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Analysis of Reversible Lane System on the large traffic network

Theses of PhD dissertation

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1. Motivation

One of the main characteristics of the development of the national economy is the constant increase in the public traffic. It is well-known, that the infrastructural circumstances and the limited resources do not permit the necessary increase of the road capacity, that is why different types of traffic anomalies evolve more and more frequently [*Tánczos, Bokor; 2003*].

Nowadays, the congestions increase generally and the number of the accidents within the European Union does not decrease with the desirable extent, either. One of the primary viewpoints of the development of traffic networks is the reduction of congestions. Regarding this the most favoured solution is the more effective use of the existing road network, the homogenization of road traffic, the increase of the number of passengers in a single vehicle and the increase of the use of shared vehicles or public transportation [*Kövesné; 2003*]. One of the principles that enable the realization of the abovementioned aims is the reversible lane system, which requires a simple technique background, and has been used in several states of the United States since as early as the 1920s [*Fisher; 2010*]. In Europe there are initiatives, too, for the application of the reversible lane system [*Wolshon, Lambert; 2006*], [*Fehérkönyv; 2012*].

It is also well-known, that the modelling of the road traffic is a complex technical and economic task [*Kövesné, Debreczeni; 2003*], namely, numerous participants act the part of the operation of the dynamic system. Beyond the traffic rules the human factors have effect on the behaviour of the vehicle traffic, as well. The operation of the system depends on several geometry features and their design, which have an effect on the traffic processes. A variety of external factors play a role, e.g. seasonal effects, weather, etc. Because of this the applicable and efficient macro or micro model has got to take into consideration all conditions that has an actual effect on the operation of the system, and the negligence of which would distort the results. Since in the practice it can be difficult to get hold on satisfying information on several details for the development of a detailed model, one often has to settle for application of incomplete and inaccurate models, the defects of which can be compensated somewhat with adaptive techniques [*Papageorgiou; 1998*], [*Papageorgiou, et al.; 2003*].

For my analyses I applied a special non-linear macroscopic model, which is suitable for the description of the operation of the reversible lane system [*Péter 2008/1*], [*Péter 2008/2*]. My work, taking into consideration the international research results in the field of the road traffic systems, wishes to put into practise and to utilize the results of the domestic intellectual base of the control theory [*Bokor, Gáspár; 2008*], [*Bokor, Palkovics; 1994*], [*Várlaki et. al.; 2008*]. The traffic optimising on the large road network is a beautiful and complex task. In this topic the application of the reversible lanes is an interesting special method, which maximally supports the change of the existing principal directions in the dynamics (time of day, seasonality etc.) of the traffic processes on the available road surface. In that case certain subsystems of the large network cease to function and give place to subsystems operating with new contacts. This control, therefore, modifies the structure of the system in an optimal way, while many practical and safety questions arise naturally. A number of surveys justify that the travel time and the waiting time was decreased by half, the number of stops was reduced by one third on those provinces, where was introduced compared to the original data. In a case when the road infrastructure of a country demands significant development, the application of this opportunity cannot be left out of account.

2. Objectives and research methods

The applicable reversible lanes for every single location should be constructed according to the needs arising from the different environmental and social endowments. My research task is traffic process modelling, namely, application of a special road network system model to investigate reversible lanes. In a wider sense the method of reversible lanes also raises security issues, and requires risk analyses. Before starting such an analysis it is important to review the possible risk factors [*Tarnai, Sághi; 2006*], to study the well-known principles of assessment and to analyse the requirements and assets related to the existing traffic control methods. One of the aims of these tests is to underpin that the new system provides at least as much safety as the currently used system.

The starting point of the system safety analysis can be an accident statistics database. However, because a new system is in the question, higher social expectations can be raised against the security of the system, than what would be necessary to ensure based upon the above analysis. One must take into account the current European transport policy, which aims to reduce the number of accidents, thus instead of calculating with the current data, an expected future value must be considered.

It should be noted that the unique composition of reversible lane system incorporates unique security issues, since in case of malfunction the most severe outcome of accidents is the head-on collision involving two or more vehicles. For this reason – in a system to be implemented – it must by all means be avoided.

The objective of my research was to achieve new scientific results in the field of modelling road traffic processes which are economically important, as well. These results have been obtained through elaborating the following areas:

- Assessment of the currently used reversible lane methods and getting acquainted with the system.
- Analysis of the realization of the above road traffic systems.
- Application of theoretical knowledge in the field of mathematics, modelling and programming.
- Integration of reversible lanes as subsystems into the models describing network systems. Mathematical modelling and analysis of the systems.
- Stochastic simulation of the integration of reversible lanes as subsystems. Exploration and analysis of the possible application of state-dependent control through changing the structure of the above road traffic systems.
- Comparative analysis between the data obtained from the model describing the network systems and the vehicle dynamics parameters. Model refinement based on the above.
- Review of environmental load, joint analysis of the data obtained from the model and measured parameters.

My studies have shown that the examination of the environmental load of a reversible lane should be considered as an important task, as well. To this end, I have created a new traffic emission model, which can be used to study the vehicles and their environmental impact in the given traffic system. Thus, my goal was to develop a method that gives estimate immission values as the output of a model describing a large traffic network.

