Research Article

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Analytical model assessing the effect of increased traffic flow intensities on the road administration, maintenance and lifetime

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Abstract: The aim of this paper is to introduce the reader to the construction of an analytical model assessing the effect of increased traffic intensities on extraordinary road traffic events on the amount of expenditures that the road administrators are forced to spend on the extra maintenance and reshaping these alternative diversion routes into the initial technical conditions. The computational mechanism of this model is based on the one hand on parameters of diversion routes temporarily transferring increased traffic intensities (e.g. motorway traffic at closure), on the other hand on approved cost databases for the assessment of road constructions and other regulations concerning the design of road maintenance and repair. In the final part of the paper the applicability of this model in practice is assessed and some negatives that are not included in the final calculation when determining the total costs of the road administrator are mentioned.

Keywords: analytical model, cost databases, diversion route, road administrator, road maintenance

1 Introduction

In case of an extraordinary traffic event on the motorway leading to its complete closure, two views can be seen at this situation. From the point of view of the road users (drivers), compared with the normal traffic situation, we will be interested primarily in the increased costs related to the diversion of all motorway traffic on the alternative diversion route. This group will include on the one hand a higher operating cost of the vehicle – the diversion route is usually longer and often goes along a geometrically more

demanding road, on the other hand higher travel costs of the driver – the time spent on the diversion route is due to its length, capacity and a density of the diverted traffic flow always significantly higher than normal traffic. However, when assessing the negative impacts of diverted traffic, it is equally important the point of view of the road administrators especially of lower classes roads, that serve as a temporary diversion route for all traffic until the restoration of two-way operation on the motorway. The following part of the paper briefly presents a proposal of an analytical model which assesses the effect of the increased traffic intensities on the amount of expenditures that the diversion route administrators are subsequently forced to spend on maintenance and reshaping these roads into the initial technical condition.

2 Main input values of the analytical model

On the basis of technical conditions and regulations relating to the design of roadways, designing maintenance and repairing of unsolicited roadways and cost databases for the assessment of road constructions, an analytical model can be compiled. This model calculates on every diversion route (or on its segment) the future total costs of the road administrator that will be necessarily spent relating to the diverted motorway traffic flow to its maintenance or total reconstruction. A precondition for such a model is the fact that all alternative motorway diversion routes run along the 1st, 2nd or 3rd class roads, which at the same time (in most cases) also consist significant roads in cities or urban agglomerations. An essential criterion for the possibility of including a road into the diversion route is the requirement for the minimum width of its roadway, which must be at least 5.50 m (lane width in every direction $a = 2.75$ m) so that in its each section it is ensured two-way operation of heavy freight vehicles [1].

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2.1 Traffic flow intensity on the diversion route

Thus, the input value of the analytical model is the value of the assumed traffic flow intensity on the diversion route, which can be determined as the sum of the diverted traffic flow intensity from the motorway and the average traffic flow intensity for the given road class that the diversion route passes through. At certain points of the Czech motorway network equipped with telematics systems, this value can be accurately determined in real time by traffic flow detectors [1, 2]. If the closed section of the motorway does not have telematics devices indicating the current traffic information, the default values in the model are the same as for lower category roads (1st, 2nd and 3rd class roads) set at the average traffic flow intensity obtained from the results of the National Traffic Survey in 2016 (CSD 2016) as shown in Table 1 and Figure 1.

Table 1: Table of average traffic flow intensities from the CSD 2016 [3, 4]

Average traffic flow intensities $RPDI_x$ on motorways and roads from the CSD 2016	
Road category	Number of all vehicles per day [vehicles/24h]
Motorways	31 070
1 st class roads	8 510
2 nd class roads	2 620
3 rd class roads	680

Figure 1: National Traffic Survey in 2016 (the sample of the output) [3]

2.2 Category and diversion route parameters

An important input value of the model is also the road category through which the motorway traffic flow will be diverted in case of extraordinary road traffic events. From the road category we can also determine the class of traffic load TDZ, the design level of the roadway, C_2 coefficient expressing the trajectory fluctuation and partial coefficient of reliability of the roadway dependence on design level of violation γ_{DI}^* according to [5] as follows:

