Budapest University of Technology and Economics

Kandó Kálmán Doctoral School

Faculty of Transportation Engineering and Vehicle Engineering
Department of Automotive Technology

Modelling of transport management processes applicable to highly automated vehicles with an emphasis on safety and efficiency issues

Theses

Pauer Gábor

Supervisor: **Dr. Török Árpád**

Budapest, 2022

Contents

1 Motivation and novelty of the research topic

The rapid development of vehicle technology implies the change of future transport systems. The decisive trend in this regard is the automatization of the vehicles reducing the need for human interventions.

The advanced driver-assistance systems (ADAS) are already available in cars increasing the autonomy of vehicles by taking over various driving tasks. Examples of such applications are the advanced emergency braking system (AEBS), lane-keeping assist system (LKAS), or adaptive cruise control (ACC). The spread of such systems is driven by increased safety and convenience achieved by them. The developments primarily focus on assisting the most common and risky driving tasks, such as detecting pedestrians and obstacles, avoiding collisions, or identifying the elements of the transport environment (Mallozzi et al., 2019).

Along with introducing various semi-autonomous features, the future of autonomous vehicles (AVs) lies in extensive network-guided systems and vision-guided features (Bimbraw, 2015). The developments aim to reach the level of high or full automation, which means that the vehicle can perform all driving functions under certain, or all conditions, while the driver may choose to drive, command, or control the vehicle.

Such a transport system is expected to have significant benefits in many terms (Becker and Axhausen, 2017; Fagnant and Kockelman, 2015; Tettamanti, Varga and Szalay, 2016; Narayanan et al., 2020; Litman, 2021):

- increased traffic safety,
- more effective traffic flows, increased road capacity, reduced travel times,
- reduced energy consumption and pollution,
- more independent mobility for non-drivers,
- reduced stress and increased productivity while traveling,
- support of vehicle sharing services.

Among the potential drawbacks, the displacement of jobs in the transport and logistics sector, security and privacy-related questions, emerging user risks, high development and vehicle costs, and social equity concerns can be mentioned (Tettamanti, Varga and Szalay, 2016; Yuen et al., 2020).

While the expectations for autonomous transport systems are high, it is difficult to estimate the future trends regarding the development and spread of the technology. Optimist industry stakeholders predict sufficiently reliable and affordable AVs for 2030, while the partial or possibly the total automation of the transport system will only become possible in several decades (Litman, 2021). However, autonomous transport services can become a reality much sooner in delimited, closed environments (e.g., business districts, university campuses, airports) due to the possibility of eliminating many hindering factors such as low-quality roads or traffic signs or unreliable wireless access.

The introduced considerations and the trends in technology highlight the importance and novelty of the topic. The expected change of future transport systems generates several new research areas. In addition to the tasks of vehicle development, it is also necessary to prepare the further elements of the transport system (infrastructure, road users, management, regulation, etc.) for the changes. This includes but is not limited to tasks related to the:

- assessment of the needs and planning of road and information technology (IT) infrastructure of AVs (Domínguez and Sanguino, 2019; Latham and Nattrass, 2019),
- understanding and evaluating of the public acceptance of AVs (Golbabaei et al., 2020; Yuen et al., 2020),
- development of control approaches at the microscopic level (e.g., path tracking, lane-changing processes of individual vehicles) (Amer et al., 2017; Xu, Shi and Ji, 2017),
- elaboration of management processes at the macroscopic level (e.g., control of AVs at intersections, network level optimization of traffic flows) (Zhu and Ukkusuri, 2015; Hult et al., 2016; Horváth, Tettamanti and Varga, 2018; Tettamanti and Varga, 2019),
- evaluation and development of regulatory framework (Hevelke and Nida-Rümelin, 2015; Claybrook and Kildare, 2018),
- investigation of safety, security, and privacy issues (Fagnant and Kockelman, 2015; Cui et al., 2019).

Given the several unknown or uncertain factors regarding the development and spread of autonomous vehicles, the related effects are difficult to estimate. Therefore, it is necessary to develop modelling frameworks to reduce uncertainty and to develop general methods for traffic-related evaluations. During my research, I sought to elaborate such procedures, focusing primarily on simulating highly automated transport systems especially considering traffic safety and efficiency.

2 Research objectives

Based on the potentials regarding the automation of vehicles, my research focuses on an autonomous passenger transport system, in which the decisions made by the vehicles are considered to be influenced by a central system. This provides the opportunity for the implementation of system level traffic management.

To represent the operation of the transport system, I aim to develop a traffic management procedure that ensures the system level minimization of losses (e.g., travel time, accident risk) related to the transport process. In light of the growing expectations for road safety, my further goal is to develop and examine the safety parameters characterizing the operation of the autonomous transport system. In other words, my work aims to model and characterize the efficiency and safety of traffic in an environment used only by AVs.

- The development of the basic models for traffic management

To achieve the research goals, developing a framework suitable for traffic management of the autonomous transport system is needed in the first step. It is necessary to examine the methods that can efficiently solve the traffic distribution problem, even in real-time environment, by managing traffic flows. It is also a fundamental research orientation to examine the possibilities to extend the basic model to consider the effects of external parameters (e.g., road toll structure, safety characteristics) on the travel demands, traffic flows, and efficiency.

- Improvement of the basic model to a dynamic model

Based on the experiences and results related to the basic model, I aim to improve the modelling framework to determine the movements and decisions of the individual vehicles. To achieve this, the discretization of the transport network and timeframe, and the combination of the tools and aims of cooperative vehicle control and real-time traffic management are needed. The developed dynamic model should be able to optimize the transport processes at the network level, while representing the safety and dynamics related constraints on the vehicle level.

