Reliability Engineering and System Safety 217 (2022) 108062

Contents lists available at ScienceDirect

Reliability Engineering and System Safety

journal homepage: www.elsevier.com/locate/ress

Introducing a novel safety assessment method through the example of a reduced complexity binary integer autonomous transport model

Gábor Pauer [*], Árpád Török

Department of Automotive Technologies, Faculty of Transportation Engineering and Vehicle Engineering, Budapest University of Technology and Economics, Műegyetem rkp. 3, Budapest 1111, Hungary

A R T I C L E I N F O

Keywords:
Autonomous transport
Cooperative traffic management
Optimization
Computational demand
Safety evaluation

A B S T R A C T

Our previous work focused on the creation of a binary integer model framework aiming at network level traffic optimization through the control of individual vehicles. High computational demand arising from time and space discretization has been identified as the main limitation of the concept. To deal with this, new methods are presented in this paper in order to reduce the complexity of the optimization process with a particular emphasis on system safety. In the first step the most relevant hazards of the system were identified and they were used as the basics of the further development process. The effects are quantified implying a significantly reduced computational demand, without threatening the feasibility of the results. Considering the fundamental requirement of ensuring safe traffic, novel methods are introduced to determine the safety level of the results provided by our model and the described hazard types. The safety indicators defined here cover factors related to the crossing movements, the average speed and average change in speed of vehicles, investigating them also at the network level. The presented methods have significant potential related to the design of real-time, safety-focused, and effective transport management processes of connected and automated mobility systems.

1. Introduction and related work

The authors' research focuses on the optimization of the transport process of an autonomous transport system through the modeling of cooperative vehicle control. In our previous article, a novel framework was published which makes it possible to map the transport processes of cooperative, connected and automated mobility (CCAM) systems [49]. To solve the traffic flow optimization problem, a binary integer model was created providing a high level of traffic safety in accordance with the occupancy grid concept [17], excluding the possibility of more than one vehicle being at the same spatial location at the same time. However, with time and space discretization and the number of vehicles encountered in real world applications, the number of binary variables may increase beyond all tractability. Therefore, the aim of this article is to present new methods to reduce the complexity of the optimization process, with a particular emphasis on system safety during the development process.

Previous studies have already shown that introducing system-level safety indicators can efficiently contribute to preventing accidents. Accordingly, in the framework of this article, we have developed safety indicators that provide an opportunity to assess the safety of the real-time operating highly automated transport systems [36,37,54].

To present the contribution of the paper from a system engineering point of view, we need to briefly review the state-of-the-art safety assessment methods related to vehicular systems. The industrial standards, ISO 26262 [29] and SOTIF (Safety of Intended Functionalities, ISO/PAS 21448 [30]), summarize the safety methods applied by the automotive sector during the development process [35,40]. ISO 26262 focuses on functional safety, assuming that vehicular systems' reliability and safety can be efficiently estimated based on the reliability characteristics of the components. However, the increasing level of automation of the automotive systems made it necessary to involve other factors affecting system safety beyond the internal components of vehicular systems as it is described in SOTIF. Besides this, due to the increasing complexity of transport processes, systems are expected to cooperate more intensively in the future than ever before [16,66]. These trends resulted in the appearance of the system-of-systems concept, reflecting the safety and reliability issues derived from the complex interaction of future transport systems.

In the case of the human driven vehicular systems, decisions are made by the driver. In autonomous transport, the decision and the execution related processes are controlled and implemented by the

* Corresponding author.
E-mail address: pgabor90@gmail.com (G. Pauer).

https://doi.org/10.1016/j.ress.2021.108062
Received 31 May 2021; Received in revised form 8 September 2021; Accepted 8 September 2021
Available online 20 September 2021

system. Accordingly, the reliability of autonomous transport is seriously affected by the reliability of the control process, which primarily depends on the relevant external conditions (such as traffic situation, lightning conditions, etc.). Following this, to estimate the reliability of autonomous systems, we have to perform an almost infinite number of tests, which in some cases can be substituted by simulation methods [59]. Our research study aims to investigate the hazards related to the cooperative processes of interacting highly automated vehicles.

Today, more and more security-critical processes are supported by highly automated or fully autonomous systems. Accordingly, it is reasonable to investigate the results achieved in other fields in the domain of autonomous spatial control of vehicle movements. Several cutting-edge methods have been developed in maritime transport to test the reliability of safety-critical navigation systems. These results were considered during the development phase of our research [13]. Thieme and Utne have developed a complex indicator system to support vehicle navigation that will improve future maritime safety [60]. On the other hand, many strong contributions were performed in the field of maritime transportation related to system engineering theory [3].

During the design phase of such complex systems, the classical deductive (top-down) [53,56] or inductive (bottom-up) approaches [42] related to the hazard identification tasks can be a rather time-consuming process [59]. Following this, in the case of highly automated, connected, and cooperative transport systems, it is reasonable to complement hazard identification methods with models focusing on analyzing historical datasets describing critical events related to the operation of the investigated systems [25,58]. In accordance with this, in order to derive the most relevant risk factors related to transport systems, we used the outcomes of the traffic accident analysis [55] and previously performed research studies related to the safety of highly automated systems [21, 28]. Accordingly, based on the reviewed studies, the most relevant safety-related factors can be identified as follows:

- Operation safety/reliability-continuous operation process [25].
- Basic safety requirement of the bijection between vehicles and spatial locations [21,28].
- Vehicle speed, acceleration and deceleration [15,25,55].
- Crossing movements [22,25].

Of course, the list still can be further detailed and extended with other relevant factors, such as different vehicle dynamic factors, like roll, pitch, yaw, etc. However, the limitations of the current study do not allow us to extend the involved factors further.

Before describing the modeling framework and the proposed methodological developments, a systematic literature review is also presented related to the traffic control modeling domain. It is a fundamental fact that the increasing volume of automated vehicles creates the possibility of controlling the transport processes more efficiently, and triggers the research work in this field [11]. The real-life traffic distribution currently depends on the decisions of the road users, but novel information and navigation systems providing dynamic data can affect drivers' behavior and choices [7,63]. Beyond that, the spread of autonomous vehicles (AVs) provides the possibility to considerably reduce random decisions influenced by external parameters (*e.g.*, congestions [19] or travel costs [23]). Besides the driving aspects of vehicles, automation also covers other fields, such as service planning, passenger-handling functions and vehicle control [18]. These processes facilitate the more efficient traffic management through controllable system components. Current studies aim to develop methodologies for this purpose.

Research in this field focuses on the control of autonomous transport at the level of individual vehicles, and on the dynamic traffic assignment at higher levels as well. Related to microscopic control approaches, parts of the transport processes of AVs are aimed to be optimized in most studies. As an example, path tracking, lane-keeping, lane-changing control processes, or parking methods can be mentioned. The former studies focus on vehicle control in lateral and longitudinal direction in order to follow a specified trajectory or lane [2,20,61], dealing also with the overtaking maneuvers consisting of two lane changes [45]. The latter approach includes control schemes utilizing the body and steering angles of vehicles [65], as well as the elaboration of optimal parking facilities for the autonomous vehicles [47]. As highlighted by Cuer et al. [12] and Sahin and Soylu [52], it is fundamental to embed qualitative and quantitative concerns ensuring also the safety of processes by redundant sub-functions.

Traffic assignment covers the macroscopic level, where the coordination process can be described as an optimal control problem [27]. In this respect, vehicle trajectories are to be controlled in an optimal way considering a part of or the whole road network, while safety and feasibility constraints have to be met. Numerous studies aimed at the development of optimal cooperative control actions of AVs at intersections [10,39,64]. The study of Zhu and Ukkusuri [69] wished to achieve system optimum based dynamic traffic assignment through the control process. Lane occupancy was used as the variable of the optimization in their study, and the total travel time was minimized by the optimal assignment of traffic volumes on the network elements.

Similarly, our previous research aimed to link the control tasks of AVs and network level traffic optimization through the binary integer modeling of cooperative vehicle control, but taking into account also individual vehicle dynamics [49]. To provide the possibility of continuous control and adjustment of the system outputs during operation, in this study the system variable was based on the position of the vehicles, and the time-space was discretized. The road network was partitioned into sufficiently small locations based on the occupancy grid concept, since one of the most important objectives of a reliable CCAM system is to significantly improve safety [46] by ensuring the prohibition of conflicting movements. Among other concepts, occupancy grid models fit this essential safety requirement. Accordingly, they can provide a reasonably robust methodological base for autonomous traffic flow management approaches.

Based on the study of Mutz et al. [44], grid maps are regarded as the cell-based representation of the environment. Their spatial model consists of equally sized plane shapes, and accordingly, the spatial unit is represented by congruent squares. Numerous grid map types can be identified, such as the occupancy grid map, the remission grid map and the likelihood-field grid map. In the case of occupancy grid maps, each spatial unit of the model includes the occupancy probability related to the given unit square [44].

The model developed by Alonso et al. [1] calculates whether the ego vehicle crosses the trajectory of another vehicle in the intersection, and applying the precedence rules to each vehicle, it also calculates whether other vehicles cross the trajectory of the ego vehicle. Although, other research studies aim to identify the occupancy states of an intersection in time and space by using environment perception systems, the objective of the referred research was to organize traffic in accordance with traffic regulations based on the information exchanged through V2X communication channels [1]. Cheng et al. [9] propose a cooperative framework as well for supporting autonomous driving maneuvers based on the data circulated through the V2X communication channels. The authors propose to utilize the potential of inter-vehicle communication solutions in a more efficient way to provide the necessary conditions for autonomous driving. The introduced hierarchical information fusion framework for cooperative sensing ensures a lower probability level of critical traffic situations caused by unsafe vehicle movements [9].

Dinh Van and his research group aimed to develop the hierarchical control system of an autonomous vehicle. The proposed method consists of the decision making module, local path planning process and the related control tasks. The decision making module is operated to identify the proper path for the vehicle. Besides this, an occupancy grid map based A* algorithm was applied to identify a safe and effective path to avoid objects [14].Similarly to our concept, time was discretized into time steps in the study focusing on the development of a multiclass cell transmission model based on the classical hydrodynamic theory [38]. With this approach, the penetration scenarios of autonomous transport system was modeled. Links were discretized into cells such that in the case of free flow speed, vehicles travel at exactly the distance of one cell per time step. Cell occupancy was defined to estimate the number of vehicles that can fit in a cell and the maximum flow related to the given cell

Beyond the cooperative vehicle control related applications, the occupancy grid concept can also be efficiently used in the case of single autonomous vehicle control systems. After the segmentation process, all classes should be clustered into different objects by the detection algorithm. Pendleton and colleagues found [50] that many recently developed state-of-the-art solutions aim to identify the occupancy grid based on the detected point clusters [41,43].

Based on the reviewed literature, it can be concluded that occupancy grid based cooperative and connected transport systems can significantly contribute to the improvement of road safety. However, it must be kept in mind that the more detailed the time and space discretization of the applied model is, the more complex the system model will be. On the one hand, this results in more accurate and efficient final results, but on the other hand, the increasing model resolution can directly lead to increasing processing time. In line with the above considerations, it is reasonable to apply system safety procedures during the identified development steps to mitigate the risks associated with the simplifications introduced, leading to an unsafe state [6].

Accordingly, the aim of this paper is to present new proposals to reduce processing time regarding the developed occupancy grid model by significantly decreasing the number of constraints, taking into account the results of the performed risk assessment procedure. Section 2 introduces the applied methodology by describing the modeling framework, the risk assessment process and the model simplification concept. In Section 3, we demonstrate the results of the developed approach and the proposed framework of safety indicators. The final conclusions are summarized in Section 4.