Table 2: Diversion route coefficients by the road category [1, 5]

Road category	TDZ	Design level of the roadway [-]	C_2 [-]	γ_{DI}^* [-]
Motorways	S	D0	1.00	0.60
1 st class roads	II	D0	1.00	0.60
2 nd class roads	IV	D1	0.70	1.00
3 rd class roads	V	D1	0.70	1.00

The number of lanes is relevant both for determining the coefficient C_1 [-], which indicates the intensity of heavy freight vehicles in the most loaded lane, and for calculating the roadway area S_j [m²]. For one-way roads with normal vehicle composition the coefficient $C_1 = 1.00$, for two-way roads with one lane in one direction $C_1 = 0.50$, with two lanes in one direction $C_1 = 0.45$ and with three or more lanes in one direction $C_1 = 0.40$. The number of lanes counts also with the increase of lanes e.g. in road gradient etc [5]. C_3 coefficient expresses the weight range of the axles of heavy freight vehicles and is determined for normal traffic load such as $C_3 = 0.50$, for unfavorable traffic load with proportion of 20% to 50% of fully loaded heavy freight vehicles such as $C_3 = 0.70$ and for very unfavorable traffic load with predominance of fully loaded heavy freight vehicles such as $C_3 = 1.00$ [4]. In case of a motorway closure due to an extraordinary traffic event, the diverted traffic flow will show an increased proportion of these vehicles, so the input value of the C_3 coefficient is in the model set on 0.70 [1].

2.3 Traffic flow speed and the roadway area

The current speed of the heavy freight vehicle (and hence the entire diverted traffic flow) on the diversion route is de-

ducted from [6–10] for a given section of the route as the minimum speed. Thanks to this minimum speed, it is possible to determine the coefficient C_4 expressing the influence of the speed of heavy freight vehicles. Depending on the current speed in a given section of the route, the coefficient C_4 is equal to 1.00 for the speed higher than 50 km/h and equal to 2.00 for the speed lower than 50 km/h or when stopping vehicles [6–15]. As already mentioned for parameter I_1 in [1, 12], the entire diversion route is divided (segmented) into m homogeneous sections with a similar character of traffic. The sections on the route then represent the input parameters of the analytical model that acquire constant values on a given segment. Each section of the route is then assigned an operational stationing st_j [km], from which man can determine the length of the section l_j [m] as the difference of its values. From the knowledge of the length of the section and the transverse gradient of the road category, the analytical model calculates the roadway area S_j for repair according to the general formula:

$$S_j = l_j \cdot (JP_j \cdot a_j + v + c), \quad j = 1 \dots m$$

where S_j is the roadway area on the j -th section in one direction [m^2], l_j is the length of the j -th section [m], JP_j is the number of lanes on the j -th section in one direction [–], a_j is the lane width on the j -th section of the diversion route [m], v is the width of the guide strip [m], c is the side-way width [m] and m is the number of sections (segments) of the route [–] [1].

The total roadway area [m^2] in one direction for the whole i -th diversion route will then be equal to:

$$S^i = \sum_{j=1}^m S_j^i$$

The input value S_j thus represents the roadway area in [m^2] corresponding to the length of the j -th section (segment) l_j of the given diversion route. This figure is important for the actual calculation of costs spending by the road administrators on its maintenance and reconstruction. It is logical that the larger roadway area is necessary to repair (in the connection with increased intensities of the heavy freight vehicles and the damage of the road structure they cause), the larger funds must be by the road administrators allocated for the reparation [1].