- Examining and improving the applicability of the dynamic model

For validation purposes, implementation of the dynamic model in MATLAB and testing on different sample road networks are required. Considering the detailed partition of the road network and timeframe, and the large number of investigated vehicles the model can result in significant computational demands. Accordingly, it is necessary to examine the possible tools of reducing the complexity of the problem, without threatening the feasibility of the solution.

- Establishment of traffic safety investigations in the autonomous transport system

With the above-described dynamic model, I aim to establish the opportunity to investigate the efficiency and traffic safety of the autonomous transport system. Besides the investigation of the optimization objective function, this requires the development of different safety indicators. The indicators should express the safety level of the determined traffic flows based on the individual and relative characteristics of the vehicle movements.

- Investigating the effects of different representations of the transport environment

The representation of the transport environment is a fundamental element of a centralized AV control and management system. The representation structure provides the link between the physical infrastructure and the theoretical model by determining the spatial characteristics of the transport processes. Current systems mainly use a square grid map, although many other representations could also be designed. Accordingly, I aim to create and apply different grid structures and analyze their effects on optimization efficiency and safety characteristics.

2.1 Hypotheses

1. It makes sense to extend the basic, static model implementing transport management and route planning tasks of an autonomous transport system to integrate the effects of external parameters on the static system optimum.
2. The discretization of the transport network and the investigated timeframe can turn the static model into one that dynamically determines the individual vehicles' movements and decisions while managing the transport processes at the network level.
3. By the appropriate reduction of the constraining expressions, the computational complexity of the elaborated transport management process can be reduced, while upholding the feasibility of the solution.
4. The safety of the traffic flows - determined by the developed model - within the autonomous transport system can be characterized based on various approaches.
5. Other representations of the transport network than the traditional square grid structure can achieve better network level efficiency and traffic flow safety in an autonomous transport system.

3 New scientific results

The most promising direction for the evolution of the road transport system is the development and future spread of highly automated vehicles. The expected change of future transport systems generates several new research areas, among which the modelling of the transport management processes and the investigation of safety and efficiency aspects were in the focus of my research. Among several other benefits, autonomous vehicles provide the opportunity to develop an efficient and safe central traffic management system by ensuring the controllability of the transport elements.

In accordance with this -considering a totally autonomous passenger transport system- my aim was to develop traffic management procedures, ensuring the system level minimization of the traffic load on the road network. As the model results, the traffic routes and vehicle trajectories were determined by the central system. Using the developed models and obtained traffic flows, my further goal was to develop and examine parameters that characterize the efficiency and safety parameters of the autonomous transport system.

The main scientific results of my research were the followings.

1. **I have developed basic efficiency-based and improved travel cost-based models for the network level management of traffic flows in the autonomous transport system. I have demonstrated the applicability of the models by solving the traffic distribution problem on three sample road networks of different character. One of the proposed methods (second model) allows for influencing the travelers' decisions by integrating the road toll structure in the model, providing the possibility to investigate the effects of external parameters.**

In the first stage of my research, I aimed to elaborate a modelling framework applicable for determining the static optimum of traffic flows in the autonomous transport system. This was achieved by the elaboration of procedures solving the classic traffic distribution problem. The applied aim of the transport management was the minimization of the total travel time on the considered road network (Eq. (1)), taking into account the sum of products of the traffic volume (x_j) and travel time (t_j) of the network elements, and the parameters regarding the missed/postponed trips between the origin (o_k) and destination (d_l) zones (volume ($X'(o_{k}\_d_l)$) and extremely high travel times ($T'(o_{k}\_d_l)$) to minimize the number of such cases).

$$F_{obj} = \sum_{j=1}^{m} (x_j * t_j) + \sum_{k,l=1}^{q,r} (X'(o_{k}\_d_l) * T'(o_{k}\_d_l)) \rightarrow min \quad (1)$$

During the procedure, the predefined travel demands had to be satisfied also considering the constraining conditions (see Table 1). In my dissertation, two types of static transport system managing models were developed, representing different transport management procedures. These models deal with traffic flows rather than individual vehicles. The objective function of the optimization problem, as well as the constraining conditions describing the models, were elaborated. For the model development, the transport network was represented by undirected graphs. Besides the structure of the road network, some of the data of the traffic distribution problem (capacity and travel time of the edges, alternative routes, travel demands) were involved in the model as predefined, constant values. The main characteristics of the basic models are summarized in Table 1.

Table 1 Characteristics of the basic models

	First model	Second model
Methodological basis:	direct management	cost-based management
Model variables:	traffic volume of the alternative and fictive routes	cost of traveling through the edges, and traffic volume of fictive routes
Aim of the optimization:	to minimize the total travel time on the road network while satisfying the most travel demands	
Constraining conditions:	value of traffic volumes was required to be non-negative and integer	
	–	cost of the edges was required to be non-negative
	predefined travel demands were required to be equal to the sum of traffic volume and missed travels	
	the capacity of the edges (infrastructure elements) was limited	

In the first model, the traffic flows were treated as system variables and were directly managed on the considered road network. Based on this approach, it was possible to organize the traffic demand structure reasonably close to the optimum.

The second model represented a cost-based management process where traffic flows have been influenced by the road toll structure. In this case, the costs of the alternative route sections were the optimized variables. Thus, the decisions of the road users were not completely excluded from this model since their willingness to travel characteristics was considered based on a predefined, cost-dependent function. The system defined the travel prices with the same objective as the first model (minimizing the total travel time on the road network while satisfying the most travel demands).

One of the main contributions of the developed models was the representation of the traffic distribution optimization problem. I have implemented the models in the MATLAB environment and demonstrated their applicability in numerical examples. The optimization was performed on three different sample networks using both models. The obtained distributions of the traffic flows were plotted on Sankey diagrams (see Figure 1 as an example).