2. Methodology

2.1. Modeling framework

Linking dynamic traffic assignment and the control of autonomous vehicles, our previous research focused on the network-level optimization of traffic demand management through the binary integer modeling of cooperative vehicle control. The optimization process aimed to satisfy the emerging travel demands while minimizing the traffic load of the road network and assuring traffic safety (avoiding collisions, taking into account speed, acceleration and deceleration limits, etc.). Using the occupancy grid concept, time-space was discretized and the road network was partitioned into directed locations based on the size of passenger vehicles.

Accordingly, the binary decision variable of the model ($x_{k,j,i}$) was 3-dimensional, representing if vehicle k is at location i at time step j (value 1) or not (value 0). The total number of considered vehicles, model time steps and locations were noted by m, t and o respectively. The constant data related to the network (orientation of locations, shortest distance between each location pair, origin and destination of vehicles) and traffic (maximum allowed speed, acceleration and deceleration) were assumed to be predefined.

The generalized representation of the previously published detailed model framework is elaborated in this article as follows.

In accordance with the aim of the optimization, the objective function summing up the distances between the current and the destination location of the vehicles within the investigated time frame is to be minimized. The function f_1 identifies the connection between the variable and the objective of the given problem.

$$y_1 = f_1\left(x_{k,j,i} * c1^{(k)} * C3\right) \rightarrow min \tag{1}$$

where

y_1: is the objective function depending on $x_{i,j,k}$,

$x_{k,j,i}$: is the variable identifying the location (i) of the kth vehicle in the time step j,

$C1 \in R^{mxo}$: is a constant binary matrix identifying the destination location (with element value of 1) of each vehicle, where $c1^{(k)}$ indicates the row vector of the matrix related to the k-th vehicle,

$C3 \in R^{o\times o}$: is a constant matrix identifying the shortest distance of all possible location pairs, where $c3_{i,q}$ indicates its element designed by the i-th row and q-th column (*i.e.*, the shortest distance between location i and q).

The constraining conditions of the control process are as follows.

The first constraining equation system is responsible for the identification of the origin locations of the vehicles:

$$x_{k,j,i} = c2_{k,i};\ \forall k, i;\ if\ j = 1 \tag{2}$$

where

$C2 \in R^{mxo}$: is a constant binary matrix determining the origin location (with element value of 1) of each vehicle, where $c2_{k,i}$ indicates its element designed by the kth row and ith column.

The second constraining expression is an inequality system based on f_2. It ensures that only one vehicle can be in a given location at a given time step excluding the origins and destinations ($c1_i$ and $c2_i$ represents the ith row of the previously introduced C_1 and C_2 matrices, respectively:

$$f_2\left(x_{k,j,i}\right) * (1 - c1_i - c2_i) \leq 1;\ \forall j, i \tag{3}$$

The next equality system based on f_3 ensures that a vehicle can only be in one location at a given time step:

$$f_3\left(x_{k,j,i}\right) = 1;\ \forall k, j \tag{4}$$

The fourth expression represented by f_4 deals with the issue of velocity by constraining the distance that can be traveled by a vehicle during a model time step:

$$f_4\left(x_{k,j,i}, x_{k,j+1,q}\right) * c3_{i,q} \leq c4;\ \forall k, j, i, q \tag{5}$$

$x_{k,j+1,q}$: is the variable identifying the location (q) of the kth vehicle in the time step $(j+1)$,

$c4$: is a constant value identifying the speed limit of the model.

The next inequality systems described by f_5 and f_6 constrain the acceleration and deceleration of the vehicles based on the same basis, comparing the traveled distances at two consecutive model time steps:

$$f_5\left(x_{k,j,i}, x_{k,j+1,q}, x_{k,j+2,r}\right) * \left(c3_{q,r} - c3_{i,q}\right) \leq c5;\ \forall k, j, i, q, r \tag{6}$$

$$f_6\left(x_{k,j,i}, x_{k,j+1,q}, x_{k,j+2,r}\right) * \left(c3_{i,q} - c3_{q,r}\right) \leq c6;\ \forall k, j, i, q, r \tag{7}$$

$x_{k,j+2,r}$: is the variable identifying the location (r) of the kth vehicle in the time step $(j+2)$,

$c5$: is a constant value identifying the acceleration limit of the model,

$c6$: is a constant value identifying the deceleration limit of the model.

To consider the acceleration limit by constraining the travelable distance also at the first model time step (when it is not possible to compare to the previous time step), additional inequalities are determined based on f_7:

$$f_7\left(x_{k,j,i}, x_{k,j+1,q}\right) * c3_{i,q} \leq c5;\ \forall\ k, i, q;\ if\ j = 1 \tag{8}$$

The last inequality system based on (f_8) prohibits the crossing movements. Accordingly, it is not allowed to assign the origin and destination location pairs (*i.e.*, four locations) of two crossing routes in a time step for any vehicle pair. Therefore, only three of this kind of location can be used by the vehicles in a time step to avoid collision.

$$f_8\left(x_{k,j,i}, x_{k,j+1,q}, x_{p,j,r}, x_{p,j+1,s}\right) * c7_{i-q,r-s} \leq 3;\ \forall k, p, j, i, q, r, s \tag{9}$$

$x_{p,j,r}$: is the variable identifying the location (r) of the pth vehicle in the time step j,

$x_{p,j+1,s}$: is the variable identifying the location (s) of the pth vehicle in time step ($j+1$), and

$C7 \in R^{o^2 \times o^2}$: is a constant binary matrix, whose elements get the value of 1 if any common location exists (excluding the starting locations) on the shortest paths between all possible route pairs (routes are marked based on their starting and ending locations).

The constructed binary integer model consists of the model variable, initial data, the objective function and the constraining conditions together.

2.2. Risk assessment

To analyze the potential risks [48] related to the planned simplifications, we investigate the expected system operation deviation modes according to the HAZOP methodology [34,51]. This method is a powerful tool in analyzing system reliability [26] and automotive systems [6], and can be effectively applied to road traffic related measures to investigate predicted deviations and problems with new technologies and processes [31]. During the analysis, we systematically evaluate from equation-to-equation if there can be expected critical deviations or not. If yes, what can be the causes of the problem? What kind of consequences can have the analyzed problem? And we also would like to clarify, whether the problems have an impact on safety or they rather influence operation efficiency. To answer these questions, we also need to understand that simplifications, in our case, directly reduce the number of constraining equations and inequalities. This approach can effectively reduce the complexity of the problem by ignoring unnecessary equations and inequalities. However, omitting constraints that were not unnecessary can lead to unsafe system states. The hazards [57] have been identified as follows:

- $Hazard_1$: The first constraint (Eq. (2)) is responsible for the identification of the origin location of the vehicles. By omitting an active constraint, vehicles entering the system may get stuck at their starting point. In this case, the given vehicle is ignored by the system, so it is not involved in any transport process. This problem can result in a significant reduction of operation safety.
- $Hazard_2$: The next inequality (Eq. (3)) does not allow more vehicles to be located in the same location at a given time step. This condition is especially safety-critical, as the violation of it directly results in collision.
- $Hazard_3$: The following constraint (Eq. (4)) ensures that a vehicle can be assigned to only one location at a given time step. This condition is essential for the operation of the binary model, the omission of which endangers the system's operability.
- $Hazard_4$: Eq. (5) represents the speed limit used in the system. If this constraint is omitted, the system is expected to assign the highest vehicle speeds. This indirectly affects the system's safety level, as the severity of accidents primarily depends on speed. Beyond this, ignoring this inequality also affects the route planning, as the forbidden routes are represented by a closely infinite distance value. Traveling in a prohibited direction can lead to dangerous situations.
- $Hazard_5$: The dynamics of vehicle motion are also influenced by the Eqs. (6)–(8)., by constraining the acceleration and deceleration. Extreme accelerations and decelerations can affect rather adversely the passenger safety characteristics.
- $Hazard_6$: The last constraining condition (Eq. (9)) concerns the prohibition of crossing movements. Similarly to Eq. (3)., this inequality is rather safety-critical, as its violation can also lead to collision.

2.3. Model simplification

The number of investigated vehicles, the time discretization as well as the detailed partitioning of the road network increase the complexity and computational demands of the control process significantly, influencing the efficiency and applicability of the developed method. Based on the structure of the introduced equalities and inequalities, it was concluded that the number of locations has an outstandingly significant impact on the computational complexity of the given problem.

One solution to reduce the number of variables would be merging the neighboring locations, but it would lead to a less efficient traffic control process due to the larger occupied space by the vehicles. Similarly, the extension of the length of the unit time steps of the model would result in less variables, but also in a less efficient control process.

However, the reduction of the number of constraints provide a better possibility to improve tractability by reducing the computational complexity of the optimization process, without threatening the feasibility of it. Therefore, the aim of our research was to elaborate methods for this purpose, especially considering the introduced hazards ($Hazard_1$, $Hazard_2$, $Hazard_3$, $Hazard_4$, $Hazard_5$) to maintain safety integrity.

2.3.1. The effect of the predefined speed limit ($method_1$)

The applied speed limit is considered based on Eq. (5) by constraining the traveled distance during a model time step. Therefore, the constraint should be introduced only in cases where the predefined distance (defined in $C3$) is higher than the value of the maximum allowed speed ($c4$). Accordingly, instead of investigating all possible location pairs, Eq. (5) needs to be taken into account only in the following cases:

$$\forall k, j,\ c3_{i,q} > c4 \tag{10}$$

Due to the introduced speed limit, the number of the further constraining expressions can also be reduced. On the one hand, we can exclude those locations from the investigation that cannot be reached from the origin of a given vehicle until the examined time step, under the defined speed limit. Furthermore, location pairs with longer distance than the speed limit can also be excluded in the cases when location pairs are compared. These cases are already treated by Eq. (5). With the introduction of the notation $c2(k)$, indicating the origin location of vehicle k assigned from $C2$, the following considerations can be applied related to the introduced constraining conditions of the control process.

Instead of $\forall j, i$, Eq. (3) has only to be taken into account in the following cases:

$$\forall j, c3_{c2(k),i} \leq (j-1) * c4 \tag{11}$$

In the case of Eq. (4), the number of considered variables can be reduced instead of the number of equalities based on the introduced concept, taking into account only those locations in function f_4, where the following condition is met:

$$c3_{c2(k),i} \leq (j-1) * c4 \tag{12}$$

Related to the constraining expressions Eqs. (6) and (7), the number of inequalities can be reduced considering only the following cases instead of $\forall k, j, i, q, r$,:

$$\forall k, j,\ c3_{i,q} \leq c4 \ and \ c3_{q,r} \leq c4 \ and \ c3_{c2(k),i} \leq (j-1) * c4 \ and \ c3_{c2(k),q} \leq j * c4 \ and \ c3_{c2(k),r} \leq (j+1) * c4 \tag{13}$$

Similarly, the relevant cases of Eq. (8) inequality system are:

$$\forall k, c3_{i,q} \leq c4 \ and \ c3_{c2(k),i} \leq (j-1) * c4 \ and \ c3_{c2(k),q} \leq j * c4;\ if\ j = 1 \tag{14}$$

In the case of Eq. (9), the number of the investigated inequalities can be reduced according to the following definition:

$$\forall k,p,j,\ c3_{i,q} \leq c4 \ and\ c3_{r,s} \leq c4\ and\ c3_{c2(k),i} \leq (j-1)*c4\ and\ c3_{c2(k),q} \leq j*c4\ and\ c3_{c2(p),r} \leq (j-1)*c4\ and\ c3_{c2(p),s} \leq j*c4 \tag{15}$$

2.3.2. The effect of predefined origin and destination locations (method$_2$)

According to the developed concept, the origin and destination locations are privileged points of the network with special characteristics:

- In these locations more than one vehicle can be present at the same time.
- Origins can be used as starting location only during the travel process, and not for transit.
- Destinations are not directed so can be used as ending location only (no further travel can take place after arrival).