2.4 Cost databases

In order to easier appraise the valuation of transport structures financed predominantly from public sources in terms of anticipated investment expenditures (new structures,

reconstruction and maintenance), investors respectively the road administrators use the so-called "Cost databases for the assessment of road constructions", whose unit prices are updated every year and are presented without a provisional item and without VAT. These databases (norms) indicate for each item of the file its price according to the defined standard per unit. The price of the normative standard is designed for basic types of road repairs and reconstructions in relation to their range. The design period for the road repairs and reconstructions is set by the road administrator [1, 16]. For roadways of roads and motorways, the design period of 25 years is usually chosen by the average traffic flow intensities (current and prospective) and the proportion of heavy freight vehicles corresponding to the given road category [1]. At the end of this period, the roadway construction is raffish and it is necessary to carry out its complete reconstruction. For upper roadway layers, their lifetime is usually chosen according to [5] by the average traffic flow intensities (current and prospective), the proportion of heavy freight vehicles and the assumed roadway construction corresponding to the given road category. For the characteristic upper roadway layers, the sub-design period t_d acquires for the 1st and 2nd class roads on average 12 years, for the 3rd class roads on average 14 years. For the replacement of the upper roadway layer, the value for all types of roads in the price level of the year 2018 is $C_{O,2018} = 720,-$ CZK/ m^2 . For the replacement of the whole roadway construction, the value for all 1st class roads in the price level of the year 2018 is $C_{R,SI,2018} = 2.010,-$ CZK/ m^2 and for all 2nd and 3rd class roads in the price level of the year 2018 is $C_{R,SII+III,2018} = 1.700,-$ CZK/ m^2 (see Table 4 according to [16, 17]).

Because all model input values are variable (they are changing every year according to the market situation, price inflation, manpower, etc.), they must be always updated on the current price level of the year [1].

2.5 Duration of the motorway closure

The last input value for calculating the total costs that will be necessary to spend on maintenance and reshaping these alternative diversion routes into their initial technical conditions is the expected duration of the motorway closure t^* . The duration of the complete motorway closure depends on many factors and takes usually hours, in exceptional cases several days. An important factor is especially the extent of the accident, the time of arrival the information via an emergency call, the accessibility of the accident site for the emergency vehicles and the time for putting the closed section back into operation.

Table 3: Cost databases for the assessment of road constructions in 2018 [16, 17]

OBJECT TYPE – ROAD CATEGORY - RECONSTRUCTION					
unit prices are presented in the price level of the year 2018, without a provisional item and without VAT					
mark	items of the file	UM	Price for the technological minimum	Price according to the defined standard	Price for the technological maximum
1	2	3	4	5	6
A.5.O.R.	Replacement of the upper roadway layer	m ²	432 CZK	720 CZK	1 080 CZK
A.5.K.DS1.R	Replacement of the whole roadway construction – motorways and 1 st class roads	m ²	1 950 CZK	2 010 CZK	2 111 CZK
A.5.K.S2.R	Replacement of the whole roadway construction – 2 nd and 3 rd class roads	m ²	1 649 CZK	1 700 CZK	1 785 CZK
A.5.R.D.R	Extension of the motorway	m ²	1 700 CZK	1 700 CZK	1 700 CZK
A.5.R.S1.R	Extension of the 1 st class road	m ²	1 700 CZK	1 700 CZK	1 700 CZK
A.5.R.S2.R	Extension of the 2 nd and 3 rd class road	m ²	1 700 CZK	1 700 CZK	1 700 CZK

Table 4: Inputs to the application based on the analytical model for the 1st class road no. I/29 [1]

ANALYTICAL MODEL INPUTS – INITIAL MODEL SETTING					
1 st class road no. I/29; operational stationing km 0,373 – km 20,060					
parameter	value	unit	parameter	value	unit
l_{max}	1250	vehicles/h	C_O	720	CZK/m ²
v_{opt}	62.5	km/h	$C_{R,SI}$	2010	CZK/m ²
H_{opt}	20	vehicles/km	$t, t_{d,SI}$	25, 12	year
c_{TN}	190	CZK/ (h*vehicle)	t_0	4	year
c_{TO}	120	CZK/ (h*vehicle)	t^*	8	h
c_{LN}	25	CZK/ (km*vehicle)	RPDI – M	31 070	vehicles/24h
c_{LO}	15	CZK/ (km*vehicle)	RPDI – SI	8 510	vehicles/24h
$l_{TNV,SI}$	31	vehicles/h	RPDI – SII	2 620	vehicles/24h
$l_{O,SI}$	321	vehicles/h	RPDI – SIII	680	vehicles/24h