3. Summary of research findings

We have seen many examples, especially in the United States, that demonstrate that the discussed solution is a well functioning and safe system, in accordance with the objectives of the European Union [*Fehérkönyv; 2012*]. An important element of the current transport policy is the development of information technology and control tools, technologies to improve road safety and security, and the analysis of integrated transport control and information systems and traffic control systems.

1^{st} Thesis

Integration of reversible lanes, as subsystems, into the models describing network systems. The mathematical modelling and analysis of the systems.

Through the improvement of the transport frame-model using general connection hyper matrix [*Péter; 2012*] I set up a new model for the definition of a possible control strategy of reversible traffic flow using differential equation systems, which corresponds with the control of a positive non-linear dynamic system based on the macroscopic model. In addition, for the cases of direction changes on any sub-network I gave the setting algorithm of the elements of the new connection matrix. The applicability of the resulting new control system was analysed by means of a large number of simulations and was found to be suitable to quantify and demonstrate the benefits of introducing reversible sections.

[*Bede, Péter; 2011/1*], [*Bede, Péter; 2011/3*], [*Bede, Péter; 2011/4*], [*Bede, Péter; 2012/1*], [*Bede, Péter; 2012/2*], [*Péter, Bede; 2010*], [*Péter, Fülep, Bede; 2011*]

I studied the modelling of reversible lane traffic system realised on any sub-network of a road network of arbitrary scale [*Peter, Basset; 2009*], [*Péter, Bokor; 2006*], [*Péter, Bokor; 2007*], [*Péter, Bokor; 2010*], [*Péter, Bokor; 2011*]. In case of reversal on any sub-network, functions of certain elements and connections between them cease to exist and new relationships and new functional elements begin to operate instead (**Fig. 1**).

$$K = \begin{bmatrix} k_{1,1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ k_{2,1} & k_{2,2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & k_{3,2} & k_{3,3} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & k_{4,2} & 0 & k_{4,4} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & k_{5,4} & k_{5,5} & 0 & 0 & 0 & 0 & 0 & 0 & k_{5,12} \\ 0 & 0 & 0 & 0 & 0 & k_{6,6} & k_{6,7} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & k_{7,7} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & k_{8,6} & 0 & k_{8,8} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & k_{9,8} & k_{9,9} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & k_{10,8} & 0 & k_{10,10} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & k_{11,10} & k_{11,11} & k_{11,12} \\ k_{12,1} & 0 & 0 & 0 & 0 & k_{12,6} & 0 & 0 & 0 & 0 & 0 & k_{12,12} \end{bmatrix}$$

Fig. 1 $\underline{\underline{\boldsymbol{K}}}(\boldsymbol{x},\boldsymbol{s})$ constructed matrix

The mathematical model leads to the analysis of a positive non-linear dynamic system. The model is essentially a macroscopic model [*Péter; 2009*].

$$\underline{\mathbf{x}}' = \langle \underline{\underline{\mathbf{L}}} \rangle^{-1} \left[\underline{\underline{\mathbf{K}}}(\underline{\mathbf{x}},\underline{\mathbf{s}})\, \underline{\mathbf{x}} + \underline{\underline{\mathbf{K}}}_{input}(\underline{\mathbf{x}},\underline{\mathbf{s}})\, \underline{\mathbf{s}} \right] \tag{1}$$

Where: $\langle \underline{\underline{\mathbf{L}}} \rangle^{-1}$ is the diagonal matrix containing the reciprocals of the internal section lengths, $\underline{\underline{\mathbf{K}}}(\mathbf{x},\mathbf{s})$ is a constructed matrix based on matrices $\underline{\underline{\mathbf{K}}}_{belső}(\mathbf{x},\mathbf{s})$ and $\underline{\underline{\mathbf{K}}}_{output}(\mathbf{x},\mathbf{s})$. Elements of $\underline{\underline{\mathbf{K}}}(\mathbf{x},\mathbf{s})$ and $\underline{\underline{\mathbf{K}}}_{input}(\mathbf{x},\mathbf{s})$ switching matrices are switching functions, that depend on density states. The physical meaning of the elements of the matrix is transfer speed.

The sample model is a non-linear positive system with 12 degrees of freedom and 7 external connections. All elements outside the main diagonal ($i \neq j$) of $\underline{\underline{\mathbf{K}}}(\mathbf{x},\mathbf{s})$ constructed matrix equal to the respective elements of $\underline{\underline{\mathbf{K}}}_{belső}(\mathbf{x})$ inner matrix. Furthermore, an i,j ($i=j$) element in the main diagonal of $\underline{\underline{\mathbf{K}}}(\mathbf{x},\mathbf{s})$ equals the inverse of the sum of the elements in column j of $\underline{\underline{\mathbf{K}}}_{belső}(\mathbf{x})$ ($j=1,2,\ldots,n$) and in column j of $\underline{\underline{\mathbf{K}}}_{output}(\mathbf{x},\mathbf{s})$ ($j=1,2,\ldots,m$).