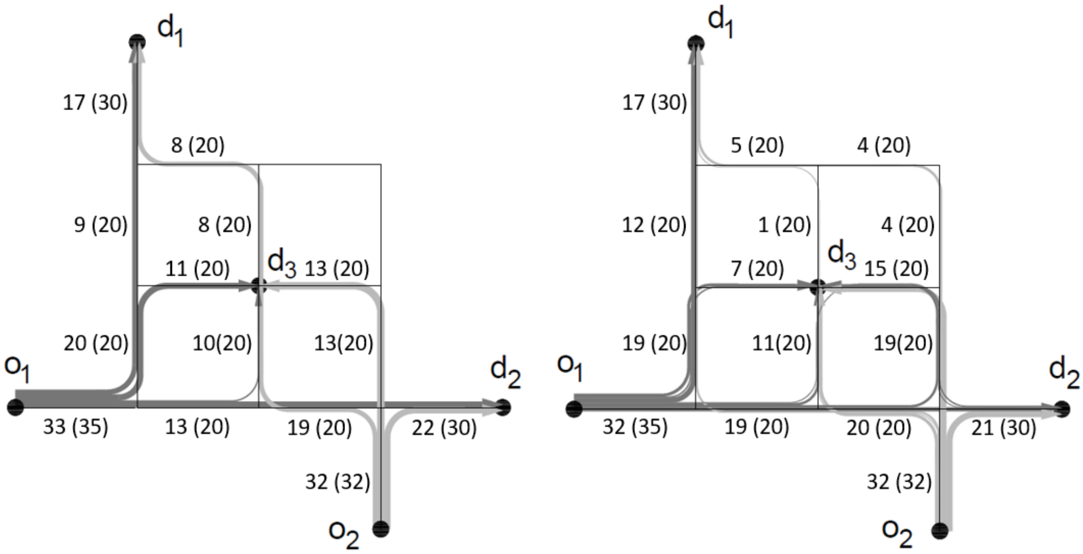

Figure 1 Resulting traffic flows of the third investigated network (left: first model, right: second model; capacity of the edges are indicated in brackets)

The cost-based second model provided equivalent or somewhat less effective results compared to the first model depending on the travel demand and road network structures. However, as a novel result, the proposed method of the second model allowed for influencing the travelers' decisions by integrating the road toll structure, providing the possibility to investigate the effects of external parameters on traffic management.

Publications related to Thesis I: (Pauer, 2017b; Török and Pauer, 2018; Pauer and Török, 2019a; Pauer and Török, 2019b; Pauer and Török, 2019c)

2. **I have developed a binary integer model that implements network level optimization of traffic flows through the vehicle level management of transport processes in the autonomous transport system. In the model, the considered timeframe and road network were discretized. The applied decision variable described the position of the individual vehicles in the discretized time domain with a binary integer value set. The model defined and integrated conditions necessary for the safe flow of traffic (limitation of speed, acceleration, deceleration, avoidance of collisions). I developed methods that significantly reduced the computational complexity of the model by excluding unnecessary or redundant constraining expressions without compromising the reliability of the results. I have demonstrated the applicability and efficiency of the reduced complexity model by solving numerical examples.**

For more detailed traffic management of the considered autonomous transport system, the basic models were modified and improved. With the discretization of the investigated time and space domains, I have developed an advanced macro-level dynamic traffic management model, which is also applicable for the management of the transport processes at the micro-level. For this purpose, a 3-dimensional decision variable ($x_{k,j,i}$) was applied describing the locations (i) of the vehicles (k) in the investigated time instants (j) with a binary integer value set.

Similar to the basic models, the aim of the advanced binary integer model was the minimization of the load of the road network while satisfying the most travel demands, taking into account the defined constraints. To achieve this, the objective function was designed to minimize the sum of the distances between the current and the destination location of the considered vehicles within the investigated time frame (Eq. (2)).

$$y_1 = f_1\left(x_{k,j,i} * c1^{(k)} * \boldsymbol{C3}\right) \rightarrow min \quad (2)$$

In the generalized form of the objective function, the vector defining the destination location of the vehicles ($c1^{(k)}$) and the matrix defining the shortest distances between the location pairs (**$\boldsymbol{C3}$**) were represented. The function aims to ensure that the vehicles reach their destination in the shortest possible time.

In the case of the elaborated advanced model, the network level traffic management was achieved through the management of individual vehicles. For the unambiguous assignment of the elementary parts of the transport network and the vehicles, I used the cell-based representation where the investigated road sections have been partitioned into directed cells (locations) of equal shape (see Figure 2).

The novel concept of dealing with individual vehicles rather than traffic flows allowed for more complex traffic management and investigation of transport-related processes, safety, and efficiency aspects. The position of the vehicles was accurately determined and managed by the model at each time moment, ensuring the respect of the defined constraints in accordance with the occupancy grid concept (Elfes, 1989).

As the constraining conditions of the model, the following considerations were applied.

- The feasibility of the results were ensured by the unambiguous assignment of the locations and the vehicles:
    - the origin locations have been assigned to the vehicles,
    - only one vehicle could be in a given location at a given time moment (excluding the origin and destination locations),
    - a vehicle could only be in one location at a given time moment.
- Traffic safety aspects were implemented by the avoidance of collisions:
    - crossing vehicle movements were prohibited in each time step of the model.
- Parameters related to vehicle dynamics were taken into account:
    - the speed, and
    - the acceleration/deceleration of the vehicles were limited at the network level.

In my dissertation, the generalized representation of the model was elaborated, and its applicability was demonstrated in two small numerical examples. As the main limitation of the concept, it has been identified that the discretization of the time and space domains and the high number of vehicles encountered in real-world applications may significantly increase the number of model variables. This could result in increasing computational complexity and processing time. To alleviate this problem, I have developed new methods to reduce the complexity of the presented transport management process.