3 The computational mechanism of the analytic model

The calculation of total costs is based on the so-called modified cost databases reflecting the increased intensity (increased proportion) of heavy freight vehicles from the diverted traffic flow compared to normal road operation. The assumption of the calculation is to linearize the dependence of the lifetime of the roadway construction on the intensity of these vehicles. As a result, cost databases are adjusted against original values which were determined

for the whole design period by the appropriate operation characteristic for the given road class (see subchapter 2.4 of this article). In short - the more heavy freight vehicles are driving through the diversion route for longer duration of the motorway closure, the faster “remaining lifetime” of the roadway will be depleted. This fact will lead to higher investment into road maintenance and reparation in a shorter time. Compared to the design period of 25 years (or the sub-design period of 12 or 14 years), the lifetime of the roadway construction will be shortened, so the road will have to be more often repaired (reconstructed). As a result, the total funding allocated to the road maintenance

and reparation for the whole design period will need to be depleted within a shorter timeframe [1].

According to [5, 17–19], the lifetime of the roadway construction is defined by the total number of design axle crossings per (sub) design period. If the number of heavy freight vehicles increases as a result of diverted motorway traffic, there will be a faster "depletion" of the remaining lifetime of the roadway construction. The "depletion" rate can be determined from simple equations:

- for the replacement of the upper roadway layer

$$N_{rd} \cdot t_d = N_{rd,D} \cdot t_{d,D}$$

- for the replacement of the whole roadway construction

$$N_{rd} \cdot t = N_{rd,D} \cdot t_D$$

where N_{rd} is the number of design axle crossings per average year of the design period for the calculation of the remaining lifetime of the roadway construction [designed vehicle axes/year], $N_{rd,D}$ is the number of design axle crossings of the diverted traffic flow due to motorway closure for the calculation of the real lifetime of the roadway construction [designed vehicle axes/year], t_d is the sub-design period for the expected lifetime of the roadway [year], $t_{d,D}$ is the expected roadway lifetime by higher intensity of heavy freight vehicles [year] and t_D is the expected lifetime of the whole roadway construction by higher intensity of heavy freight vehicles [year] [1, 18].

3.1 Total costs of the road administrator

Based on the calculation of the supposed roadway lifetime $t_{d,D}$ and the whole roadway construction t_D by higher intensities of heavy freight vehicles, we can determine the so-called modified cost databases such as:

$$C_{O,D} = \frac{C_O}{365 \cdot t_{d,D}}, \quad C_{R,S I,D} = \frac{C_{R,S I}}{365 \cdot t_D},$$

$$C_{R,S II+III,D} = \frac{C_{R,S II+III}}{365 \cdot t_D}$$

where $C_{O,D}$ is the modified price value coefficient for the replacement of the upper roadway layer by higher intensity of heavy freight vehicles [CZK/(m²*day)], C_O is the price value coefficient for the replacement of the upper roadway layer by normal intensity of heavy freight vehicles [CZK/m²], $C_{R,S I,D}$ is the modified price value coefficient for the replacement of the whole roadway construction for the motorways and 1st class roads by higher intensity of heavy freight vehicles [CZK/(m²*day)], $C_{R,S I}$ is the price

value coefficient for the replacement of the whole roadway construction for the motorways and 1st class roads by normal intensity of heavy freight vehicles [CZK/m²], $C_{R,S II+III,D}$ is the modified price value coefficient for the replacement of the whole roadway construction for the 2nd and 3rd class roads by higher intensity of heavy freight vehicles [CZK/(m²*day)] and $C_{R,S II+III}$ is the price value coefficient for the replacement of the whole roadway construction for the 2nd and 3rd class roads by normal intensity of heavy freight vehicles [CZK/m²] [1].