The nonzero elements of $\underline{\underline{\mathbf{K}}}(x,s)$ constructed matrix are the following:

$$\begin{gathered}
k_{1,1} = -\beta_{2,1}(1-\alpha_{12,1})S(x_2)V(x_2,x_1)E(x_1) - AU_2(t)\alpha_{12,1}S(x_{12})V(x_{12},x_1)E(x_1) \\
k_{2,1} = \beta_{2,1}(1-\alpha_{12,1})S(x_2)V(x_2,x_1)E(x_1) \\
k_{2,2} = -\frac{\beta_{3,2}\alpha_{3,2})S(x_3)V(x_3,x_2)E(x_2)}{1-\alpha_{12,1}} - \beta_{4,2}(1-\frac{\alpha_{3,2}}{1-\alpha_{12,1}})S(x_4)V(x_4,x_2)E(x_2) \\
k_{3,2} = \frac{\beta_{3,2}\alpha_{3,2})S(x_3)V(x_3,x_2)E(x_2)}{1-\alpha_{12,1}} \\
k_{3,3} = -k_{2,3}(t)\beta_{o2,1}S(s_2)V(s_2,x_3)E(x_3) \\
k_{4,2} = \beta_{4,2}(1-\frac{\alpha_{3,2}}{1-\alpha_{12,1}})S(x_4)V(x_4,x_2)E(x_2) \\
k_{4,4} = -S(x_5)V(x_5x_4)E(x_4) \\
k_{5,4} = S(x_5)V(x_5x_4)E(x_4) \\
k_{5,5} = -S(s_3)V(s_3,x_5)E(x_5) \\
k_{5,12} = BU_2(t)\beta_{5,12}\alpha_{5,12}S(x_5)V(x_5,x_{12})E(x_{12}) \\
k_{6,6} = -\beta_{8,6}(1-\alpha_{12,6})S(x_8)V(x_8,x_6)E(x_6) - AU_1(t)\alpha_{12,6}S(x_{12})V(x_{12},x_6)E(x_6) \\
k_{6,7} = \beta_{6,7}S(x_6)V(x_6,x_7)E(x_7) \\
k_{7,7} = -\beta_{6,7}S(x_6)V(x_6,x_7)E(x_7) \\
k_{8,6} = \beta_{8,6}(1-\alpha_{12,6})S(x_8)V(x_8,x_6)E(x_6) \\
k_{8,8} = -\frac{\beta_{9,8}\alpha_{9,8})S(x_9)V(x_9,x_8)E(x_8)}{1-\alpha_{12,6}} - \beta_{10,8}(1-\frac{\alpha_{9,8}}{1-\alpha_{12,6}})S(x_{10})V(x_{10},x_8)E(x_8) \\
k_{9,8} = \frac{\beta_{9,8}\alpha_{9,8})S(x_9)V(x_9,x_8)E(x_8)}{1-\alpha_{12,6}} \\
k_{9,9} = -\beta_{o6,9}S(s_6)V(s_6,x_9)E(x_9) \\
k_{10,8} = \beta_{10,8}(1-\frac{\alpha_{9,8}}{1-\alpha_{12,6}})S(x_{10})V(x_{10},x_8)E(x_8) \\
k_{10,10} = -S(x_{11})V(x_{11}x_{10})E(x_{10}) \\
k_{11,10} = S(x_{11})V(x_{11}x_{10})E(x_{10}) \\
k_{11,11} = -S(s_7)V(s_7,x_{11})E(x_{11}) \\
k_{11,12} = BU_1(t)\beta_{11,12}\alpha_{11,12}S(x_{11})V(x_{11}x_{12})E(x_{12}) \\
k_{12,1} = AU_2(t)\alpha_{12,1}S(x_{12})V(x_{12},x_1)E(x_1) \\
k_{12,6} = AU_1(t)\alpha_{12,6}S(x_{12})V(x_{12},x_6)E(x_6) \\
k_{12,12} = -BU_2(t)\beta_{5,12}\alpha_{5,12}S(x_5)V(x_5,x_{12})E(x_{12}) \\
\qquad - BU_1(t)\beta_{11,12}\alpha_{11,12}S(x_{11})V(x_{11}x_{12})E(x_{12})
\end{gathered} \tag{2}$$

In the course of this process, in order to optimize the network, the traffic flow direction can be changed on different sub-networks independently. This gives opportunity for a new principled control method in the field of optimal control of network processes (e.g. traffic density), which is based on the dynamic structure change of the network graph. In the model, as in reality, the geometry elements in question do not disappear, of course, but form a variable network through their new functions and connections.

It can be concluded that there are two types of connection forms (**Fig. 2**):

- Constant geometrical connection: in this case, the geometrical connection remains the same in the course of all direction changes; the transfer direction may be different.
- Directional connection: in this case the geometrical connection depends on the direction of traffic flow.