The destination and origin locations of vehicles is determined in $C1$ and $C2$ matrices. Based on that, we can introduce $c8 \in R^o$ binary vector identifying if a location is origin or destination of any vehicle (with element value of 1), or not.

The constraining expressions can be reduced due to the above described characteristics as follows.

With the identification of origins and destinations at a common vector ($c8$), we can directly exclude all inequalities related these locations from Eq. (3), considering only the following cases (instead of $\forall j, i$):

$$\forall j, c8_i = 0 \tag{16}$$

In the case of Eq. (4), the number of the investigated cases cannot be cut, as a vehicle can only be in one location at a given time step considering all locations of the network (including origins and destinations) ($Hazard_3$).

Furthermore, the investigated cases in Eq. (5) cannot be reduced based on this concept, as that would harm the safety integrity of the system by allowing to exceed the speed limit for steps including origin or destination locations ($Hazard_4$). Note that the speed limit is responsible for the prohibition of traveling backwards, since the orientation of the locations is ensured by the fact that a distance value close to infinity was assigned to all unwanted directions (*e.g.*, backward steps) on the network.

According to this (due to the orientation of the graph), the speed limit ensures that a vehicle cannot enter any origin or leave any destination locations. Consequently, by excluding these cases from the investigation, the number of constraints defined by Eqs. (6)–(9) can be reduced.

Instead of $\forall k, j, i, q, r$, Eqs. (6) and (7) should only deal with the following cases:

$$\forall k,j, \left(c8_i = 0\ or\ c2_{k,i} = 1\right)\ and\ \left(c8_q = 0\ or\ c2_{k,q} = 1\ or\ c1_{k,q} = 1\right)\ and\ \left(c8_r = 0\ or\ c1_{k,r} = 1\right) \tag{17}$$

Similarly, the relevant cases of Eq. (8) based on the applied concept are:

$$\forall k, \left(c2_{k,i} = 1\right)\ and\ \left(c8_q = 0\ or\ c1_{k,q} = 1\right);\ if\ j = 1 \tag{18}$$

Note that it was not necessary to include here the cases when ($c8_i = 0$), since the location of any vehicle at the first time instant ($j = 1$) is an origin location by definition.

In the case of Eq. (9), $\forall k,p,j,i,q,r,s$ should be reduced to the following cases:

$$\forall k,p,j, \left(c8_i = 0\ or\ c2_{k,i} = 1\right)\ and\ \left(c8_q = 0\ or\ c1_{k,q} = 1\right)\ and\ \left(c8_r = 0\ or\ c2_{p,r} = 1\right)\ and\ \left(c8_s = 0\ or\ c1_{p,s} = 1\right) \tag{19}$$

2.3.3. The effect of the predefined acceleration/deceleration constraints (method$_3$)

The predefined acceleration and deceleration constraints are considered based on Eqs. (6) and (7) comparing the traveled distances at two consecutive model time steps. Related to these expressions, it can be concluded that it is enough to investigate only those route pairs whose relative length (the difference in the distances of the location pairs defining the routes) is greater than the defined acceleration/deceleration limit. Accordingly, $\forall k,j,i,q,r$ cases of Eqs. (6) and (7) can be reduced to:

$$\forall k,j, c3_{q,r} - c3_{i,q} > c5, \text{in case of Eq. (6), and} \tag{20}$$

$$\forall k,j, c3_{i,q} - c3_{q,r} > c6 \text{ in case of Eq. (7).} \tag{21}$$

The other constraining expressions cannot be further reduced based on this concept, as none of them considers two consecutive route pairs of one vehicle.

The acceleration limit is applied at the first model time step separately by Eq. (8), investigating the first two locations of the vehicles. This constraining condition is relevant only if the predefined distance of the investigated location pair is higher than the value of the maximum allowed acceleration:

$$\forall k, c3_{i,q} > c5;\ if\ j = 1 \tag{22}$$

Based on this approach, the further constraining expressions (where the relation of two locations is investigated) could also be reduced. However, since this can only be taken into account in the first time step (for $j = 1$), it would exclude so few cases that we have not considered further investigation in this article.

2.3.4. Prohibition of route crossings (method$_4$)

During the prohibition of the crossing movements of the vehicles, cases when the examined route pairs do not have any common elements can be directly excluded from the investigation. Accordingly, Eq. (9) should only be investigated in the following cases instead of $\forall k,p,j,i,q,r,s$:

$$\forall k,p,j, c7_{i-q,r-s} = 1 \tag{23}$$

As this concept is based on the comparison of route pairs (investigating 4 locations), it cannot be applied to reduce the number of cases examined for the other defined constraining expressions.

2.3.5. Introducing a heuristic to ensure continuous reduction of the distance from the destination (method$_5$)

To further reduce computational complexity, heuristics for route planning have been developed.

According to our first proposal, it should be restricted for each vehicle to increase the distance between its destination and the current location. This consideration contributes to the implementation of more rational route planning by preferring to stop and wait with the vehicle rather than take significant detours. Although some inequalities need to be introduced to take the heuristic into account, the total number of constraining expressions can be reduced by the approach excluding a massive amount of cases from the previously introduced constraints.

The above presented heuristic is represented by f_9 and it has been integrated into the model constraints. Notation $c1(k)$ indicates the destination location of vehicle k assigned from $C1$.

$$f_9\left(x_{k,j,i}, x_{k,j+1,q}\right) * c9_{i-c1(k),q-c1(k)} \leq 1;\ \forall k,j,i,q \tag{24}$$

$C9 \in R^{o^2 \times o^2}$: is a constant binary matrix representing all possible route pairs, where the element $c9_{i-q,r-s}$ identify with a value of 1, if $c3_{i,q} < c3_{r,s}$.

To reduce the number of these constraining inequalities to the minimum, the previously introduced methodological approaches related to the speed limit and the effect of the predefined origin and destination zones can also be used here. Furthermore, we can conclude from Eq. (24) also that the constraint should be introduced only in the cases when $c9_{i-c1(k),q-c1(k)} = 1$. Thus, the investigated cases of Eq. (24)

have been reduced to:

$$\forall k,j,\ c3_{i,q} \le c4\ and\ c3_{c2(k),i} \le (j-1)*c4\ and\ c3_{c2(k),q} \le j*c4\ and\ \left(c8_i = 0\ or\ c2_{k,i} = 1\right)\ and\ \left(c8_q = 0\ or\ c1_{k,q} = 1\right)\ and\ c9_{i-c1(k),q-c1(k)} = 1 \tag{25}$$

The further constraining expressions examining location pairs can be reduced by excluding those cases that have already been considered by the introduced heuristic. However, as we have already taken some constraints into account when implementing this approach (see Eq. (25)), it is not desirable to apply further reduction based on it in case of Eqs. (4) and (5), to avoid the exclusion of the same cases from both constraining expressions, which would harm the safety integrity of the system ($Hazard_3$ and $Hazard_4$).

Based on the examined heuristic, the investigated cases related to Eqs. (6) and (7) can be reduced to:

$$\forall k,j, c9_{i-c1(k),q-c1(k)} = 0\ and\ c9_{q-c1(k),r-c1(k)} = 0 \tag{26}$$

Similarly, the relevant cases of Eq. (8) using the applied consideration are:

$$\forall k,\ c9_{i-c1(k),q-c1(k)} = 0;\ if\ j = 1 \tag{27}$$

For Eq. (9), the reduced number of cases are:

$$\forall k,p,j,\ c9_{i-c1(k),q-c1(k)} = 0\ and\ c9_{r-c1(p),s-c1(p)} = 0 \tag{28}$$

2.3.6. Introducing a heuristic to reduce potential loops in the travel process ($method_6$)

With the intention to reduce potential loops in the travel processes of the vehicles, the following heuristic (based on f_{10}) has been elaborated, and embedded in the model.

$$f_{10}\left(x_{k,j,i}, x_{k,j+1,q}\right) * c7_{c2(k)-i,i-q} \le 1;\ \forall k,j,i,q \tag{29}$$

Applying the methods related to the speed limit, the effect of the predefined origin and destination zones and the previously introduced heuristic, the number of the investigated cases of Eq. (29) can be reduced to:

$$\forall k,j,\ c3_{i,q} \le c4\ and\ c3_{c2(k),i} \le (j-1)*c4\ and\ c3_{c2(k),q} \le j*c4\ and\ \left(c8_i = 0\ or\ c2_{k,i} = 1\right) and\ \left(c8_q = 0\ or\ c1_{k,q} = 1\right) and\ c3_{i,c1(k)} \ge c3_{q,c1(k)}\ and\ c7_{c2(k)-i,i-q} = 1 \tag{30}$$

With similar considerations to the previously introduced heuristic, those constraining expressions of the model which have not been built in this approach yet can be reduced (to avoid the exclusion of the same cases from more constraints - $Hazard_3$ and $Hazard_4$ related to Eqs. (4) and (5)).

For Eqs. (6) and (7), the remaining cases to investigate are:

$$\forall k,j,\ c7_{c2(k)-i,i-q} = 0\ and\ \ c7_{c2(k)-q,q-r} = 0 \tag{31}$$

The reduced number of cases related to Eq. (8) can be described as:

$$\forall k,\ c7_{c2(k)-i,i-q} = 0;\ if\ j = 1 \tag{32}$$

Finally, the relevant cases of Eq. (9) using the above consideration are:

$$\forall k,p,j,\ c7_{c2(k)-i,i-q} = 0\ and,\ c7_{c2(p)-r,r-s} = 0 \tag{33}$$

2.3.7. Summarizing the applicability of the elaborated simplifications related to the introduced constraints

The relation of the model constraints and the proposed methods to reduce the complexity of the optimization problem are summarized in Table 1.

The filled cells in the table indicate the constraining expressions whose investigated cases can be reduced based on the simplification solutions marked by the columns of Table 1, showing also the notation of the equation in which the reduction is presented. As it has been mentioned earlier, to ensure the safety integrity of the system, during the development of the simplification methods, we tried to avoid double, mutual simplifications. Two simplification methods were never used together to reduce the number of each other's equations, as this could lead to the omission of cases that could be critical to the system's operation and its safety characteristics. Thus, the given simplification method was not applied for constraints that were considered during its development process.

In line with this fact, the limited applicability of $method_4$ (limited to Eq. (9) due to the investigation of 4 locations) is quite advantageous from a system safety point of view. Since the constraint of crossing motions contains the most inequalities, the reduction of it is critical to complexity. However, due to the previously introduced concept of avoiding the mutual application of simplifications, it would not be appropriate to apply $method_4$ to other constraints, taking into account $Hazard_6$. Similar correlations can be identified for $method_3$ and $Hazard_5$ as well as $method_2$ and $Hazard_1$.

3. Results and discussion

3.1. Expected effects of simplifications

To evaluate the expected effects of the above methods, we have implemented numerical investigations in the case of three example networks. The structure of the networks and the results of the partition process are illustrated in Fig. 1. The orientation of the locations is indicated by arrows. Destination locations are not oriented (empty), origins are marked by gray background.

The first network represents a simple junction, containing 12 nodes and 12 edges. The second network with 10 nodes and 14 edges models a two-lane road section where the vehicles can change lanes. The third network also consists of lanes with the same orientation, but is more complex than the previous one, containing 16 nodes and 24 edges. Based on the size of passenger vehicles, 5 m long locations are used for segmentation. The defined investigated time interval (t) was divided into 1

Table 1
Relation of the model constraints and methodological approaches for simplification.

