Spain	$\tilde{R}$ = 100 - 47.5ΔDU - 45.7ΔFI - 44.0ΔMP - 38.7ΔEN	0.73	0.20	0.19	0.18	0.16
Turkey	$\tilde{R}$ = 100 - 54.1ΔDU - 38.9ΔFI - 45.6ΔMP - 30.4ΔEN	0.72	0.23	0.17	0.19	0.13
UK	$\tilde{R}$ = 100 - 50.0ΔDU - 48.3ΔFI - 41.4ΔMP - 32.8ΔEN	0.75	0.22	0.21	0.18	0.14
USA	$\tilde{R}$ = 100 - 48.1ΔDU - 41.9ΔFI - 38.8ΔMP - 26.4ΔEN	0.74	0.23	0.20	0.19	0.12

countries and regions, was considered, but they can be numerous and at most in the context of an individual country or group of countries. For example, with decreasing cultural differences with Germany for these factors, respectively, 0.20, 0.15, 0.25, 0.10, the success of communication at the expense of each of them will increase accordingly: $\Delta R_1 = 0.20 \cdot 49.9 = 9.8$; $\Delta R_2 = 0.15 \cdot 43.2 = 6.5$; $\Delta R_3 = 0.25 \cdot 41.6 = 10.4$; $\Delta R_4 = 0.10 \cdot 31.6 = 3.2$ points; and all at ΔR = 29.9 points. The predicted success of communication will be $R = YR + \Delta R = 40.1 + 29.9 = 70$ points. With a decrease in the same size of cultural differences with China, France and the United States, the success of communications will increase by 31.1, 32.3, 28.2 points, respectively and will amount to 54.2, 82.1, 60.5 points, respectively.

Similar prediction calculations can be made in other countries and regions of the world with a set of different combinations of factor characteristics.

4 Conclusions

Business is a multicultural phenomenon and, therefore, entrepreneurs and managers cannot afford to take a guided look at the world through the prism of their own values and prospects: «our way of life and our values are the best and only possible, and everything else is not worthy of attention as something underdeveloped and imperfect». Mistake is also made by businessmen from all other cultures, depending on how similar they are to their own culture, which is perceived as correct, normal and superior to all other. It should be emphasized that the right to conduct international business and the implementation of cross-cultural communications is an approach based on the equal value of different cultures and the recognition of cultural differences as good, which ensures the harmony of the mankind existence. However, it is fair to point out that these differences lead one to disappointment, due to the difficulty of their perception, confusion and unpredictability. The proposed developments in the article, which are based on statistical measures and models, minimize confusion and create opportunities for quantitative perceptions of intercultural differences and the predictability of communication responses from the standpoint of the Ukrainian business culture. The obtained results of the study are new and can be used in development of the cross-cultural communication strategies, as well as in justifying the ways of adapting to different types of intercultural differences and improving the efficiency of communications in the process of business trips.

References

[1] MARTYNYSHYN, Y., KOVALENKO, Y. *Art of management and educational technologies of preparation of managers of social and cultural activity* (in Ukrainian). Bila Tserkva: O. V. Pshonkivskyj, 2018. ISBN 978-617-604-144-3.

[2] FUNAKAWA, A. *Transcultural management. A new approach for global organizations*. San Francisco: Jossey-Bass, 1997. ISBN 978-078-790-323-7.

[3] MEAD, R. *Cross-cultural management communication*. Chichester: Wiley, 1992. ISBN 978-047-193-718-0.

[4] ADLER, N. J. *International dimensions of organizational behaviour*. Boston: Cengage Learning, 2007. ISBN 978-032-436-074-5.

[5] PRIMECZ, H., ROMANI, L., SACKMANN, S. *Cross-cultural management in practice: culture and negotiated meanings*. Cheltenham: Edward Elgar Pub, 2012. ISBN 978-184-980-407-3.

[6] LEWIS, R. *Cross-cultural communication*. London: Transcreen Publications, 2008. ISBN 978-095-343-983-6.

[7] NORALES, F. *Cross-cultural communication: concepts, cases and challenges*. New York: Cambria Press, 2006. ISBN 978-097-735-673-7.

[8] VARNER, I., BEAMER, L. *Intercultural communication in the global workplace*. New York: McGraw-Hill Education, 2010. ISBN 978-007-337-774-2.

[9] GESTELAND, R. *Cross-cultural business behavior: a guide for global management*. Copenhagen: CBS Press, 2012. ISBN 978-876-300-238-7.

[10] MARTYNYSHYN, Y., KOVALENKO, Y. Formation of the modern system management of life society. *Bulletin of Kyiv National University of Culture and Arts. Series in Management of Social and Cultural Activity* (in Ukrainian) [online]. 2018, 1, p. 7-24. ISSN 2616-7573, eISSN 2617-1104. Available from: https://doi.org/10.31866/2616-7573.1.2018.143383

[11] MEAD, R. *International management: cross-cultural dimensions*. Chichester: John Wiley and Sons Ltd, 1998. ISBN 978-063-120-003-1.

[12] MERKIN, R. S. *Saving face in business: managing cross-cultural interactions*. New York: Palgrave Macmillan, 2018. ISBN 978-113-759-173-9.

[13] REYNOLDS, S., VALENTINE, D. *Guide to cross-cultural communication*. Upper Saddle River: Prentice Hall, 2003. ISBN 978-013-049-784-0.

[14] ABRAHAM, B. *Statistical methods for forecasting*. New York: Wiley-Interscience, 2013. ISBN 978-047-176-987-3.