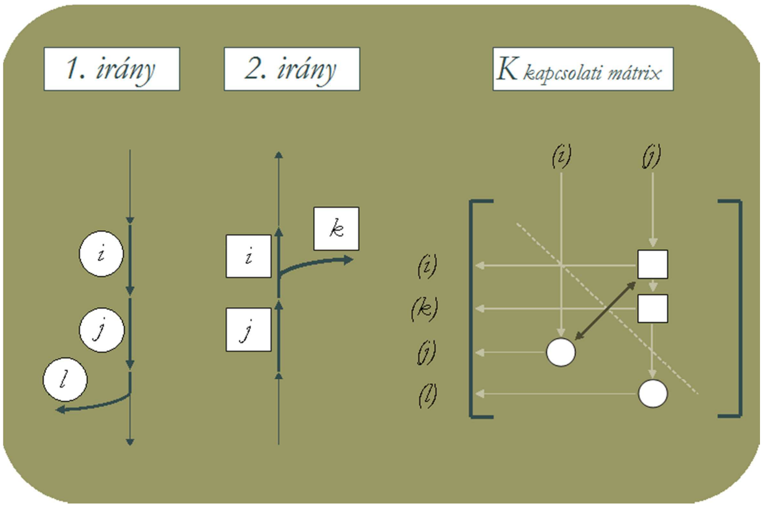

Fig. 2 Two traffic flow directions and the connection matrix

The connection matrix contains a lot of information. In this case, two things must be highlighted: it indicates whether there is a connection between elements *i* and *j*, and if so, the direction of the transfer.

- All connections, which are not affected by the change of direction, remain unchanged in the connection matrix.
- In case of connections, which are affected by the direction change, the connections related to directions *1* and *2* are mutually exclusive.
- In case of permanent geometric connection the connections are mirrored over the main diagonal due to the direction change of the traffic flow.
- In case of connections with a single direction there is no mirroring, these are shown in only one direction.

- Finally, for the sake of safe operation, it is essential that the connection changes in the connection matrix are not performed simultaneously. In a case of a direction the disconnection is performed in two steps. For example, in case of direction 1, at first all input connections are terminated, however, all internal and output connections remain operable as long as the sub-network is not completely empty.

My mathematical model describing the network is a positive non-linear dynamic system; the model is essentially a macroscopic model. The applicability of the new principled optimal control method, which is based on the dynamic structure change of the network graph, was studied on a sample network depending on the traffic density.

2nd Thesis

Analysis and a proposal of implementation of reversible lanes, as subsystems.

A new model for describing and control a traffic system consisting of complex junctions and several traffic lights was constructed with the possibility of implementing reversible lanes. A new specified control method was developed for the solution of the problem of left turning lanes and for the more efficient control of traffic processes. The in this way developed model was successfully applied to the section consisting of 16 traffic lights and 40 junctions on Üllői St between Ecseri St and Kálvin Sq and a proposal was made to change the order of traffic with the introduction of a reversible lane. The simulation of the whole system proved that the proposed model is effective with the present traffic light configuration. It also has been found that the obtained results are consistent with the traffic values obtained based on measurements on reversible lane systems realised in practice and published by other researchers [*PB; 2003*], [*Golub; 2012*].

[*Bede, et. al.; 2010/2*], [*Bede, Péter; 2011/1*], [*Bede, Péter; 2011/2*], [*Bede, Péter; 2011/3*],[*Bede, Péter; 2011/4*], [*Bede, Péter; 2012/1*], [*Bede, Péter; 2012/2*], [*Bede, Péter; 2013*], [*Péter, Bede; 2010*]

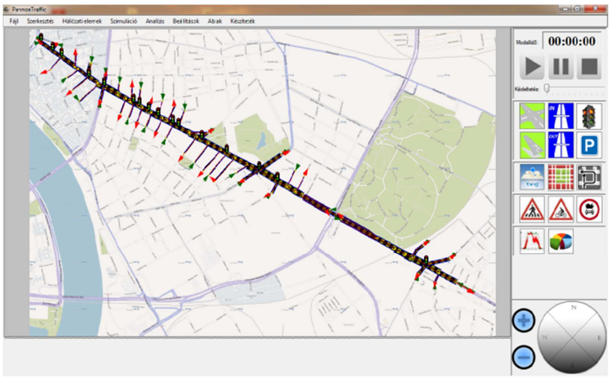

Fig. 3 The construction of the model

The construction of the model is based on a map, as it is shown in **Fig. 3**, hence I gave the length of the sections according to the real scale. First, the simulation was run in accordance with the original state of the network then I reversed the direction of one lane (outbound of downtown) in the morning hours. The results of the two types of simulations are shown in **Figs. 4-5**.

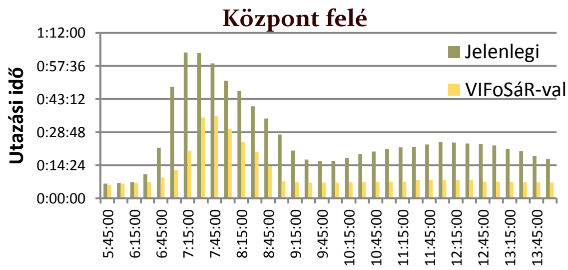

Fig. 4 Average travel times on the downtown bound lanes in different departure times

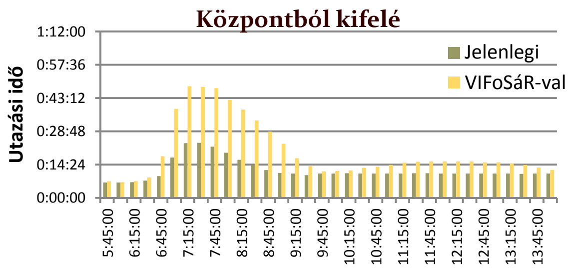

Fig. 5 Average travel times on the outbound lanes in different departure times

The following conclusions can be drawn: if the downtown bound traffic gains an extra lane during the morning peak hours, the access time in most cases will be reduced by more than 60%, by one half on average, while if a lane is taken away from the opposite direction traffic, the increase in travel time will be at most 30%. As the traffic simulation software is suitable for extracting individual processes therefore, hereinafter, it can also be used to search the optimal path, taking into account the individual needs.