		Methodological approaches for simplification					
		$method_1$	$method_2$	$method_3$	$method_4$	$method_5$	$method_6$
Constraints of the model	Eq. (2)	–	–	–	–	–	–
	Eq. (3)	Eq. (11)	Eq. (16)	–	–	–	–
	Eq. (4)	Eq. (12)	–	–	–	–	–
	Eq. (5)	Eq. (10)	–	–	–	–	–
	Eq. (6)	Eq. (13)	Eq. (17)	Eq. (20)	–	Eq. (26)	Eq. (31)
	Eq. (7)	Eq. (13)	Eq. (17)	Eq. (21)	–	Eq. (26)	Eq. (31)
	Eq. (8)	Eq. (14)	Eq. (18)	Eq. (22)	–	Eq. (27)	Eq. (32)
	Eq. (9)	Eq. (15)	Eq. (19)	–	Eq. (23)	Eq. (28)	Eq. (33)
	Eq. (24)	Eq. (25)	Eq. (25)	–	–	Eq. (25)	–
	Eq. (29)	Eq. (30)	Eq. (30)	–	–	Eq. (30)	Eq. (30)

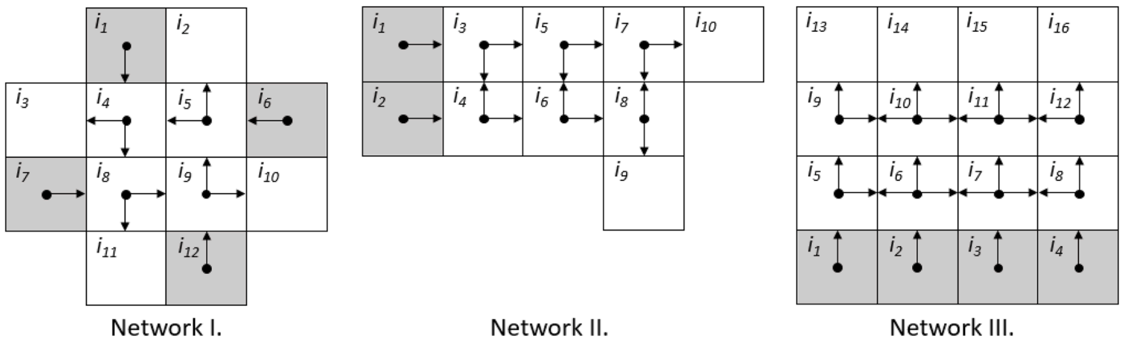

Fig. 1. Structure of the example road networks.

s time steps.

The applied initial data are summarized in Table 2.

As the first step of the analysis, the optimization of traffic demand management was performed based on the introduced binary integer model ignoring the simplification solutions (baseline case). According to the aim of our study, the focus of this process was to determine the total number of equations and inequalities together constituting the constraints of the optimization task. Following this, the number of the constraining formulas were 403,316; 197,700 and 1,249,428 for the three baseline cases, respectively.

The developed simplification methods were then adopted to the basic systems of constraining equalities and inequalities, and their effects were evaluated. To facilitate the investigation of the casual effect on complexity of each simplification, the ceteris paribus principle was applied. This also means that if a simplification method is used, only the related equation or inequality system was considered (*e.g.*, Eq. (5) in case of $method_1$), and the further constraining expressions were reduced by that approach. The impacts of the simplifications are given in Table 3.

The complexity of the problem was reduced significantly by some of the developed simplification solutions, even when used alone. The number of constraining expressions decreased by more than 80% in the first and third cases as a result of $method_1$ developed based on the effects of the predefined speed limit. Related to all three networks, the reduction was more than 85% in case of applying $method_4$ alone, which aimed to directly exclude some cases – when the compared route pairs do not have any common elements – from the investigation of possible crossing vehicle movements. The reduction in the number of constraining expressions varied between 46.8–73.8% when $method_2$ or $method_5$ was applied. The effects of $method_2$ and $method_5$ were lower (2.3–9.6%), but that is partly due to the small size of the example networks. With the increase of the number of potential steps on the network (edges), the effect of the method developed based on the principle of reducing potential loops ($method_5$) also increased. For most methods the rate of decrease was greater on networks with multiple locations.

To evaluate the combined causal effect of simplification pairs on complexity, we applied a pairwise comparison method. For this purpose,

Table 3
The extent of reduction achieved by the simplification solutions in the three cases.

	First case (Network I.) (%)	Second case (Network II.) (%)	Third case (Network III.) (%)
$method_1$	85.2	69.9	80.6
$method_2$	73.8	46.8	62.0
$method_3$	2.9	3.4	2.3
$method_4$	87.2	85.2	89.7
$method_5$	66.0	66.3	66.7
$method_6$	5.6	6.2	9.6

Table 4
The extent of reduction achieved by the pairwise combination of the simplification solutions in the third case.

	Third case (Network III.) (%)
$method_1$ & $method_2$	93.4
$method_1$ & $method_3$	80.9
$method_1$ & $method_4$	98.1
$method_1$ & $method_5$	93.1
$method_1$ & $method_6$	83.9
$method_2$ & $method_3$	63.8
$method_2$ & $method_4$	94.0
$method_2$ & $method_5$	84.8
$method_2$ & $method_6$	66.8
$method_3$ & $method_4$	93.2
$method_3$ & $method_5$	67.7
$method_3$ & $method_6$	12.6
$method_4$ & $method_5$	96.3
$method_4$ & $method_6$	91.6
$method_5$ & $method_6$	68.8

Table 2
Initial data of the three investigated cases.

	First case (NETWORK I.)		Second case (Network II.)		Third case (Network III.)	
m	4		4		4	
t	4 s		4 s		4 s	
o	12		10		16	
v_limit	15 m/s		15 m/s		15 m/s	
acc_limit	10 m/s^2		10 m/s^2		10 m/s^2	
dec_limit	10 m/s^2		10 m/s^2		10 m/s^2	
	Origin	Destination	Origin	Destination	Origin	Destination
$K = 1$	1	10	1	9	1	15
$k = 2$	1	2	1	10	1	16
$k = 3$	6	11	2	10	2	16
$k = 4$	7	2	2	9	3	13

the most complex third network was used. Results are summarized in Table 4.

Combining the methods proved to be effective. Apart from the combination of the two least effective methods ($method_3$ and $method_6$), each pairing resulted in a reduction of at least 63% compared to the baseline case. In several cases (especially for the most effective methods according to previous results), the combined casual effect resulted in reduction by more than 90%, which implies a significantly reduced computational complexity.

3.2. Application in a realistic scenario

The applicability of the developed model with the introduced simplifications was tested in a more realistic scenario. For this purpose, a bigger network (32 nodes, 40 edges) representing the junction of two 2 × 2 lane roads was used and the number of considered vehicles was increased. The size of the locations and the length of the time steps, as well as the defined speed, acceleration and deceleration constraints were not modified. The structure of the partitioned network is illustrated in Fig. 2. Junctions with similar structure are widely used in the Hungarian road network. An example can be found in Budapest at Lat.: 47.46363; Lon.: 19.03361. The annual average daily traffic (AADT) goes through this intersection is 29,800 pcu/day [5].

With the application of the refined model, a close-optimum feasible solution can be found related to any defined travel demand structure. Using the optimization method, our aim was also to investigate the efficiency of the developed control procedure based on the number of vehicles able to pass through the junction in a unit of time, keeping in mind that the capacity of a junction depends strongly on the structure of travel demands [8,67].

At the first step, the defined traffic load was uniform and quite complex from all directions (demand structure 1), 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 (and arriving also into an inner lane) on all four branches of the junction. In this way, a total of 20 vehicles were considered during the optimization ($m = 20$). By running the optimization program several times, we examined the minimum length of (t) time interval which was enough for the vehicles to go through the junction. Based on this, a rough estimation of the capacity of the junction was determined for the defined travel demand structure. Note that this estimation is based on a constant demand volume over the examined time period, so the practical capacity of the junction could be even higher if more vehicles arrived continuously.

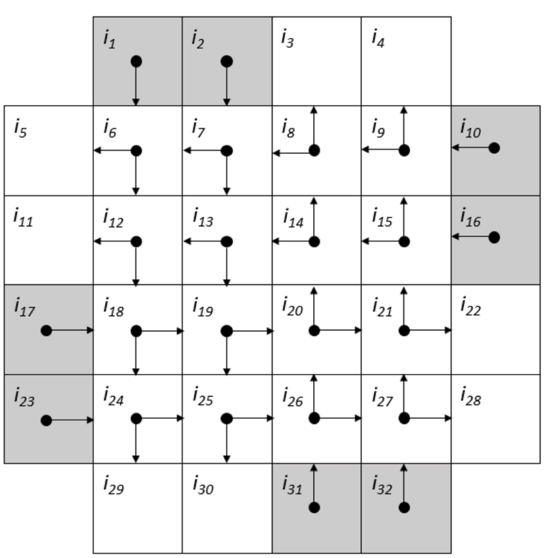

Fig. 2. Structure of the road network in the realistic scenario.

Based on the results of the optimization, the junction was emptied in 8 s in the case of demand structure 1. The resulting routes per vehicle were summarized in the columns of Table 5.

Note that in the case of the presented, close-optimal feasible solution, a vehicle ($k = 12$) has not yet reached its designed destination; however, it has already made the turning maneuver and passed through the most important conflict points, so the solution was considered appropriate. The value of the objective function (y_1) was 1535.

Considering that 20 vehicles passed through the junction in 8 s, with a rough estimate 9000 vehicles ($20 * 3,600/8$) can pass in an hour even in case of this diversified demand structure, where the ratio of vehicles going left, straight and right was 2:1:2 on all branches.

This performance is outstandingly good compared to the results of studies examining the capacities of current, traditional junctions. Barna and Schuchmann [4] used a simulation model to examine the performance of different types of junctions based on average travel time losses. In their study, a simpler demand structure was applied with a lower ratio of turning vehicles (ratio of vehicles going left, straight and right was 1:3:2 on all branches). According to their results, the capacity of an uncontrolled (no traffic lights or roundabout) intersection of 2 × 1 lane roads was approximately 2000 vehicle/h, which could be increased to 3000 vehicle/h if a separate lane for all turning directions is provided on one of the crossing roads.

The intersection with the most similar structure to our example was a traffic light controlled junction in the cited study. Although this junction had one more lane on each branches (3 inbound and 2 outbound lanes), the maximum capacity of it was only a total of 4400–5200 vehicle/h, depending on the period time of the traffic light control. This capacity increased to 6000–6200 vehicle/h in case of adding one more lane on the main branch [4].

Beyond the theoretical comparisons, we can also consider real examples, such as the second case study introduced in the report of Jenior et al. [32], investigating the intersection of Route 19 (Sulaski Highway) and Route 380 (*N* Bridge Street) near Charleston in the United States. The mentioned signalized four-legged intersection of a 4- and a 6-lane road, with a total traffic volume of 5780 vehicle/h is characterized by poor operational performance. In light of this, we can see that the proposed novel traffic management concept can significantly improve the efficiency of the currently applied solutions.

With the simplification of the demand structure (*e.g.*, lower ratio of left turns), the efficiency of the developed control model may be even higher than previously presented. One example is shown below, where the previously used demand structure was modified by replacing one of the left-turning movements with a straight forward movement for all branches of the junction (demand structure 2-ratio of vehicles going left, straight and right is 1:2:2). In this case, the junction was emptied by the process in 6 s (see the Table 6), which would imply a 12,000 vehicle/h ($20 * 3,600/6$) theoretical capacity.