For the above-described purpose, I have identified the reduction of the number of constraining expressions as the best possible solution. By excluding the unnecessary or redundant cases from the investigation, the number of equalities and inequalities describing the constraints of the model could be reduced without compromising the feasibility of the results or decreasing the efficiency of the traffic management process.

The base principle of the developed simplification methods was the exclusion of different possible values of the variable from the investigation in the case of the constraints representing the applied speed, acceleration, and deceleration limits. Furthermore, based on the specific characteristics of the predefined origin and destination locations (e.g., vehicles could not enter any origin or leave any destination location during their travel), their examination was also omitted for some of the constraining expressions. Highlighting an example: during the development of the model, the constraint ensuring the compliance with speed limit was investigated considering all possible values of the variable as follows in Eq. (3).

$$f_4\left(x_{k,j,i}, x_{k,j+1,q}\right) * c3_{i,q} \leq c4;\ for\ each\ k, j, i, q \tag{3}$$

where $c3_{i,q}$ represented the distance between location i and q traveled in time moments j and $(j+1)$, and $c4$ represented the constant value of the maximum allowed speed.

However, according to the concept of the relevant simplification method, it has been identified that the investigated cases can be reduced by constraining only those cases when the predefined shortest distance between the investigated locations (defined in $\boldsymbol{C3}$) was higher than the value of the maximum allowed speed. Accordingly, the investigated cases defined by the condition of Eq. (3) should be complemented by the following condition of Eq. (4). Thus, instead of investigating all possible location pairs, the considered cases could be reduced to:

$$for\ each\ k, j, i, q;\ if\ c3_{i,q} > c4 \tag{4}$$

When I implemented the elaborated considerations, it was crucial not to compromise the feasibility of the solution. Since these methods were intended to modify the model, system safety procedures were applied to mitigate the potential safety risks associated with them. Hence, I have put a particular emphasis on functional safety during the development process, and have identified the potential hazards arising from inappropriate changes in the model. As an example, $hazard_4$ represented the risk of omitting the speed limit, affecting the system's safety level (the severity of accidents depends on speed) and the reliability of the route planning (the forbidden routes were represented by a closely infinite distance).

The effects of the introduced methods were investigated through numerical examples. The results implied a significant reduction (above 90% by the combined use of the methods) in the number of investigated constraining expressions without compromising the reliability of the model results (Table 2). Thus, the applicability of the model was greatly improved by the developed methods by increasing the number of manageable variables and decreasing the runtime.

Table 2 The extent of reduction achieved by the simplification methods (example)

	Reduction in the number of investigated expressions
$method_1$	80.6%
$method_2$	62.0%
$method_3$	2.3%
$method_1$ & $method_2$	93.4%
$method_1$ & $method_3$	80.9%
$method_2$ & $method_3$	63.8%
$method_1$ & $method_2$ & $method_3$	93.6%

The improved applicability of the advanced model was demonstrated in a realistic scenario, modelling a road junction with 32 locations as illustrated in Figure 2 (20 vehicles were investigated for 8 seconds). The total number of equations and inequalities of the optimization task was around 16,000-29,000 depending on the applied travel demand structure, resulting in a runtime of 10-88 seconds (using the following hardware: Intel(R) Core(TM) i7-2620M CPU (2,70GHz), 4GB RAM).

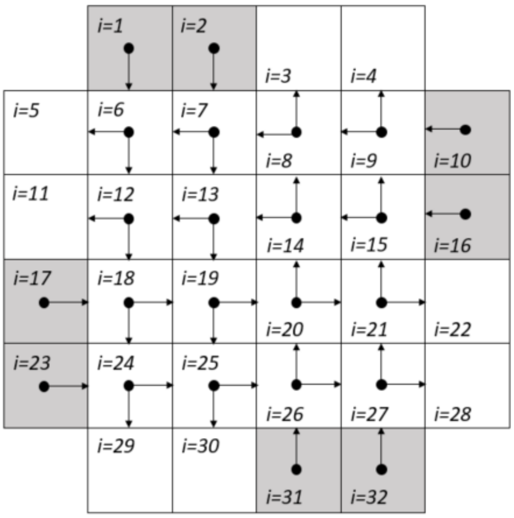

Figure 2 Structure of the road network in the realistic scenario

Based on the results of the optimization, the junction was emptied in 8 seconds in the case of demand structure I (assuming two vehicles turning right and one going straight ahead in the outer lane, and two vehicles intending to turn left from the inner lane at all four branches of the junction). The resulting routes per vehicle are summarized in the columns of Table 3.

Table 3 Results of the optimization process in the realistic scenario (demand structure I)

k	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Orig.	1	1	1	2	2	10	10	10	16	16	17	17	23	23	23	31	31	32	32	32
Dest.	29	5	5	22	22	5	4	4	30	30	3	3	28	29	29	11	11	4	28	28
$j = 1$	1	1	1	2	2	10	10	10	16	16	17	17	23	23	23	31	31	32	32	32
$j = 2$	1	1	5	2	13	10	4	10	16	14	17	17	25	23	23	31	31	21	32	32
$j = 3$	6	1	5	2	21	10	4	10	16	13	17	17	25	23	29	26	31	9	32	28
$j = 4$	18	5	-	7	22	9	-	10	15	25	17	17	26	29	-	13	31	4	28	-
$j = 5$	29	-	-	20	-	6	-	4	14	30	18	17	28	-	-	11	26	-	-	-
$j = 6$	-	-	-	22	-	5	-	-	13	-	19	17	-	-	-	-	14	-	-	-
$j = 7$	-	-	-	-	-	-	-	-	25	-	8	18	-	-	-	-	12	-	-	-
$j = 8$	-	-	-	-	-	-	-	-	30	-	3	14	-	-	-	-	11	-	-	-

By the simplification of the travel demand structure (replacing one of the left-turning movements with a straightforward movement at all branches of the junction – demand structure II), the junction was emptied by the process in 6 seconds (see Table 4).