3^{rd} *Thesis*

Comparison of data obtained from the model describing the network system with vehicle dynamics parameters, and the validation of the model based on the comparison.

According to the developed traffic system model I demonstrated, based on statistical system identification, that the model validated by on vehicle measurements enables the identification of true individual speed and engine performance data. By means of homogeneity assessment and nonparametric statistical analysis of the concurrently simulated and GPS-measured massive realizations of stochastic time series relating to the network path, I found that the two samples in both cases can be considered homogeneous at a very high level (at least 95%).

[*Bede, Péter; 2009/3*], [*Bede, Péter; 2010/1*], [*Bede, Péter; 2010/2*]

I analysed the velocity and acceleration processes describing the motion of individual vehicles on the large network. The speed profile that takes into account the actual traffic was extracted from the macroscopic network model representing the traffic. With the model I gave the traffic change relating to the entire network. The individual movement process resulting from the model was compared with the actual measured velocity and acceleration processes and engine performance data. I have carried out the validation of the model based on the individual speed and acceleration processes obtained from it.

The measured and simulated velocity distributions were compared by non-parametric statistical analyzes. The calculations satisfactorily confirmed the simulation results of the modelling process. The individual vehicle power requirements were calculated from the speed data, as well, which values are proved also through non-parametric statistical analysis, that from technical point of view the deviation between the values measured in the actual circumstances, calculated using GPS data and calculated by the model is negligible, thus, the power requirement can be calculated from the speed profile.

The non-parametric statistical probe aimed at the analysis of homogeneity. The probe is essentially a χ^2 test for the analysis of the homogeneity of random variables. The question of whether two random variables (the one measured by the GPS device and the other simulated by the traffic model) can be regarded as having the same distribution? Namely, are the two samples from the same multitude? The assumed joint distribution function itself is not in the probe, since it is not known. During the probe we divide the interval containing the two random variables into r parts. In the i^{th} interval ($i=1,2, \dots ,r$), there are ν_i and μ_i parts respectively, where

$\Sigma\nu_i$, $=N$ and $\Sigma\mu_i$ $=M$. It is a homogeneous sample and in case of $N\rightarrow\infty$ and $M\rightarrow\infty$ it follows a χ^2 distribution parameterized with *r-1*.

$$Eqv \coloneqq \chi^2 = NM\left(\sum_{k=1}^{r}\frac{\left(\frac{v_k}{N}-\frac{u_k}{M}\right)^2}{v_k+u_k}\right) \tag{3}$$

4th Thesis

The refinement of the model based on the comparison of the obtained data and the vehicle dynamics parameters.

With the statistical system identification application I demonstrated that in case of acceleration profiles calculated from speed profiles, which are derived from the macroscopic simulation, extremely "unrealistic" acceleration and deceleration values may occur locally, i.e. in the small neighbourhood of a point in time. I performed filtering regarding heuristic statistical criteria and recalculated the speed and acceleration profiles based on the above. I showed that in the speed profiles the difference between the original and the corrected values are insignificant after filtering. It has been stated that statistical filtering is important in the dynamic analysis of individual vehicles moving in the traffic system, however, the filtering effect is negligible in the statistical processes analysed by the macroscopic traffic model. These results may help in the more efficient and reliable modelling of complex traffic processes.

[*Bede, Péter; 2010/1*], [*Bede, Péter; 2010/3*], [*Bede,* Péter; 2011/2]

Therefore, filtering was performed, and according to this I re-calculated the velocity and acceleration profiles. I found that in case of velocity profiles the difference between the original and the corrected values are insignificant after filtering (0.46% for the whole time period; 5.68% deviation for the critical points). In the urban traffic the problem was triggered by the operation of traffic lights and by the discrete simulation method using the Euler method. It can be concluded that the effect of filtering is insignificant in the statistical processes (e.g. speed) analysed by the macroscopic traffic model.

However, for the optimal routes (optimal trajectories) of the individual vehicles derived from the model, the calculated velocity and acceleration profiles must take into account the fact that unrealistic acceleration and deceleration values cannot occur, not even occasionally. Thus the filtering is important in case of switchover to the microscopic models.

The hereby discovered phenomenon pointed out to an interesting new problem in connection with the macroscopic traffic models. The elimination of this phenomenon has resulted in the development of the model, which in this case was realized so that the developed model analyses the acceleration values at all points in time and if any of them is out of range, it limits the peak acceleration and deceleration to the permissible range automatically. Thus the model makes the calculations with the speed function corresponding to these values.