Total costs of the road administrator for the i -th route will be determined from the equation:

$$I_2^i = \sum_{j=1}^m I_{2,j}^i = \sum_{j=1}^m \left[\frac{t^*}{24} \cdot S_j^i \cdot (C_{O,D,j}^i + C_{R,D,j}^i) \right], \quad i = 1 \dots n$$

where $I_{2,j}^i$ are costs of the road administrator on the j -th section of the i -th diversion route on the roadway maintenance, reparation and reconstruction [CZK], t^* is the expected duration of the motorway closure [h], S_j^i is the roadway area on the j -th section of the i -th diversion route in one direction [m²], $C_{O,D,j}^i$ is the modified price value coefficient for the replacement of the upper roadway layer on the j -th section of the i -th diversion route by higher intensity of heavy freight vehicles [CZK/(m²*day)], $C_{R,D,j}^i$ is the modified price value coefficient for the replacement of the whole roadway construction on the j -th section of the i -th diversion route by higher intensity of heavy freight vehicles [CZK/(m²*day)] - for the 1st class roads is $C_{R,D} = C_{R,S I,D}$ and for the 2nd and 3rd class roads is $C_{R,D} = C_{R,S II+III,D}$, m is the number of sections (segments) of the i -th diversion route [-] and n is the number of alternative diversion routes to a motorway [-] [1].

3.2 Remaining lifetime of the roadway

In connection with the real lifetime of the roadway construction, the so-called "remaining lifetime" can be determined - the theoretical time period during which the road should still be able to carry the normal traffic load typical for this road category (therefore the load after reopening the motorway and decreasing the intensity of diverted traffic flow). This time period, however, will be lower than the design period for roadway reparations and reconstructions for that road. This real lifetime then can be converted by the so-called modified cost databases for the assessment of road constructions for the given year to the amount of funds that will be necessary to allocate on reparations and reconstructions of that road (or its section), so that the roadway construction will have the same parame-

ters for the given class of traffic load TDZ as at the beginning of the design period [1].

We can determine the remaining lifetime as:

- replacement of the upper roadway layer

$$t_{Z,dD} = t_d - \frac{t_d}{t_{d,D}} \cdot \frac{t^*}{8760} - \frac{t^*}{8760} - t_0$$

- replacement of the whole roadway construction

$$t_{Z,D} = t - \frac{t}{t_D} \cdot \frac{t^*}{8760} - \frac{t^*}{8760} - t_0$$

where $t_{Z,dD}$ is the expected remaining lifetime of the upper roadway layer by the normal intensity of heavy freight vehicles after reopening the motorway [year], t_d is the sub-design period for the expected lifetime of the roadway [year], $t_{d,D}$ is the expected roadway lifetime by higher intensity of heavy freight vehicles [year], $t_{Z,D}$ is the expected remaining lifetime of the whole road construction by the normal intensity of heavy freight vehicles after reopening the motorway [year], t is the design period for roadway reparations and reconstructions [year], t_D is the expected lifetime of the whole roadway construction by higher intensity of heavy freight vehicles [year], t^* is the expected duration of the motorway closure [h] and t_0 is the time period from the last reconstruction of the whole roadway [year] [1].

3.3 Practical applicability of the model – a case study

In order to verify the functionality of this proposed analytical model, in [1] there was created an application that (after entering the input technical parameters of the selected road section) evaluates this section with the so-called impedance - financial equivalent. For the calibration and verification of the calculation mechanism, two real sections of roads were selected in the South Bohemian Region in the Písek district, where measurements and traffic surveys were made in 2016. It was a section of the 1st class road no. I/29 between the towns Písek and Bernartice, and a section of the 2nd class road no. II/159 between the villages Albrechtice nad Vltavou - Týn nad Vltavou. First, each route was passing by a floating measuring vehicle in both directions to determine the approximate driving time between two points on the route. Subsequently, a camera survey with a time axis was carried out from which it was possible to determine both the average driving time of heavy freight vehicles (between these points in the given direction of ride - see in Figure 2) and the intensity of traffic flow. The remaining model input data (number of lanes,

road layout, etc.) for segmentation the road into homogeneous sections were obtained from publicly available map data and internet applications.