Table 4 Results of the optimization process in the realistic scenario (demand structure II)

k	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Orig.	1	1	1	2	2	10	10	10	16	16	17	17	23	23	23	31	31	32	32	32
Dest.	29	5	5	30	22	5	4	4	11	30	22	3	28	29	29	3	11	4	28	28
$j = 1$	1	1	1	2	2	10	10	10	16	16	17	17	23	23	23	31	31	32	32	32
$j = 2$	12	1	1	13	2	8	10	10	14	16	19	17	25	23	23	20	31	21	32	32
$j = 3$	18	1	5	19	7	8	4	10	12	16	21	17	25	23	29	14	26	15	28	32
$j = 4$	29	5	-	30	13	7	-	10	11	14	22	19	26	23	-	3	20	4	-	28
$j = 5$	-	-	-	-	19	5	-	4	-	13	-	20	28	29	-	-	14	-	-	-
$j = 6$	-	-	-	-	22	-	-	-	-	30	-	3	-	-	-	-	11	-	-	-

The results implied the implementation of an outstandingly efficient traffic management procedure considering the capacity of the junction. Based on the obtained values, the number of vehicles able to pass through the intersection in an hour was estimated at 9,000-12,000 (depending on the ratio of vehicles going left, straight, and right). According to the study of Barna and Schuchmann (2017), the maximum capacity of a traffic light-controlled junction with a similar structure is around 4,400-5,200 vehicles/hour.

Publications related to Thesis II: (Török and Pauer, 2018; Pauer and Török, 2021; Pauer and Török, 2022)

3. **I have defined indicators applicable for the safety assessment of traffic in the investigated highly automated transport system. The elaborated safety indicators examined different types of risks, considering the spatial and temporal characteristics of the vehicle movements and the speed characteristics of the vehicles in the network. I have demonstrated the applicability of the safety indicators by presenting a numerical example.**

Focusing on the safety aspects of traffic flows in the autonomous transport system, I have defined indicators characterizing the level of road safety in the case of the obtained results determined by the elaborated binary integer model. The different indicators examined different types of risks.

The presented formulas considered the spatial and temporal characteristics of the travel processes and the speed data of the vehicles by the following safety indicators:

- CM: the indicator expressed the risks arising from crossing vehicle movements, calculating the number and temporal distance of these maneuvers, as follows in Eq. (5).

$$CM = \sum_{\substack{k,h,j,u,i,q,r,s=1 \\ k \neq h \\ u \neq j}}^{m,m,(t-1),(t-1),o,o,o,o} c7_{i-q,r-s} * (x_{k,j,i} * x_{k,j+1,q} * x_{h,u,r} * x_{h,u+1,s}) * \frac{1}{(u-j)^2} \quad (5)$$

where $c7_{i-q,r-s}$ was 1, if the shortest path between locations i and q, and the shortest path between locations r and s contained any common locations (excluding the starting location of the routes), otherwise 0. Thus, the product of the first two factors in the summation has identified with a value of 1, if any two vehicles (k and h) traveled routes ($i - q$ and $r - s$) that intersect, at any time steps ($j, (j + 1)$ and $u, (u + 1)$) during the investigated time interval. The third multiplication factor was formed based on the temporal distance of the starting time moments of the crossing movements.

- CF: the indicator represented the risks arising from close following vehicle maneuvers by summing those cases when any of the vehicles arrived at a location that was left by another vehicle at the same time step.
- $\overline{VN}$: the indicator implied the level of safety by the average speed at the network level, calculated as the mean of the speed data of all vehicles in the consecutive time steps over the investigated time interval.

- σ_{VV}: the indicator characterized the level of safety based on the inhomogeneity of speed values at the vehicle level, interpreted as the mean of the empirical standard deviation of the individual vehicle speeds in the consecutive time steps.
- σ_{VN}: by this indicator, the inhomogeneity of speed values was also examined at the network level, as the empirical standard deviation of the speed data of all vehicles in the consecutive time steps over the entire examined time interval.

In all cases, the lower value of the indicator implied a safer flow of traffic. This was due to the lower number or higher temporal distance of crossing or close following vehicle movements (CM, CF), the lower or more similar speed data of the different vehicles ($\overline{VN}$, σ_{VN}), or the more even individual vehicle speeds with fewer accelerations and decelerations (σ_{VV}).

Based on the applied considerations, the road safety level of any transport system can be assessed, compared, and ranked. I presented the functionality through a numerical example by comparing two feasible solutions ($FS1, FS2$) of an optimization task performed on the previously presented network (Figure 2). Based on the results (summarized in Table 5), $FS2$ proved to be a more favorable solution also in terms of safety and efficiency (y_1 denotes the value of the objective function).

Table 5 Values of the safety indicators in the case of the compared solutions

	$FS1$	$FS2$	Difference ($FS2/FS1$)
y_1 [m]	1130	1125	-0,4%
CM	49.056	48.444	-1.2%
CF	12	10	-16.7%
$\overline{VN}$ [m/s]	8.333	8.696	+4.4%
σ_{VV}	1.963	1.861	-5.2%
σ_{VN}	2.985	2.935	-1.7%

Publications related to Thesis III: (Török and Pauer, 2016; Pauer, 2017a; Török, Pauer and Berta, 2017b; Török and Pauer, 2017; Pauer, Sipos and Török, 2019; Pauer and Török, 2022)

4. **I have demonstrated that the application of different grid structures for road network representation has an effect on the efficiency and safety of the traffic flows resulting from the developed traffic management model. I have investigated and quantified the effects through a numerical example representing an intersection. Based on this experimentation, I have pointed out that with the use of grid structures based on different polygons (e.g., hexagons, triangles), better traffic management results can be achieved both in terms of efficiency and safety, compared to the traditionally used square grid structure.**

In the case of the developed binary integer traffic management model, the road network was represented by a square grid in accordance with the occupancy grid concept. The applied grid structure provided the link between the physical infrastructure and the theoretical model; however, the previous research orientations were not primarily aimed at examining the effects of different representation methods.