5th Thesis

Analysis of environmental load

> I developed a new method for analyzing the impact of environmental load with speed profile. I pointed out that, unlike calculating with regular traffic cycles, more accurate, truer emission values can be obtained with speed profile derived from the model. With this so-called environmental load method a correlation analysis was carried out aimed at studying the stochastic relationship between the values obtained from the simulation and the actual measured values of the real traffic. On that basis, I have shown that in case of urban traffic tight correlation can be estimated between the consumption both in the measured and the simulated values. There is also a tight correlation between the consumption and the specific stoppage time in case of point to point traffic. These results provide a methodological basis for creating more efficient and more reliable traffic planning procedures.
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> [*Bede, et. al.; 2011*], [*Bede, Trencséni; 2012*]

The key aim of achieving sustainable surface transport is to reduce the emissions harmful substances to the environment, which can be achieved in two ways. On the one hand, by using environmentally conscious methods during the construction of the individual vehicles, on the other hand, by controlling the vehicles by means of appropriate traffic control tools. These two approaches can be analysed in a complex model consisting of the models describing the behaviour of the individual vehicles and determining the operation of the traffic network and of the relationships between them. The aim of the research is to review the factors affecting the consumption of the vehicle and to estimate their significance, as well. The specific consumption rate is always to be interpreted for a period of time, or for the distance travelled in that period. The distance that can be travelled in a given time, and vice versa: the time required to cover a given distance - considering the rules of the road – is limited by the traffic and weather conditions. Thus, the traffic characteristics play a primary role in the present study.

The traffic is described according to the classical definitions fundamentally by three variables, of which the traffic density [*vehicles/km*] and the volume of traffic [*vehicles/h*] can be specified only in view of the number of vehicles. From a traffic participant point of view this information is not available. The third characteristic of the traffic is the average speed [*km/h*], which is defined based on the individual vehicle speeds and the given number of vehicles. However, the speed profile of the analysed vehicle can be given between any two points of the network at any time, as well.

Accordingly, I studied the speed profiles measured in real traffic conditions in a given period of time, and assigned to them the consumption values obtained during the measurement. In addition, the Advisor vehicle model was run on the large-scale traffic network with the speed profiles extracted from the traffic simulation. From the software I obtained the consumption values which were assigned to the speed profiles originating from the simulation. I showed that in case of measured and simulated speed profiles the consumption is affected by both the specific stoppage count and the specific stoppage time, but in urban traffic the consumption is stronger correlated with the specific number of stops in both cases. The speed profiles with early morning and late evening departures, which were measured in sparse traffic, were excluded from the simulation. This is a typical characteristic of the traffic measured outside of residential areas, so the analysed properties of these speed profiles are corresponding with the ones of non-residential areas. I analysed and demonstrated that outside of residential areas the measured and simulated velocity profiles show a tight correlation between the consumption and the specific stoppage time.

4. Application of the results and the future research directions

Special problems arise during the practical implementation of reversible lane traffic systems which originate from the direction change. During the safety analysis of the system the greatest emphasis must be laid on the comprehensive preparation and on the execution of the direction change. Therefore excellent and reliably functioning measuring, evaluation and control tools and information equipments providing clear signals are necessary for the drivers. These characteristics and the conditions of the automatic blocking of the system must be analysed in course of preparing the system design based on the modelling. In the practical implementation it must be ensured, in any case, that the vacation of the lane actually ends before opening it for the opposite direction traffic.

In the applied literature we have met functioning reversible lane traffic systems and case studies conducted in relation to them, so the results of the simulation model can be compared with real data and the rationale of the simulation is justifiable. It follows that the modelling, simulation and measurement techniques presented here are suited for and can be used to perform further planning tasks during the design of reversible lane traffic systems.

The characteristics of individual vehicles, necessary for further investigations, could be obtained from the model describing the transport network. These characteristics could be used for traffic simulation and as input in vehicle models. The linking of the two models offer new opportunities for further researches, thus consumption, noise and various complex environmental load analyses can be performed.

During the environmentally conscious vehicle development manufacturers strive to further reduce vehicle emissions. Nowadays the reduction of harmful emissions, which directly harm nature, is not the only target, but the reduction of greenhouse gases causing climate change, i.e. CO_2 is also essential. In addition to these microscopic emission reduction strategies macroscopic emission reduction is becoming increasingly important as well. An example of such a method is the emission-based optimization of traffic networks, which is a new, effective and complex solution for emission-based traffic control. The urban traffic control has been mostly open-loop control, i.e. the operation of the traffic lights was based on a preset algorithm. Nowadays increasingly more closed-loop traffic control is used, in which the traffic light operation is based on processing the information of detectors placed in different junctions, in order to control the vehicle flow optimally. In case of using a video-based system, in which the categories of passing vehicles can be identified, the control can be carried out on the basis of the emission of the traffic, as well.

The above described high-performance traffic simulation model is required for the planning of control systems of such type, which is also an interesting area for further research in the future.