The above presented examples illustrate the applicability and efficiency of the proposed model. The defined safety constraints were satisfied by the feasible solutions. The total number of equations and inequalities of the optimization task was 28,715 in case of demand structure 1, and 16,392 in case of the modified demand structure and 6 s time interval. The calculations were not performed in a hardware and software environment optimized for performance and computational time. The MATLAB software and a laptop with Intel(R) Core(TM) i7–2620 M CPU (2,70 GHz) and 4GB RAM were used, the computational time was 87.98 s and 10.49 s for the presented examples, respectively.

3.3. Evaluation of the safety characteristics of the system

Complementing traffic models with estimations on traffic safety and system reliability is of high importance [24]. The safe operation of the transport system is highly affected by the temporal and spatial distance of the vehicles, as well as by the homogeneity of speed and acceleration characteristics of the system components [62,68]. Decreasing the role of

Table 5
Result of the optimization process in the realistic scenario (demand structure 1).

Vehicle (k)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Origin	1	1	1	2	2	10	10	10	16	16	17	17	23	23	23	31	31	32	32	32
Destination	29	5	5	22	22	5	4	4	30	30	3	3	28	29	29	11	11	4	28	28
$t = 1$	1	1	1	2	2	10	10	10	16	16	17	17	23	23	23	31	31	32	32	32
$t = 2$	1	1	5	2	13	10	4	10	16	14	17	17	25	23	23	31	31	21	32	32
$t = 3$	6	1	5	2	21	10	4	10	16	13	17	17	25	23	29	26	31	9	32	28
$t = 4$	18	5	–	7	22	9	–	10	15	25	17	17	26	29	–	13	31	4	28	–
$t = 5$	29	–	–	20	–	6	–	4	14	30	18	17	28	–	–	11	26	–	–	–
$t = 6$	–	–	–	22	–	5	–	–	13	–	19	17	–	–	–	–	14	–	–	–
$t = 7$	–	–	–	–	–	–	–	–	25	–	8	18	–	–	–	–	12	–	–	–
$t = 8$	–	–	–	–	–	–	–	–	30	–	3	14	–	–	–	–	11	–	–	–

Table 6
Result of the optimization process in the realistic scenario ($y_1 = 1,130$) (demand structure 2).

Vehicle (k)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Origin	1	1	1	2	2	10	10	10	16	16	17	17	23	23	23	31	31	32	32	32
Destination	29	5	5	30	22	5	4	4	11	30	22	3	28	29	29	3	11	4	28	28
$t = 1$	1	1	1	2	2	10	10	10	16	16	17	17	23	23	23	31	31	32	32	32
$t = 2$	12	1	1	13	2	8	10	10	14	16	19	17	25	23	23	20	31	21	32	32
$t = 3$	18	1	5	19	7	8	4	10	12	16	21	17	25	23	29	14	26	15	28	32
$t = 4$	29	5	–	30	13	7	–	10	11	14	22	19	26	23	–	3	20	4	–	28
$t = 5$	–	–	–	–	19	5	–	4	–	13	–	20	28	29	–	–	14	–	–	–
$t = 6$	–	–	–	–	22	–	–	–	–	30	–	3	–	–	–	–	11	–	–	–

human drivers, the increased safety has been advocated as one of the major benefits of autonomous transport systems [33]. In our paper, we have developed methodological approaches to investigate factors characterizing the road safety level of the traffic process determined by the elaborated model. As a result of these methods, safety indicators have been developed.

The new indicators can be used for comparing the results of the traffic optimization process from the safety point of view, *e.g.*, concerning different road network types (different node types, partitioning process with various size or shape of locations, etc.), or travel demand structures. Another field of application is the possibility to rank the several, equally effective feasible solutions obtained for the same problem.

The refined methods aiming to develop the indicators characterizing the safety level of the optimized traffic flow structure can be described as follows. During the safety indicator development process, we paid a special attention to handle and monitor the predefined Hazards, accordingly the introduced methods are strongly related to them. Based on the reviewed research studies on highly automated systems, we identified the main hazards of the system as follows:

- $Hazard_1$ Vehicles entering the system get stuck at their starting point.
- $Hazard_2$ Assigning more vehicles to the same location at a given time step; that is, the departure-destination pairs are not assigned to vehicles in a non-bijective way at a given time step.
- $Hazard_3$ Assigning one vehicle to more location at a given time step.
- $Hazard_4$ Exceeding the speed limit.
- $Hazard_5$ Exceeding the acceleration or deceleration limit.
- $Hazard_6$ Enabling the crossing movements of vehicles entering at least one identical location in a given time interval.

Safety indicator related to the crossing movements of vehicles ($CM - Hazard_6$)

The safety indicator considering the risk arising from crossing vehicle movements was formed on the basis of the number and temporal distance of these actions (Eq. (34)).

$$CM = \sum_{\substack{k,h,j,u,i,q,r,s=1 \\ k\neq h \\ u\neq j}}^{m,m,(t-1,\ t-1),o,o,o,o} c7_{i-q,r-s} * \left(x_{k,j,i} * x_{k,j+1,q} * x_{h,u,r} * x_{h,u+1,s}\right) * \frac{1}{(u-j)^2} \tag{34}$$

The product of the first two factors in the summation identifies with a value of 1, if any two vehicles (k and h) have traveled sections (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.

Based on the elaborated formula, the value of CM becomes higher with the increasing number of crossing vehicle movements (meaning more summands in the summation). Furthermore, the value of the summands gets higher if the crossing movements take place in shorter time intervals. Accordingly, a lower value of a CM safety indicator implies a safer flow of traffic.

Average speed at the network level ($\overline{VN} - Hazard_4$)

The average speed at the network level was formulated as the average of the average speeds of the vehicles traveling on the road network. A fundamental criterion of the interpretation is to perform the calculations below considering at least two time moments ($t \geq 2$).

To develop the indicator, the formula describing the average speed of the vehicles was defined (Eq. (35)).

$$\overline{V_k} = \frac{\sum_{j,i,q=1}^{(t-1),o,o} x_{k,j,i} * x_{k,j+1,q} * c3_{i,q}}{(t-1) - \sum_{j=1}^{(t-1)} x_{k,j,c1(k)} - \sum_{j=1}^{(t-1)} x_{k,j+1,c2(k)}} \tag{35}$$

That is, the average speed of vehicle k is calculated by dividing the sum of the lengths of the road sections it travels by the number of time steps elapsed between the start of the vehicle from its origin and the arrival to its destination. To determine the correct number of the considered time steps, the sum of time steps spent in the origin location, as well as the sum of time steps spent in the destination location were subtracted from the total number of the investigated $(t-1)$ time steps.

In this way, the value of the denominator would be 0 only if the vehicle did not leave its origin location for the entire investigated timeframe. In this case, the average speed for the given vehicle is undefined.

The network level average speed is then calculated by averaging the average speed of vehicles, as described in Eq. (36).

$$\overline{VN} = \frac{1}{m - \sum_{k,i=1}^{m,o}\left(x_{k,t,i} * c2_{k,i}\right)} * \sum_{\substack{k=1 \\ x_{k,t,c2(k)} \neq 1}}^{m} \overline{V_k} \tag{36}$$

Since the average speed is undefined for vehicles that do not leave their origin, these cases are excluded from the summation (ensured by the condition described below the lower bound of the summation). Thus, the denominator is also reduced by the number of these vehicles to avoid distortion. The network level average speed is undefined if no investigated vehicle leaves its origin location.

A lower value of indicator $\overline{VN}$ implies a safer flow of traffic in the case of equally efficient control processes, by the lower average speeds of the vehicles.

Homogeneity of speed at the vehicle level (σ_{VV} − *Hazard*$_4$)

The homogeneity of speed values at the vehicle level is elaborated as the mean of the standard deviation of the individual vehicle speeds per time step ($t \geq 2$).

For the calculation of this safety indicator, the standard deviation of the speed data of a vehicle is determined per time step in Eq. (37).

$$\sigma_{V_k} = \sqrt{\sum_{\substack{j,i,q=1 \\ x_{k,j,i}=1 \\ x_{k,j+1,q}=1 \\ x_{k,j,c1(k)} \neq 1 \\ x_{k,j+1,c2(k)} \neq 1}}^{(t-1),o,o} \left(x_{k,j,i} * x_{k,j+1,q} * c3_{i,q} - \overline{V_k}\right)^2 \Bigg/ \left(t-1-\sum_{j=1}^{(t-1)} x_{k,j,c1(k)} - \sum_{j=1}^{(t-1)} x_{k,j+1,c2(k)}\right)} \tag{37}$$

Note that when generating the speed data per time step (first term of the subtraction in the numerator), only those terms are considered (according to the conditions described below the lower bound of the summation) that characterize the actual movement process of the vehicle. In line with the formula of the standard deviation, the denominator refers to the number of time steps describing this movement process. The standard deviation is undefined for vehicles not leaving their origin locations.

Based on the above, the indicator of the homogeneity of speed at the vehicle level is formed by averaging the σ_{V_k} data of the vehicles that started the travel process (Eq. (38)).

$$\sigma_{VV} = \frac{1}{m - \sum_{k,i=1}^{m,o}\left(x_{k,t,i} * c2_{k,i}\right)} * \sum_{\substack{k=1 \\ x_{k,t,c2(k)} \neq 1}}^{m} \sigma_{V_k} \tag{38}$$

The indicator refers to the evenness of the speed of the individual vehicles per time step. Therefore, a lower value of indicator σ_{VV} implies a safer flow of traffic through more even vehicle speeds.

Homogeneity of speed at the network level (σ_{VN} − *Hazard*$_4$)

The homogeneity of speed values at the network level is interpreted as the standard deviation of the average speeds of the vehicles over the entire examined time interval. The indicator can be calculated from the average speed of the vehicles and the average speed at the network level, according to the standard deviation formula (Eq. (39)).

$$\sigma_{VN} = \sqrt{\sum_{\substack{k=1 \\ x_{k,t,c2(k)} \neq 1}}^{m} \left(\overline{V_k} - \overline{VN}\right)^2 \Bigg/ \left(m - \sum_{k,i=1}^{m,o}\left(x_{k,t,i} * c2_{k,i}\right)\right)} \tag{39}$$

Using the above formula, only the vehicles that have left their origin locations are considered.

The indicator refers to the similarity of the average speeds of the different vehicles. Thus, a lower value of indicator σ_{VN} implies a safer flow of traffic due to a smaller difference between the average speeds of individual vehicles.

Average change in speed at the network level ($\overline{\Delta VN}$ − *Hazard*$_5$)

In our model, the change in speed is interpreted based on the difference of the traveled distances during two consecutive time steps. The average change in speed (per time step pairs) at network level refers to the volume and extent of accelerations and decelerations, and is determined as the mean of the average changes in speed of all vehicles traveling on the network. Accordingly, the absolute value of the changes in speed have been used to formulate this indicator (regardless of whether the vehicle is accelerating or decelerating). Since the investigation requires two consecutive model time steps in this regard, at least three time moments must be taken into account for the equations below ($t \geq 3$).