As a novel contribution, I have investigated the effects of applying different grid structures to further analyze the efficiency and safety aspects of traffic management in the autonomous transport system. For this purpose, I have constructed road networks (R) of a similar area, created based on different polygons (Figure 3). The size of the polygons was determined by assuming an inscribed circle of the same radius.

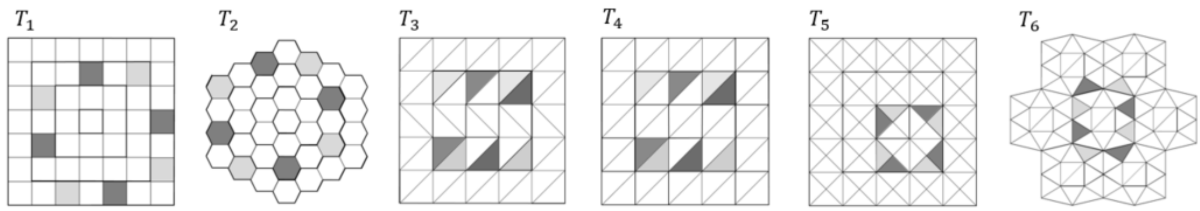

Figure 3 Schematic illustration of the applied grid structures
(dark grey cells: origin locations, light grey cells: destination locations)

With the help of the developed binary integer modelling framework, the efficiency of the optimization was assessed in the different scenarios based on the value of the objective function and the traveled distance ($Dist$) of the vehicles. In addition, the safety characteristics of the results were determined based on the previously introduced indicators (Table 6).

Table 6 Comparison of the results related to the different road network structures

	R^{T_1}	R^{T_2}	R^{T_3}	R^{T_4}	R^{T_5}	R^{T_6}
$Area$ [m^2]	600	585	655	655	583	624
y_1 [m]	1005	475	1346	945	865	1061
$Dist$ [m]	320	245	273	270	260	282
CM	40.813	26.083	25.702	31.846	35.444	29.557
CF	10	5	12	12	14	13
$\overline{VN}$ [m/s]	9.143	7.903	6.825	6.740	8.125	6.868
σ_{VV}	2.456	2.109	1.961	1.663	2.798	1.758
σ_{VN}	3.270	2.985	2.538	2.397	2.997	2.453

My results indicated that the application of different grid structures for road network representation could significantly influence the results of traffic optimization. I have revealed unfavorable values in terms of efficiency and safety parameters in the case of the traditionally used square grid structure, compared to many of the other investigated representation methods.

The use of hexagons as the base polygon of grid generation proved to be the most efficient solution, as it was presumed based on the highest number of connections between the elements of the network. In this case, the safety indicators related to the crossing and close following vehicle movements were also favorable; however, the high efficiency resulted in a relatively high average speed at the network level. It must also be noted that the high number of connections between the locations might result in an increase in computational complexity.

The triangle-based grid structures could be characterized by lower complexity compared to the square grids (each location had only three neighboring locations). However, several presented structures provided results of similar or slightly better efficiency and more favorable safety characteristics compared to the obtained traffic flows of the square grid representation.

Publications related to Thesis IV: (Török, Pauer and Berta, 2017a; Török, Berta and Pauer, 2018; Pauer and Török, 2021; Pauer and Török, 2022)

4 Application and scope for future works

The developed basic models were applicable to manage the traffic flows in the autonomous transport system, aiming to minimize the networks' traffic load. The novel contribution of the second model focused on influencing the travel processes during traffic optimization by integrating external parameters in the model. Using the elaborated concept, considering other external factors (e.g., traffic safety, pollution) as external costs becomes feasible in the traffic management process. In my dissertation, I managed to express the "willingness to travel" with a simplified, linear cost-dependent traffic volume function. However, the data-based, more accurate definition of this correlation (either for individuals or groups of travelers) is also an important task for realistic modelling. Validation of the model would be supported by the application to an extensive urban road network.

Using the above-described results, I elaborated an advanced traffic management model that represents transport processes at the vehicle level while implementing a network level traffic optimization process. The advanced model provided the possibility for a more complex traffic management and more detailed analysis of the safety and efficiency of the traffic flows. The conditions necessary for safe traffic were also considered. By refining the applied assumptions, the model can be improved so that it describes more precisely the operation of the autonomous transport system. This can include the distinction of the different traffic maneuvers (e.g., turning), the consideration of different technical parameters of the vehicles, or the interpretation of initial speed and acceleration at the origins.

To reduce the computational complexity and enhance the applicability of the model, I have developed simplification methods. As it was presented through numerical examples, the elaborated concept enables efficient and safe traffic management. The model thus provides a basis for the central management of vehicles in autonomous transport systems, taking into account the network level optimum. Based on the appropriate representation of the transport network, the model can be used to manage the traffic processes of small, closed systems (e.g., private vehicle fleets of university campuses) or infrastructure elements (e.g., road sections, junctions). At the same time, by connecting such subsystems, the traffic management of larger territorial units is also possible using the developed concept. The efficiency and applicability of the model can be further increased by implementing the time-consuming computations within a more advanced software and hardware environment optimized for solving linear equation and inequality systems and optimization tasks. My future work will focus on further reducing the complexity of the model based on different approaches. For example, heuristics can be applied to decrease the number of cases to be considered (e.g., designing and delimiting the number of alternative routes between the origin and destination zones).