References of the author associated with the theses

Bede, Péter; 2009/3	Péter T. – Bede Zs.: Egyedi sebességfolyamatok kinyerése, nagyméretű városi úthálózatok modellezése során, *Innováció és fenntartható felszíni közlekedés konferencia (IFFK-2009). Budapest, Magyarország, 2009.09.03-2009.09.05,* 2009
Bede, Péter; 2010/1	Bede Zs. – Péter T.: Nagyméretű közlekedési hálózati modell továbbfejlesztése, *Városi közlekedés*, *L. évfolyam 4. szám 236-238 p.* 2010. augusztus
Bede, Péter; 2010/2	Bede Zs., Péter T.: The extraction of unique velocity processes from a macro model, *Periodica Polytechnica -Transportation engineering 38:(1) pp. 105 - 111,* 2010
Bede, Péter; 2010/3	Bede Zs., Péter T.: Egyedi gyorsulásértékek figyelembe vétele a közúti közlekedési hálózatok makro modellezésénél, *Innováció és fenntartható felszíni közlekedés konferencia (IFFK-2010). Budapest, Magyarország, 2010.09.02-2010.09.04 (ISBN: 978-963-88875-1-1),* 2010
Bede, et. al.; 2010/2	Bede Zs., Péter T. – Stróbl A. – Fazekas S.: A változtatható irányú forgalmi sávok alkalmazása a városi közlekedésirányításban. (Egy hálózati analízis.), *Innováció és fenntartható felszíni közlekedés konferencia (IFFK-2010). Budapest, Magyarország, 2010.09.02-2010.09.04 (ISBN: 978-963-88875-1-1),* 2010
Péter, Bede; 2010	Péter T., Bede Zs.: A változtatható irányú forgalmi sávokkal működő közúti közlekedési rendszer matematikai modellezése, *Közlekedéstudományi Szemle*, LX. évfolyam 3. szám 46-56 p. 2010. június
Bede, et. al.; 2011	Bede Zs., Szabó B., Trencséni B.: Környezetterhelés vizsgálata a forgalmi viszonyok változásának függvényében, *Innováció és fenntartható felszíni közlekedés konferencia (IFFK-2011). Budapest, Magyarország, 2011.08.29-2011.08.31 pp.132-140 Paper 22. (ISBN: 978-963-88875-3-5)* 2011
Bede, Péter; 2011/1	Bede Zs., Péter T.: The mathematical modeling of Reversible Lane System, *Periodica Polytechnica-Transportation engineering 39:(1) pp. 1-6,* 2011
Bede, Péter; 2011/2	Bede Zs., Péter T.: The development of large traffic network model, *Periodica Polytechnica-Transportation engineering 39:(1) pp. 7-14,* 2011
Bede, Péter; 2011/3	Bede Zs., Péter T.: Optimal Control in Reversible Lane System Modelling *9th European Workshop Advenced Control and Diagnosis, Budapest, Hungary, 17-18 November, Paper 61 pp. 1 - 4* 2011

Bede, Péter; 2011/4	Bede Zs., Péter T.: Változtatható irányú forgalmi sáv modellezése, nagyméretű hálózatokon *Innováció és fenntartható felszíni közlekedés konferencia (IFFK-2011). Budapest, Magyarország, 2011.08.29-2011.08.31 pp. 88 – 93, Paper 15. (ISBN: 978-963-88875-3-5)* 2011
Péter, Fülep, Bede; 2011	Péter T., Fülep T., Bede Zs.: The application of a new principled optimal control for the dynamic change of the road network graph structure and the analysis of risk factors, *13th EAEC European Automotive Congress, Valencia, Spain, 13-16 June, Paper E44 pp. 1 - 11* 2011
Bede, Péter; 2012/1	Bede Zs., Péter T.: Egy budapesti modell, a változtatható irányú forgalmi sávok kialakítására, nagyméretű közlekedési hálózatokon *Innováció és fenntartható felszíni közlekedés konferencia (IFFK-2012). Budapest, Magyarország, 2012.08.29-2012.08.31 pp. 91-95, Paper 14. (ISBN: 978-963-88875-3-5)* 2012
Bede, Péter; 2012/2	Bede Zs., Péter T.: The analysis of Reversible Lanes Systems on large road traffic network *Proceedings of the TVL-1 - First Workshop on Transport, Vehicle and Logistics (organized by the PhD Schools of the Faculty of Transportation Engineering and Vehicle Engineering, BME, Budapest, 2012, paper No. KJK2012-1-K3, pp. 1 – 8 (ISBN 978-963-313-062-9),* 2012
Bede, Trencséni; 2012	Bede Zs., Trencséni B.: A közúti járművek károsanyag-kibocsátásának modellezése, *Közlekedéstudományi Szemle LXII. évfolyam 3. szám pp. 17-24* 2012
Bede, Péter; 2013	Bede Zs., Péter T.: Optimal control with the dynamic change of the structure of the road network, *Transport* 2013, megjelenés alatt