To create the indicator, the formula describing the absolute value of the average change in the speed of a vehicle is calculated with Eq. (40).

$$\overline{\Delta VA_k} = \frac{\sum_{j,i,q,r=1}^{(t-2),o,o,o} x_{k,j,i} * x_{k,j+1,q} * x_{k,j+2,r} * \sqrt{\left(c3_{q,r} - c3_{i,q}\right)^2} + \sum_{i,q=1}^{o,o} x_{k,1,i} * x_{k,2,q} * c3_{i,q}}{(t-2) - \sum_{j=1}^{(t-2)} x_{k,j,c1(k)} - \sum_{j=1}^{(t-2)} x_{k,j+2,c2(k)} + \left(1 - x_{k,2,c2(k)}\right)} \tag{40}$$

The formula divides the sum of the absolute values of the differences in the distances traveled during the successive time step pairs by the number of time step pairs. The distance traveled in the first time step is added separately, as the previous time step is not interpreted in this case. The maximum number of time step pairs is (t− 2), but the time spent in the origin or destination location is excluded in this case as well. The last term of the denominator increases the number of considered time steps by 1 if the vehicle leaves the origin location in the first time step (when the previous time step is not interpreted). The average change in speed is undefined for vehicles that do not leave their origin during the investigated time period.

The network level average change in speed is calculated as the mean of the $\overline{\Delta VA_k}$ values (Eq. (41)).

$$\overline{\Delta VN} = \frac{1}{m - \sum_{k,i=1}^{m,o}\left(x_{k,t,i} * c2_{k,i}\right)} * \sum_{\substack{k=1 \\ x_{k,t,c2(k)} \neq 1}}^{m} \overline{\Delta VA_k} \tag{41}$$

Analogously to the previous considerations, only the vehicles that have started the travel process are considered. The indicator is undefined if none of the vehicles leave their origin locations.

A lower value of the average change in speed at the network level indicates that the examined vehicles accelerate or decelerate on average less or to a lesser extent, thus a safer flow of traffic can be assumed through smoother driving.

Homogeneity of the changes in speed at the vehicle level ($\sigma_{\Delta VV}$ − *Hazard*$_5$)

The indicator expressing the evenness of accelerations and decelerations at the vehicle level is determined as the mean of the standard deviations of the changes in speed of individual vehicles ($t \geq 3$).

To determine the standard deviation, it was necessary to distinguish the direction of the change in speed (*i.e.*, whether the vehicle accelerates or decelerates). Accordingly, the mean of the changes in speed of a vehicle is determined with Eq. (42), considering also the direction of the changes in speed.

$$\overline{\Delta V_k} = \frac{\sum_{j,i,q,r=1}^{(t-2),o,o,o} x_{k,j,i} * x_{k,j+1,q} * x_{k,j+2,r} * \left(c3_{q,r} - c3_{i,q}\right) + \sum_{i,q=1}^{o,o} x_{k,1,i} * x_{k,2,q} * c3_{i,q}}{(t-2) - \sum_{j=1}^{(t-2)} x_{k,j,c1(k)} - \sum_{j=1}^{(t-2)} x_{k,j+2,c2(k)} + \left(1 - x_{k,2,c2(k)}\right)} \tag{42}$$

The formula follows the same principles as Eq. (40), but the difference in the distances traveled during two successive time steps refers to the direction of the speed change in this case, by the sign of the first term of the numerator.

The standard deviation of the changes in speed of a vehicle can be then calculated according to Eq. (43).

$$\sigma_{\Delta V_k} = \sqrt{\frac{\sum\limits_{\substack{j,i,q,r=1\\ x_{k,j,i}=1\\ x_{k,j+1,q}=1\\ x_{k,j+2,r}=1\\ x_{k,j,c1(k)}\neq 1\\ x_{k,j+2,c2(k)}\neq 1}}^{(t-2),o,o,o} \left(x_{k,j,i} * x_{k,j+1,q} * x_{k,j+2,r} * \left(c3_{q,r} - c3_{i,q}\right) - \overline{\Delta V_k}\right)^2 + \sum\limits_{\substack{i,q=1\\ x_{k,1,i}=1\\ x_{k,2,q}=1\\ x_{k,1,c1(k)}\neq 1\\ x_{k,2,c2(k)}\neq 1}}^{o,o} \left(x_{k,1,i} * x_{k,2,q} * c3_{i,q} - \overline{\Delta V_k}\right)^2}{(t-2) - \sum_{j=1}^{(t-2)} x_{k,j,c1(k)} - \sum_{j=1}^{(t-2)} x_{k,j+2,c2(k)} + \left(1 - x_{k,2,c2(k)}\right)}} \tag{43}$$

Similarly to Eq. (37), only those terms are considered in the summation which characterize the actual movement process of the vehicle. The denominator equals to the number of time step pairs considered for the given vehicle. In the case of the first time step, the previous time step is not interpreted; therefore, the expressions related to this time step are added separately both in the case of the numerator and the denominator. The formula can only be interpreted for vehicles leaving their origin locations during the examined time period.

The indicator representing the vehicle level homogeneity of the changes in speed is determined as the mean of the elaborated $\sigma_{\Delta V_k}$ data (Eq. (44)).

$$\sigma_{\Delta VV} = \frac{1}{m - \sum_{k,i=1}^{m,o} \left(x_{k,t,i} * c2_{k,i}\right)} * \sum_{\substack{k=1\\ x_{k,t,c2(k)}\neq 1}}^{m} \sigma_{\nabla V_k} \tag{44}$$

The indicator represents the evenness of the changes in speed per time steps pairs (accelerations and decelerations) of the individual vehicles. Thus, a lower value of indicator $\sigma_{\Delta VV}$ implies the smoother movement of the vehicles on average, which can be considered safer.

Homogeneity of the changes in speed at the network level ($\sigma_{\Delta VN}$ − *Hazard*$_5$)

Similarly to the investigation of speed values, the homogeneity of the changes in speed is also determined at the network level (Eq. (45)).

$$\sigma_{\Delta VN} = \sqrt{\sum_{\substack{k=1\\ x_{k,t,c2(k)}\neq 1}}^{m} \left(\overline{\Delta VA_k} - \overline{\Delta VN}\right)^2 \Big/ \left(m - \sum_{k,i=1}^{m,o} \left(x_{k,t,i} * c2_{k,i}\right)\right)} \tag{45}$$

However, it is important to note that this indicator alone does not refer to the level of safety. While at the network level, the homogeneous speed distribution is particularly favorable in terms of road safety (*e.g.*, in the case of a long, straight road section, conflicts often arise between vehicles traveling at different speeds), it is not necessarily true in the case of the change in speed that refers to the average volume and extent of accelerations and decelerations. In this regard, the lower standard deviation (*i.e.*, the most even distribution of accelerations and decelerations) is favorable for all individual vehicles, regardless of the average value characterizing the network.

The indicator of the homogeneity of the changes in speed at the network level is worth examining only if the values of the previously introduced $\overline{\Delta VN}$ and $\sigma_{\Delta VV}$ indicators are the same for the two compared alternatives. In this case, the alternative with a lower value of indicator $\sigma_{\Delta VN}$ can be considered safer because of the lower presumed number of vehicles traveling with extreme high changes in speed values.

3.4. Demonstration of the applicability of the developed safety indicators

A numerical example was elaborated with the aim of presenting the functionality of the introduced safety indicators. The realistic scenario representing the junction of two 2 × 2 lane roads (see Fig. 2) was used for this purpose with demand structure 2. A feasible solution (*FS*1) for this problem was already presented in Table 6. In that case, the value of the objective function (y_1) was 1130.

The calculations are again performed applying a longer computational timeframe to produce a comparable result. A feasible solution (*FS*2) slightly closer to the optimum ($y_1 = 1{,}125$) was found in 49.33 s by the previously introduced hardware, as presented in Table 7.

The two feasible solutions were compared using the proposed safety indicators. The calculations were performed in the MATLAB software, with the results summarized in Table 8.

The solutions are similar to each other. In both cases the route crossing gets empty in 6 s. The minimized objective function was slightly lower in the case of *FS*2, ensuring the lower traffic load of the road network, in accordance with the aim of the optimization.

The safety indicators have to be assessed in accordance with the aim of the considered problem. The traffic was investigated at a road junction, the representation of the road network as well as the structure of travel demands were the same in both investigated cases. Thus, the indicator describing the best the safety level is *CM*, since it considers the risk arising from crossing vehicle movements. In the presented cases, the number of crossing vehicle movements were the same. However, the lower value of *CM* shows that these movements took place farther apart in time in the case of *FS*2, indicating a safer flow of traffic (although the difference is relatively small).

The “price” of efficiency was that the average speed and the average change in speed at the network level were 2.6% and 1% higher compared to *FS*1, respectively. However, the standard deviations of the speed values per time step indicate a safer flow of traffic through the smoother driving at the vehicle level (σ_{VV} was 5.2% lower in the second case, while $\sigma_{\Delta VV}$ was almost the same). The relative variances of vehicle speeds and speed changes were also lower at the network level in the case of *FS*2, based on the values of σ_{VN} and $\sigma_{\Delta VN}$. However, these indicators are less relevant for a road junction.

Table 7
$FS2$ in the realistic scenario ($y_1 = 1,125$) (demand structure 2).

Vehicle (k)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Origin	1	1	1	2	2	10	10	10	16	16	17	17	23	23	23	31	31	32	32	32
Destination	29	5	5	30	22	5	4	4	11	30	22	3	28	29	29	3	11	4	28	28
$t = 1$	1	1	1	2	2	10	10	10	16	16	17	17	23	23	23	31	31	32	32	32
$t = 2$	12	1	1	13	2	8	10	10	14	16	19	17	25	23	23	20	31	21	32	32
$t = 3$	12	1	5	25	2	7	10	4	13	16	21	18	26	23	29	8	31	15	28	32
$t = 4$	18	1	–	30	13	5	10	–	11	14	22	19	28	29	–	3	20	4	–	32
$t = 5$	29	5	–	–	19	–	4	–	–	13	–	20	–	–	–	–	14	–	–	28
$t = 6$	–	–	–	–	22	–	–	–	–	30	–	3	–	–	–	–	11	–	–	–

Table 8
Values of the safety indicators related to the compared feasible solutions (realistic scenario, demand structure 2).

y_1	$FS1$ 1130	$FS2$ 1125	Difference (%) ($FS2$ /$FS1$)
CM	49.056	48.444	- 1.2%
$\overline{VN}$	8.875	9.104	2.6%
σ_{VV}	1.963	1.861	- 5.2%
σ_{VN}	1.297	1.117	- 13.9%
$\overline{\Delta VN}$	8.008	8.088	1.0%
$\sigma_{\Delta VV}$	8.152	8.186	0.4%
$\sigma_{\Delta VN}$	2.144	2.029	- 5.4%

3.5. The contributions of the research

The present research contributes to system safety by further developing the classical development model related to highly automated transport systems [59]. In the first step, in line with the traditional approach, the system functions were identified through presenting the objective function and the applied constraining conditions of the autonomous transport model. According to the introduced methodology, besides the classical top-down [53,56] and bottom-up [42] methods, we applied critical accident scenarios [58,64] to determine the hazards affecting the systems' operation. The combined application of the three methodologies allowed us to achieve more reliable results.

The general procedure applied through our research has been illustrated by the following flowchart (Fig. 3), highlighting the main contributions of the paper.

In light of the defined functionalities, the following step is to evaluate the efficiency of the model. In the case of incomplete, inadequate functionality, or violation of safety rules, the system has to be redesigned. At this stage, it is crucial to pay significant attention to the hazards identified at the beginning of the process. As a key contribution, we have developed several methodological approaches that can significantly reduce the complexity of the system ensuring also the feasibility and the reliability of the solutions. The defined formulas of the simplification methods refer specifically to the presented model, however, along the considerations behind them, the complexity of other transport models can also be reduced.

As a main contribution, the results of our research makes it possible to significantly increase the systems' safety by introducing novel safety indicators characterizing the operation process of the system, which have to be determined on the basis of the previously identified hazards. Accordingly, we have presented several concepts that can be used to characterize the safety level of highly automated transport systems. As a specific contribution, the expressions describing these indicators have been introduced in a detailed way. To present the applicability and functionality of the developed methods and indicators, numerical examples have been provided.