Figure 2: Písek – entry to the section of the 1st class road no. I/29 in km 0,373 [1]

As a numerical example, the applicability of the proposed model (the output of the model in the financial equivalent) on the 1st class road no. I/29 is demonstrated in Table 4 and Table 5 below.

According to the output from the application, higher intensities of the diverted traffic flow from motorways will have the impact beside normal operation expressed by the financial equivalent (impedance) totally 50.42 CZK on the 1st class road no. I/29 on the j -th homogenous section with operational stationing km 0,373 – km 0,458.

Unfortunately due to the limited paper range it is not possible to present a comprehensive numerical example but only a sample from [1] to demonstrate the applicability of the model.

4 Discussion

As you can see at first glance, the analytic algorithm for calculating the total costs of the road administrator I_2 uses certain simplifications. Firstly, compared to the premise of this model, not all 1st, 2nd and 3rd class roads have the same construction composition. Furthermore, not all roads are in perfect default condition, so the negative impacts of diverted traffic flow can be shown up significantly on roads at the limit of their lifetime compared to recently reconstructed roads. Last but not least, the financial equivalent for the replacement of the upper roadway layer or the whole roadway construction is based on approved cost

Table 5: The sample of the outputs from the application based on the analytical model for one homogeneous section j of the 1st class road no. I/29 [1]

ANALYTICAL MODEL OUTPUTS – PARAMETER I_2					
1 st class road no. I/29; j -th homogeneous section with operational stationing km 0,373 – km 0,458					
parameter	value	unit	parameter	value	unit
$I_{N,j}$	31	vehicles/h	N_{rd}	226 300	designed vehicle axes/ year
$I_{O,j}$	121	vehicles/h	$N_{rd,D}$	226 300	designed vehicle axes/ year
C_1	0.50	-	t_D	25	year
C_2	1.00	-	$t_{d,D}$	12	year
C_3	0.50	-	$t_{Z,dD}$	8	year
C_4	2.00	-	$t_{Z,D}$	21	year
$\gamma_{DI^*,j}$	0.60	-	$C_{O,D}$	0.1598	CZK/ (m ² *day)
S_j	403.75	m ²	$C_{R,SI,D}$	0.2148	CZK/ (m ² *day)
$I_{2,j}$	50.42	CZK			

databases, but it can't be generalized to all roads of the same class (each road administrator of the given road uses apart from these cost databases its own pricelists). In spite of all these deficiencies, the analytical model also brings into the calculation of total costs I_2 other factors in accordance with [5, 18–21], which have a major effect on the negative impacts of the diverted traffic flow. These externalities are subsequently expressed by the financial equivalent, of which is the road administrator in case of higher intensities (proportion) of heavy freight vehicles more loaded compared to the road management in normal operation.

5 Conclusion

The added value of the proposed analytical model (created application assessing the effect of increased traffic flow intensities on the road administration, maintenance and lifetime) is on one hand the fact, that is prepared (usable) for all Czech road categories and it calculates with all detectable technical parameters. On the other hand, nowadays in the Czech Republic there is no system tool for calculation negative impacts on less significant roads in case of extraordinary traffic situation on motorways expressed by the financial equivalent (impedance). The main problem why there are no existing practices in road management is the fact that the road administrators are in the Czech Republic different. Ministry of Transportation of the Czech Republic is the owner of all motorways and 1st class roads but Regional Authorities are owners of all 2nd and 3rd class

roads. In case of closure and diversion all motorway traffic on less category roads, Regional Authorities will logically demand more funding for their reparations from the Ministry, which is not desirable. But it is not excluded, that in the future there will be the request to propose a system tool for financial compensation between different road owners and the analytical model presented in this paper might have a benefit for further negotiations.

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