Literature referred to in the present summary

Bokor, Gáspár; 2008	Bokor J., Gáspár P.: Irányítástechnika járműdinamikai alkalmazásokkal, *könyv, 288 p.* 2008
Bokor, Palkovics; 1994	Bokor J., Palkovics L.: Modern control theory applied to vehicle dynamics, *VSDIA '94, Proceedings of the 4th mini conference on vehicle system dynamics, identification and anomalies, Budapest, 1994 pp. 74-87,* 1994
Fehérkönyv; 2012	Fehér könyv, Útiterv az egységes európai közlekedési térség megvalósításához – Úton egy versenyképes és erőforrás-hatékony közlekedési rendszer felé, *Brüsszel, 2011.3.28. COM(2011) 144*, 2011
Fisher; 2010	J. E. Fisher: Transportation Topics and Tales: Milestones in Transportation History in Southern California, *Manuscript.* 2010 (http://www.ladot.lacity.org/about_history.htm)
Golub; 2012	Golub, A.: Perceived Costs and Benefits of Reversible Lanes in Phoenix, Arizona, *ITE JOURNAL / february 2012, pp. 38-42,* 2012
Kövesné; 2003	Kövesné G. É: A globalizáció hatása a városi közlekedési rendszer fejlesztésére, *Városi Közlekedés XLII. évf. 2.sz. 2003. április p. 61-66*, 2003
Kövesné, Debreczeni; 2003	Kövesné G. É., Debreczeni G.: Intelligens közúti közlekedési rendszerek és út-jármű rendszerek matematikai modellezése és analízise, *Kutatási jelentés BME Közlekedésüzemi Tanszék. Budapest, 2003. pp 1-49.*, 2003
Papageorgiou, et al.; 2003	Papageorgiou, M., Diakaki, C, Dinopoulou, V., Kotsialos A., and Wang Y.: Review of Road Traffic *Control Strategies Proceedings of The IEEE Vol. 91, No. 12, December* 2003
Papageorgiou; 1998	Papageorgiou, M.: Some Remarks on Macroscopic Traffic Flow Modelling, *Transportation Research A 32(5), pp.323-329*, 1998
Peter, Basset; 2009	T. Peter, M. Basset: Application of new traffic models for determine optimal trajectories, *Sessions 1 Automation and Mechatronics. (1-C-1 Sistem Modelling and Control). Oct.21-Oct.23, INTERNATIONAL FORUM ON STRATEGIC TECHNOLOGIES (IFOST 2009) HoChiMinh City University of Technology, (Vietnam), pp.89-94*, 2009
Péter, Bokor; 2006	Péter T., Bokor J.: Járműforgalmi rendszerek modellezése és irányításának kutatása, *A jövő járműve*, 2006/1–2

Péter, Bokor; 2007	Péter T., Bokor J.: Nagyméretű közúti közlekedési hálózatok nemlineáris modelljének kapcsolati hipermátrixa, *A jövő járműve*, 2007/1–2
Péter, Bokor; 2010	T. Peter, J. Bokor: Modeling road traffic networks for control, *Annual International Conference on Network Technologies & Communications NTC 2010 29 - 30 November 2010, Phuket Beach Resort, (Thailand), pp. 18-22. Paper Code: 21.* 2010
Péter, Bokor; 2011	T. Peter, J. Bokor: New road traffic networks models for control, *GSTF International Journal on Computig, Volume 1, Number 2, pp. 227-232. DOI: 10.5176_2010-2283_1.2.65*, February 2011
Péter; 2008/1	Péter T.: Szoftverfejlesztés a BME –en: Nagyméretű közúti közlekedési hálózatok analízisére és tervezésére. *Budapest, 2008. Magyar Mérnökakadémia: Innováció és Fenntartható Felszíni Közlekedés Konferencia IFFK* 2008
Péter; 2008/2	Péter T.: Tetszőleges méretű nemlineáris közúti közlekedési hálózatok modellezése speciális hálózati gráffal, amelyben a gráf csúcsai általánosított szakaszok, a gráf élei a csúcsok közötti kooperálót leíró dinamikus relációk. A jövő járműve, 2008/3–4, 2008
Péter; 2009	Péter T.: Járműforgalmi rendszerek modellezése és irányítása, célok, kutatási területek és eredmények. *A jövő járműve, IV:(1-2) 59-78* 2009
Péter; 2012	Peter, T.: Modeling nonlinear road traffic networks for junction control, *International Journal of Applied Mathematics and Computer Science (AMCS), 2012, Vol. 22, No. 3. pp. 723-732. DOI: 10.2478/v1006-012-0054-1*, 2012
Tánczos, Bokor; 2003	Tánczos Lné, Bokor Z.: A közlekedés társadalmi költségei és azok általános és közlekedési módtól függő hazai sajátosságai, *Közlekedéstudományi Szemle, 2003/8, p. 281-291*, 2003
Tarnai, Sághi; 2006	Tarnai G., Sághi B.: A biztonsági követelmények kockázati alapú meghatározása *Vezetékek Világa XI. évf. 1 szám 2006 március pp. 3-7* 2006
Várlaki, et al.; 2008	Várlaki P., Nádai L., Bokor J.: Number archetypes and 'background' control theory concerning the fine structure constant, *Acta Polytechica Hungarica vol. no.: 5, Issue no.: 2, pp. 71-104*, 2008
Wolshon, Lambert; 2006	B. Wolshon, L. Lambert: Reversible lane systems: Synthesis of practice, *Journal of Transportation Engineering, vol. 132, pp. 933–944*, December 2006.