4. Conclusion

The research presented in this paper builds on the expected spread of autonomous vehicles, which facilitates the possibilities of ensuring effective and safe traffic management. Based on the reviewed literature, the authors expect that some of the largest challenges of automotive safety engineering will be identifying and implementing critical test scenarios occurring due to the SoS (System of Systems) nature of the future transport. Experts will need to consider more and more factors influencing the safety and reliability of systems. For this purpose, the flexibility and adaptability of the applied methods will be a crucial issue to cover the system's entire life cycle.

Assuming an autonomous transport system, a binary integer model has been developed by the authors aiming at network level traffic optimization through the control of individual vehicles, providing solutions to the emerging system safety issues. The elaborated model framework has been presented in its generalized representation. To consider the expected risks related to the model, hazards of the system components were systematically defined and described, also taking into account the SoS nature of complex transport systems.

Identifying the high computational demands as the main limitation of the concept, several methodological approaches have been presented

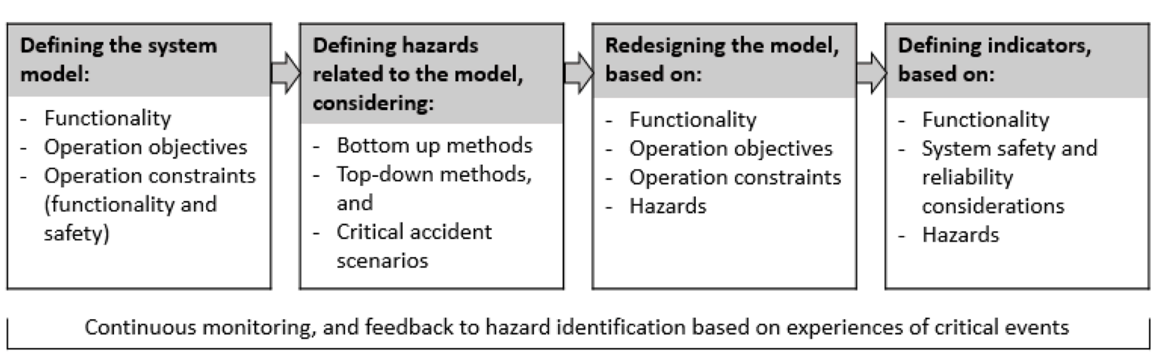

Fig. 3. The applied research procedure and contributions.

aiming to reduce the complexity of the optimization process. The elaborated simplification solutions reduce the number of constraints to a great extent without threatening the safety of the system. The methods aiming to exclude cases from the investigation based on the predefined speed limit ($method_1$) and the identification of common elements of compared route pairs ($method_4$) proved to be the most effective, resulting in more than 80% reduction in the number of constraining expressions. The integrated use of the methodological approaches for simplification is possible, the relations with the model constraints have been summarized in a table.

The expected effects of the introduced simplifications have been quantified based on numerical investigations in the case of three example networks. The casual effects have been revealed based on the ceteris paribus principle, while pairwise comparisons have been made to examine the combined effects as well. The most effective methods were able to reduce the number of considered constraining expressions by more than 80%, implying a significantly reduced computational complexity. The introduced methods used different approaches and heuristics, but future studies can reveal several other concepts for the purpose of further excluding constraining conditions. These may set up limitations for the investigated cases (*e.g.,* prohibition of certain routes for some vehicles), but the feasibility of the solution must be ensured.

The applicability of the developed model with the simplification solutions was demonstrated in the case of a realistic scenario using the representation of a road junction of two 2 × 2 lane roads as the base network. Feasible, close-optimal solutions were determined by the elaborated model in reasonable time in the case of two different travel demand structures. Based on rough estimations, the results showed an outstanding performance of the elaborated process related to the capacity utilization of the junction compared to traditional control modes (*e.g.*, traffic lights). The further investigation of the performance for different types of intersections and as a function of the travel demands forms another promising task for future research.

As the provision of system safety is a fundamental requirement of processes dealing with traffic management, methodological approaches have been developed to characterize the safety level of the traffic distribution determined by the model. The introduced safety indicators are strongly related to the described hazards. Accordingly, safety indicators aim to investigate the crossing movements of vehicles, and cover factors related to the average speed and average change in speed also at the network level, and at the level of individual vehicles. As it has also been demonstrated by a numerical example, the indicators can be used for comparing the results of the traffic optimization process from the safety point of view.

Summing up, the novel framework can support the evolution of cooperative vehicle control related solutions, but on the other hand, it can be efficiently applied to define safety critical scenarios of autonomous transport systems as well. Considering that the developed evaluation methodology is capable of characterize the safety level of certain scenarios, it can be used to select the most hazardous cases and to define the corner case scenarios. The authors' future work will primarily focus on the use of these approaches to investigate the safety performance of using different road network types (different node types, partitioning process with various size or shape of locations, etc.), and travel demand structures.

Examining the system's limitations, we need to mention two aspects that will require further improvements in the future. On the one hand, we must emphasize that the presented method is primarily suitable for coordinating the processes of a fully autonomous system. However, the flexibility of the model makes the system possible also to handle non-autonomous participants. Although this requires further development and research, we can already say that the developed safety indicators are also suitable for the characterization of hybrid systems. On the other hand, it should also be mentioned that the resolution of the system can be further increased, which can contribute to the improvement of the efficiency of the traffic management process; however, the expected increase in complexity may require further simplification solutions. From a reliability engineering and system safety perspective, both development orientations will expectedly result in a large number of new hazards. For instance, as the system will expectedly not control the external participants entering the system, we can only estimate their decisions, which involves several risks, such as hazardous situations due to erroneous predictions or a change of decision. Besides this, as the resolution increases, we can expect a slowdown in the running speed, resulting in numerous hazardous situations—for example, the delayed synchronization of the participants' decisions.

CRediT authorship contribution statement

Gábor Pauer: Conceptualization, Writing – original draft, Methodology, Visualization. **Árpád Török:** Conceptualization, Writing – review & editing, Supervision, Methodology.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The research reported in this paper was supported by the Hungarian Academy of Science (HAS) by providing the Janos BOLYAI Scholarship.

The research was supported by the Ministry of Innovation and Technology NRDI Office within the framework of the Autonomous Systems National Laboratory Program.

References

[1] Alonso J, Milanés V, Pérez J, Onieva E, González C, de Pedro T. Autonomous vehicle control systems for safe crossroads. Transp Res Part C Emerg Technol 2011; 19(6):1095–110. https://doi.org/10.1016/j.trc.2011.06.002.

[2] Amer NH, Zamzuri H, Hudha K, Kadir ZA. Modeling and control strategies in path tracking control for autonomous ground vehicles: a review of state of the art and challenges. J Intell Robot Syst 2017;86:225–54. https://doi.org/10.1007/s10846-016-0442-0.

[3] Banda OAV, Kannos S, Goerlandt F, van Gelder PHAJM, Bergström M, Kujala P. A systemic hazard analysis and management process for the concept design phase of an autonomous vessel. Reliab Eng Syst Saf 2019;191:106584. https://doi.org/10.1016/j.ress.2019.106584.

[4] Barna S, Schuchmann G. The performance of road level junctions-the applicability of roundabout nodes with traffic lights (in Hungarian) Közlekedéstudományi Szemle 2017;67(6):30–7. https://doi.org/10.24228/KTSZ.2017.6.3.

[5] Barna, Z., Farkas, L., Kovács, V.Z., Macsinka, K. 2017. Bicycle network plan. Sustainable transport development in Budapest-Road safety and bicycle-friendly developments in the XI. district (in Hungarian). VEKOP-5.3.1-15-2016-00007; Tsz.: 052/2017/03. URL: https://docplayer.hu/105727949-Fenntarthato-kozlekedesfejlesztes-budapesten.html [accessed 10 June 2021].

[6] Beckers K, Holling D, Côté I, Hatebur D. A structured hazard analysis and risk assessment method for automotive systems-a descriptive study. Reliab Eng Syst Saf 2017;158:185–95. https://doi.org/10.1016/j.ress.2016.09.004.

[7] Ben-Akiva M, De Palma A, Kaysi I. Dynamic network models and driver information systems. Transp Res Part A Gen 1991;25(5):251–66. https://doi.org/10.1016/0191-2607(91)90142-D.

[8] Chen A, Yang H, Lo KH, Tang WH. Capacity reliability of a road network: an assessment methodology and numerical results. Transp Res Part B Methodol 2002; 36(3):225–52. https://doi.org/10.1016/S0191-2615(00)00048-5.

[9] Cheng X, Duan D, Yang L, Zheng N. Cooperative intelligence for autonomous driving. ZTE Commun 2019;17(2):44–50.

[10] Colombo A, Del Vecchio D. Least restrictive supervisors for intersection collision avoidance: a scheduling approach. IEEE Trans Autom Control 2015;60(6): 1515–27. https://doi.org/10.1109/TAC.2014.2381453.

[11] Csiszár C, Földes D. System model for autonomous road freight transportation. Promet Traffic Transp 2018;30(1):93–103. https://doi.org/10.7307/ptt.v30i1.2566.

[12] Cuer R, Piétrac L, Niel E, Diallo S, Minoiu-Enache N, Dang-Van-Nhan C. A formal framework for the safe design of the Autonomous driving supervision. Reliab Eng Syst Saf 2018;174:29–40. https://doi.org/10.1016/j.ress.2018.01.014.

[13] de Vos J, Hekkenberg RG, Banda OAV. The impact of autonomous ships on safety at sea-a statistical analysis. Reliab Eng Syst Saf 2021;210:107558. https://doi.org/10.1016/j.ress.2021.107558.