Considering the investigated autonomous transport system, I have defined methodological approaches applicable for the characterization of the safety level of the implemented traffic processes. Using the presented indicators, the different results of the traffic management scenarios can be evaluated from the safety point of view. The different indicators refer to different types of risks. The results provide the opportunity for future works to examine, compare and rank the safety characteristics of the autonomous transport systems. By the use of the elaborated approaches, traffic management related to different network types, traffic or travel demand structures, optimization objectives, etc., can be assessed. In the model, identical technical parameters (e.g., braking characteristics) of the vehicles were assumed, which was necessary for the safe implementation of the defined traffic processes. However, ensuring that various technical parameters and conditions of the vehicles can be taken into account is an important task for future research. To this end, the data provided by the vehicles to the central system about themselves is essential.

As a novel contribution, I examined the effects of representing the transport network using different grid structures to further assess the efficiency and safety aspects of traffic management in the autonomous transport system. My findings indicated that the application of different grid structures for road network representation could significantly influence the efficiency and safety aspects of traffic optimization. In the course of the research, the network structures were determined intuitively. However, the obtained results suggest that the optimization of the grid structure representing the network will be an important development orientation in the future. An essential direction for further research could be to increase the resolution of the network representation structure, as this will allow low-speed operations such as pedestrian-vehicle interaction to be handled. This would also solve the problem of covering real infrastructure elements with any grid structure in a more flexible way. In addition to the above, it should be mentioned that the current 2D method can be flexibly extended to a 3D environment, which can, for instance, help to solve problems related to autonomous systems such as control of complex UAV (Unmanned Aerial Vehicle) systems.

List of related own publications

Pauer, G. (2017a). Development Potentials and Strategic Objectives of Intelligent Transport Systems Improving Road Safety. Transport and Telecommunication, 18(1), 15-24. https://doi.org/10.1515/ttj-2017-0002

Pauer, G. (2017b). Defining the Optimization Process of Traffic Distribution Problem with Linear Programming Approach in case of Autonomous Transportation System. MOSATT 2017 Modern Safety Technologies in Transportation: Proceedings of the International Scientific Conference, Herlány, Slovakia. pp. 124-130. ISBN 978-80-553-2864-5

Pauer, G., Sipos, T., & Török, Á. (2019). Statistical Analysis of the Effects of Disruptive Factors of Driving in Simulated Environment. Transport, 34(1), 1-8. https://doi.org/10.3846/transport.2019.6724

Pauer, G., & Török, Á. (2019a). Forgalom optimalizáció különböző felépítésű hálózatokon autonóm közlekedési rendszerben [Traffic optimization on networks of different structures in an autonomous transport system]. IX. Közlekedéstudományi Konferencia, Győr, Hungary, 2019.03.21-2019.03.22.

Pauer, G., & Török, Á. (2019b). Static System Optimum of Linear Traffic Distribution Problem Assuming an Intelligent and Autonomous Transportation System. Periodica Polytechnica Transportation Engineering, 47(1), 64-67. https://doi.org/10.3311/PPtr.11548

Pauer, G., & Török, Á. (2019c). Comparing System Optimum Based and User Decision Based Traffic Models in an Autonomous Transport System. Promet - Traffic & Transportation, 31(5), 581-589. https://doi.org/10.7307/ptt.v31i5.3151

Pauer, G., & Török, Á. (2021). Binary integer modeling of the traffic flow optimization problem, in the case of an autonomous transportation system. Operations Research Letters, 49(1), 136-143. https://doi.org/10.1016/j.orl.2020.12.004

Pauer, G., & Török, Á. (2022). Introducing a novel safety assessment method through the example of a reduced complexity binary integer autonomous transport model. Reliability Engineering & System Safety, 217, 108062. https://doi.org/10.1016/j.ress.2021.108062

Török, Á., Berta, T., & Pauer, G. (2018). A hazai infrastruktúra információs szempontból kritikus szakaszainak azonosítása statisztikai vizsgálatok alapján [Identification of information-critical sections of the domestic infrastructure based on statistical studies]. VIII. Közlekedéstudományi Konferencia, Győr, Hungary, 2018.03.22-2018.03.23.

Török, Á., Pauer, G., & Berta, T. (2017a). Identification of Critical Infrastructure Sections Related to the Role of Information System. MOSATT 2017 Modern Safety Technologies in Transportation: Proceedings of the International Scientific Conference, Herlány, Slovakia. pp. 184-190. ISBN 978-80-553-2864-5

Török, Á., Pauer, G., & Berta, T. (2017b). Analysing The Impact of Road Information System on Traffic Safety. Procedia Engineering, 187, 712–721. https://doi.org/10.1016/j.proeng.2017.04.445

Török, Á., & Pauer, G. (2016). Intelligens közlekedési rendszerek közlekedésbiztonsági rangsorolása [Road safety ranking of Intelligent Transport Systems]. Statisztikai Szemle, 94(4), 418-434. https://doi.org/10.20311/stat2016.04.hu0418

Török, Á., & Pauer, G. (2017). Assessment of the Current Status of Intelligent Transport Systems Serving the Improvement of Road Safety in Hungary. Periodica Polytechnica Transportation Engineering, 45(2), 77-83. https://doi.org/10.3311/pptr.9279

Török, Á., & Pauer, G. (2018). Optimization of Linear Traffic Distribution Problem in terms of the Road Toll Structure Assuming an Autonomous Transportation System. International Journal for Traffic and Transport Engineering, 8(1), 112-124. https://doi.org/10.7708/ijtte.2018.8(1).08

Bibliography

Amer, N. H., Zamzuri, H., Hudha, K., & Kadir, Z. A. (2017). Modelling and Control Strategies in Path Tracking Control for Autonomous Ground Vehicles: A Review of State of the Art and Challenges. Journal of Intelligent & Robotic Systems, 86(2), 225–254. https://doi.org/10.1007/s10846-016-0442-0