[14] Dinh Van N, Sualeh M, Kim D, Kim GW. A hierarchical control system for autonomous driving towards urban challenges. Appl Sci 2020;10(10):3543. https://doi.org/10.3390/app10103543.
[15] Du L, Goerlandt F, Kujala P. Review and analysis of methods for assessing maritime waterway risk based on non-accident critical events detected from AIS data. Reliab Eng Syst Saf 2020;200:106933. https://doi.org/10.1016/j.ress.2020.106933.
[16] Ed-daoui I, El Hami A, Itmi M, Hmina N, Mazri T. Resilience assessment as a foundation for systems-of-systems safety evaluation: application to an economic infrastructure. Saf Sci 2019;115:446–56. https://doi.org/10.1016/j.ssci.2019.02.030.
[17] Elfes A. Using occupancy grids for mobile robot perception and navigation. Computer 1989;22(6):46–57. https://doi.org/10.1109/2.30720.
[18] Földes D, Csiszár C, Tettamanti T. Automation levels of mobility services. J Transp Eng Part A Syst 2021;147(5). https://doi.org/10.1061/JTEPBS.0000519.
[19] Friesz TL, Kim T, Kwon C, Rigdon MA. Approximate network loading and dual-time-scale dynamic user equilibrium. Transp Res Part B Methodol 2011;45(1):176–207. https://doi.org/10.1016/j.trb.2010.05.003.
[20] Fu R, Li Z, Sun Q, Wang C. Human-like car-following model for autonomous vehicles considering the cut-in behavior of other vehicles in mixed traffic. Accid Anal Prev 2019;132:105260. https://doi.org/10.1016/j.aap.2019.105260.
[21] Ghadhab M, Junges S, Katoen JP, Kuntz M, Volk M. Safety analysis for vehicle guidance systems with dynamic fault trees. Reliab Eng Syst Saf 2019;186:37–50. https://doi.org/10.1016/j.ress.2019.02.005.
[22] Gil M. A concept of critical safety area applicable for an obstacle-avoidance process for manned and autonomous ships. Reliab Eng Syst Saf 2021;214:107806. https://doi.org/10.1016/j.ress.2021.107806.
[23] Gonzales EJ, Daganzo CF. Morning commute with competing modes and distributed demand: user equilibrium, system optimum, and pricing. Transp Res Part B Methodol 2012;46(10):1519–34. https://doi.org/10.1016/j.trb.2012.07.009.
[24] Guikema S, Gardoni P. Reliability estimation for networks of reinforced concrete bridges. J Infrastruct Syst 2009;15(2). https://doi.org/10.1061/(ASCE)1076-0342(2009)15:2(61).
[25] Hegde J, Rokseth B. Applications of machine learning methods for engineering risk assessment-a review. Saf Sci 2020;122:104492. https://doi.org/10.1016/j.ssci.2019.09.015.
[26] Huang C, Li L. Architectural design and analysis of a steer-by-wire system in view of functional safety concept. Reliab Eng Syst Saf 2020;198:106822. https://doi.org/10.1016/j.ress.2020.106822.
[27] Hult R, Campos GR, Steinmetz E, Hammarstrand L, Falcone P, Wymeersch H. Coordination of cooperative autonomous vehicles - toward safer and more efficient road transportation. IEEE Signal Process Mag 2016;33(6):74–84. https://doi.org/10.1109/msp.2016.2602005.
[28] Hunt ER, Hauert S. A checklist for safe robot swarms. Nat Mach Intell 2020;2(8):420–2. https://doi.org/10.1038/s42256-020-0213-2.
[29] ISO 26262. Road vehicles-functional safety, international standard. Geneva, Switzerland: ISO International Organisation for Standardisation; 2018.
[30] ISO/PAS 21448. Road vehicles-safety of the intended functionality (SOTIF). Geneva, Switzerland: ISO International Organisation for Standardisation; 2019.
[31] Jagtman HM, Hale AR, Heijer T. A support tool for identifying evaluation issues of road safety measures. Reliab Eng Syst Saf 2005;90(2–3):206–16. https://doi.org/10.1016/j.ress.2004.11.002.
[32] Jenior, P., Haas, P., Butsick, A., Ray, B. Capacity analysis for planning of junctions (CAP-X) tool user manual. Technical Report User Manual-TBD 2018. Report No. FHWA-SA-18-067, Contract or Grant No. DTFH61-16-D-00017. URL: >http://www.cmfclearinghouse.org/collateral/FHWA-SA-18-067%20CAP-X%202018%20Tool%20User%20Guide%20(Final).pdf [accessed 19 July 2021].
[33] Khastgir S, Brewerton S, Thomas J, Jennings P. Systems approach to creating test scenarios for automated driving systems. Reliab Eng Syst Saf 2021;215:107610. https://doi.org/10.1016/j.ress.2021.107610.
[34] Kletz TA. Hazop-Past and future. Reliab Eng Syst Saf 1997;55(3):263–6. https://doi.org/10.1016/S0951-8320(96)00100-7.
[35] Koschuch M, Sebron W, Szalay Z, Török Á, Tschiürtz H, Wahl I. Safety & security in the context of autonomous driving. 2019. In: Proceedings of the IEEE international conference on connected vehicles and expo (ICCVE); 2019. p. 1–7. https://doi.org/10.1109/ICCVE45908.2019.8965092. 2019.
[36] Lee J, Mitici M. An integrated assessment of safety and efficiency of aircraft maintenance strategies using agent-based modeling and stochastic Petri nets. Reliab Eng Syst Saf 2020;202:107052. https://doi.org/10.1016/j.ress.2020.107052.
[37] Leveson N. A systems approach to risk management through leading safety indicators. Reliab Eng Syst Saf 2015;136:17–34. https://doi.org/10.1016/j.ress.2014.10.008.
[38] Levin MW, Boyles SD. A multiclass cell transmission model for shared human and autonomous vehicle roads. Transp Res Part C Emerg Technol 2016;62:103–16. https://doi.org/10.1016/j.trc.2015.10.005.
[39] Liang Y, Zhang S, Wang Y. Data-driven road side unit location optimization for connected-autonomous-vehicle-based intersection control. Transp Res Part C Emerg Technol 2021;128:103169. https://doi.org/10.1016/j.trc.2021.103169.
[40] Martin H, Ma Z, Schmittner C, Winkler B, Krammer M, Schneider D, Amorim T, Macher G, Kreiner C. Combined automotive safety and security pattern engineering approach. Reliab Eng Syst Saf 2020;198:106773. https://doi.org/10.1016/j.ress.2019.106773.
[41] Maturana D, Scherer S. VoxNet: a 3D convolutional neural network for real-time object recognition. In: Proceedings of the IEEE/RSJ international conference on intelligent robots and systems (IROS); 2015. p. 922–8. https://doi.org/10.1109/IROS.2015.7353481. 28 September –3 October 2015.
[42] Mauborgne P, Deniaud S, Levrat E, Bonjour E, Micaelli J-P, Loise D. Operational and system hazard analysis in a safe systems requirement engineering process-application to automotive industry. Saf Sci 2016;87:256–68. https://doi.org/10.1016/j.ssci.2016.04.011.
[43] Mouhagir H, Cherfaoui V, Talj R, Aioun F, Guillemard F. Trajectory planning for autonomous vehicle in uncertain environment using evidential grid. IFAC PapersOnLine 2017;50(1):12545–50. https://doi.org/10.1016/j.ifacol.2017.08.2193.
[44] Mutz F, Veronese LP, Oliveira-Santos T, de Aguiar E, Cheein FAA, De Souza AF. Large-scale mapping in complex field scenarios using an autonomous car. Expert Syst Appl 2016;46:439–62. https://doi.org/10.1016/j.eswa.2015.10.045.
[45] Naranjo JE, Gonzalez C, Garcia R, de Pedro T. Lane-change fuzzy control in autonomous vehicles for the overtaking maneuver. IEEE Trans Intell Transp Syst 2008;9(3):438–50. https://doi.org/10.1109/TITS.2008.922880.
[46] Narayanan S, Chaniotakis E, Antoniou C. Shared autonomous vehicle services: a comprehensive review. Transp Res Part C Emerg Technol 2020;111:255–93. https://doi.org/10.1016/j.trc.2019.12.008.
[47] Nourinejad M, Bahrami S, Roorda MJ. Designing parking facilities for autonomous vehicles. Transp Res Part B Methodol 2018;109:110–27. https://doi.org/10.1016/j.trb.2017.12.017.
[48] Zheng XW, Li HN, Gardoni P. Life-cycle probabilistic seismic risk assessment of high-rise buildings considering carbonation induced deterioration. Eng Struct 2021;231:111752. https://doi.org/10.1016/j.engstruct.2020.111752.
[49] Pauer G, Török Á. Binary integer modeling of the traffic flow optimization problem, in the case of an autonomous transportation system. Op Res Lett 2020;49(1):136–43. https://doi.org/10.1016/j.orl.2020.12.004.
[50] Pendleton SD, Andersen H, Du X, Shen X, Meghjani M, Eng YH, Rus D, Ang MH. Perception, planning, control, and coordination for autonomous vehicles. Machines 2017;5(1):6. https://doi.org/10.3390/machines5010006.
[51] Sage AP, White EB. Methodologies for risk and hazard assessment: a survey and status report. IEEE Trans Syst Man Cybern 1980;10(8):425–46. https://doi.org/10.1109/TSMC.1980.4308532.
[52] Sahin B, Soylu A. Multi-layer, multi-segment iterative optimization for maritime supply chain operations in a dynamic fuzzy environment. IEEE Access 2020;8:144993–5005. https://doi.org/10.1109/ACCESS.2020.3014968.
[53] Sahin B, Yazidi A, Roman D, Soylu A. Ontology-based fault tree analysis algorithms in a fuzzy environment for autonomous ships. IEEE Access 2021;9:40915–32. https://doi.org/10.1109/ACCESS.2021.3061929.
[54] Saqib N, Siddiqi MT. Thresholds and goals for safety performance indicators for nuclear power plants. Reliab Eng Syst Saf 2005;87(2):275–86. https://doi.org/10.1016/j.ress.2004.05.006.
[55] Shannon D, Jannusch T, David-Spickermann F, Mullins M, Cunneen M, Murphy F. Connected and autonomous vehicle injury loss events: potential risk and actuarial considerations for primary insurers. Risk Manag Insur Rev 2021;24(1):5–35. https://doi.org/10.1111/rmir.12168.
[56] Singh V, Pitale M. Impact of automotive system safety design on machine learning based perception systems. In: Proceedings of the 4th IEEE international conference on industrial cyber-physical systems (ICPS); 2021. p. 591–6. https://doi.org/10.1109/ICPS49255.2021.9468225. 2021.
[57] Sinha P. Architectural design and reliability analysis of a fail-operational brake-by-wire system from ISO 26262 perspectives. Reliab Eng Syst Saf 2011;96(10):1349–59. https://doi.org/10.1016/j.ress.2011.03.013.
[58] Sipos T, Mekonnen A, Szabó Z. Spatial econometric analysis of road traffic crashes. Sustainability 2021;13(5):2492. https://doi.org/10.3390/su13052492.
[59] Szalay Z. Next generation X-in-the-loop validation methodology for automated vehicle systems. IEEE Access 2021;9:35616–32. https://doi.org/10.1109/ACCESS.2021.3061732.
[60] Thieme CA, Utne IB. A risk model for autonomous marine systems and operation focusing on human-autonomy collaboration. J Risk Reliab 2017;231(4):446–64. https://doi.org/10.1177/1748006X17709377.
[61] Törő O, Bécsi T, Aradi S. Design of lane keeping algorithm of autonomous vehicle. Period Polytech Transp Eng 2016;44(1):60–8. https://doi.org/10.3311/PPtr.8177.
[62] van Nes N, Brandenburg S, Twisk D. Improving homogeneity by dynamic speed limit systems. Accid Anal Prev 2010;42(3):944–52. https://doi.org/10.1016/j.aap.2009.05.002.
[63] Wahle J, Bazzan ALC, Klügl F, Schreckenberg M. Decision dynamics in a traffic scenario. Phys A Stat Mech Appl 2000;287(3–4):669–81. https://doi.org/10.1016/S0378-4371(00)00510-0.
[64] Wang X, Qin D, Cafiso S, Liang KK, Zhu X. Operational design domain of autonomous vehicles at skewed intersection. Accid Anal Prev 2021;159:106241. https://doi.org/10.1016/j.aap.2021.106241.

[65] Xu D, Shi Y, Ji Z. Model-free adaptive discrete-time integral sliding-mode-constrained-control for autonomous 4WMV parking systems. IEEE Trans Indust Electron 2017;65(1):834–43. https://doi.org/10.1109/TIE.2017.2739680.
[66] Xu Z, Saleh JH. Machine learning for reliability engineering and safety applications: review of current status and future opportunities. Reliab Eng Syst Saf 2021;211:107530. https://doi.org/10.1016/j.ress.2021.107530.
[67] Yang H, Bell MGH. Models and algorithms for road network design: a review and some new developments. Transp Rev 1998;18(3):257–78. https://doi.org/10.1080/01441649808717016.
[68] Yu R, Abdel-Aty M. An optimal variable speed limits system to ameliorate traffic safety risk. Transp Res Part C Emer Technol 2014;46:235–46. https://doi.org/10.1016/j.trc.2014.05.016.
[69] Zhu F, Ukkusuri SV. A linear programing formulation for autonomous intersection control within a dynamic traffic assignment and connected vehicle environment. Transp Res Part C Emerg Technol 2015;55:363–78. https://doi.org/10.1016/j.trc.2015.01.006.