Barna, S., & Schuchmann, G. (2017). Szintbeni közúti csomópontok teljesítőképessége – Jelzőlámpával irányított körforgalmú csomópontok alkalmazhatósága [The performance of road level junctions – The applicability of roundabout nodes with traffic lights]. Közlekedéstudományi Szemle, 67(6), 30–37. https://doi.org/10.24228/ktsz.2017.6.3

Becker, F., & Axhausen, K. W. (2017). Literature review on surveys investigating the acceptance of automated vehicles. Transportation, 44(6), 1293–1306. https://doi.org/10.1007/s11116-017-9808-9

Bimbraw, K. (2015). Autonomous Cars: Past, Present and Future - A Review of the Developments in the Last Century, the Present Scenario and the Expected Future of Autonomous Vehicle Technology. Proceedings of the 12th International Conference on Informatics in Control, Automation and Robotics, Colmar, France. pp. 191-198. https://doi.org/10.5220/0005540501910198

Claybrook, J., & Kildare, S. (2018). Autonomous vehicles: No driver. . .no regulation? Science, 361(6397), 36–37. https://doi.org/10.1126/science.aau2715

Cui, J., Liew, L. S., Sabaliauskaite, G., & Zhou, F. (2019). A review on safety failures, security attacks, and available countermeasures for autonomous vehicles. Ad Hoc Networks, 90, 101823. https://doi.org/10.1016/j.adhoc.2018.12.006

Domínguez, J. M. L., & Sanguino, T. J. M. (2019). Review on V2X, I2X, and P2X Communications and Their Applications: A Comprehensive Analysis over Time. Sensors, 19(12), 2756. https://doi.org/10.3390/s19122756

Elfes, A. (1989). Using occupancy grids for mobile robot perception and navigation. Computer, 22(6), 46–57. https://doi.org/10.1109/2.30720

Fagnant, D. J., & Kockelman, K. (2015). Preparing a nation for autonomous vehicles: opportunities, barriers and policy recommendations. Transportation Research Part A: Policy and Practice, 77, 167–181. https://doi.org/10.1016/j.tra.2015.04.003

Golbabaei, F., Yigitcanlar, T., Paz, A., & Bunker, J. (2020). Individual Predictors of Autonomous Vehicle Public Acceptance and Intention to Use: A Systematic Review of the Literature. Journal of Open Innovation: Technology, Market, and Complexity, 6(4), 106. https://doi.org/10.3390/joitmc6040106

Hevelke, A., & Nida-Rümelin, J. (2015). Responsibility for Crashes of Autonomous Vehicles: An Ethical Analysis. Science and Engineering Ethics, 21(3), 619–630. https://doi.org/10.1007/s11948-014-9565-5

Horváth, M. T., Tettamanti, T., & Varga, I. (2018). Az autonóm járműforgalom modellezhetősége mikroszkopikus forgalomszimulációs szoftverben [Modelling of autonomous vehicle traffic in a microscopic traffic simulation software]. Közlekedéstudományi Szemle, 68(2), 34-44. https://doi.org/10.24228/KTSZ.2018.2.3

Hult, R., Campos, G. R., Steinmetz, E., Hammarstrand, L., Falcone, P., & Wymeersch, H. (2016). Coordination of Cooperative Autonomous Vehicles: Toward safer and more efficient road transportation. IEEE Signal Processing Magazine, 33(6), 74–84. https://doi.org/10.1109/msp.2016.2602005

Latham, A., & Nattrass, M. (2019). Autonomous vehicles, car-dominated environments, and cycling: Using an ethnography of infrastructure to reflect on the prospects of a new transportation technology. Journal of Transport Geography, 81, 102539. https://doi.org/10.1016/j.jtrangeo.2019.102539

Litman, T. (2021, August 16). Autonomous Vehicle Implementation Predictions - Implications for Transport Planning. Victoria Transport Policy Institute. https://www.vtpi.org/avip.pdf

Mallozzi, P., Pelliccione, P., Knauss, A., Berger, C., & Mohammadiha, N. (2019). Autonomous Vehicles: State of the Art, Future Trends, and Challenges. Automotive Systems and Software Engineering, 347–367. https://doi.org/10.1007/978-3-030-12157-0_16

Narayanan, S., Chaniotakis, E., & Antoniou, C. (2020). Shared autonomous vehicle services: A comprehensive review. Transportation Research Part C: Emerging Technologies, 111, 255–293. https://doi.org/10.1016/j.trc.2019.12.008

Tettamanti, T., & Varga, I. (2019). Az autonóm járművek forgalmi hatásai: a jármű-és forgalomirányítás kihívásai [The effect of autonomous vehicles: new challenges of vehicle and traffic control]. Közlekedéstudományi Szemle, 69(1), 35-41. https://doi.org/10.24228/KTSZ.2019.1.4

Tettamanti, T., Varga, I., & Szalay, Z. (2016). Impacts of autonomous cars from a traffic engineering perspective. Periodica Polytechnica Transportation Engineering, 44(4), 244-250. https://doi.org/10.3311/PPtr.9464

Xu, D., Shi, Y., & Ji, Z. (2017). Model-Free Adaptive Discrete-Time Integral Sliding-Mode-Constrained-Control for Autonomous 4WMV Parking Systems. IEEE Transactions on Industrial Electronics, 65(1), 834–843. https://doi.org/10.1109/tie.2017.2739680

Yuen, K. F., Wong, Y. D., Ma, F., & Wang, X. (2020). The determinants of public acceptance of autonomous vehicles: An innovation diffusion perspective. Journal of Cleaner Production, 270, 121904. https://doi.org/10.1016/j.jclepro.2020.121904

Zhu, F., & Ukkusuri, S. V. (2015). A linear programming formulation for autonomous intersection control within a dynamic traffic assignment and connected vehicle environment. Transportation Research Part C: Emerging Technologies, 55, 363–378. https://doi.org/10.1016/j.trc.2015.01.006