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Safety aspects of critical scenario identification for autonomous transport

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Abstract

An important part of the definition of sustainability is safety. This study is based on the basic concept of connected transport systems. After defining the basic model, the research aims to simplify the models of highly automated transport systems that are suitable for safety assessment of critical scenarios, including various safety aspects. Accordingly, the basic safety requirements of autonomous systems responsible for the management of traffic processes are summarized. Based on the derived requirements, some of the most relevant safety indicators and the constraints of the simplification process are listed.

Keywords

Safety of traffic management processes, safety indicators, safety constraints

1. Introduction

Safety is an important part of the definition of sustainability. The easiest way to underpin this statement with widely accepted documents is to refer to the *Global Sustainable Development Report* (Messerli et al., 2019). This well-known study confirms that transportation including traffic safety plays an important role in sustainability. It also states that intelligent urban technologies should contribute to the reduction of CO_2 emission efficiently and to the development of traffic safety to achieve sustainable development goals.

Consequently, when examining conscious sustainability, we must definitely address the safety of autonomous systems in future transport systems (Mikusova, 2017). Nowadays, research aims at further improving the safety characteristics of modern, highly automated systems (Fu et al., 2019; Huang and Li, 2020). The present research aims to investigate the safety characteristics of autonomous road transport systems as a binary integer-programming problem.

Mathematical modeling of road traffic processes has been studied in several previous studies (Lo and Szeto, 2002; Szeto and Lo, 2004; Waller and Ziliaskopoulos, 2006; Yperman, 2007; Yperman et al., 2007; Tampère et al., 2011; Torok et al., 2014; Tettamanti et al., 2016; Pauer and Török, 2019). The automation of transport systems is greatly supported by the spread of infocommunication and vehicle technologies. Földes, Csiszár and Tettamanti (2021) draw attention to the fact that the level of automation of a system is significantly influenced by vehicle and traffic control, among other things. Based on Mikusova's results, the safety of transport systems is supported by many vehicle systems. Still, the author emphasizes that the interconnection and extension of these systems can contribute to reducing the safety risk of transport systems as an additional system-level factor (Mikusova, 2017). In their research, Lengyel, Tettamanti, and Szalay 2020) paid special attention to examining the expected conflicts between the autonomous transport systems of the future and the transport infrastructure of the present. Their results confirmed that future transport systems could not be adapted to the current infrastructure requirements in all areas, as it is expected that infrastructure will also need to be redesigned. Zöldy (2018) and Szendro et al. (2014) dealt more thoroughly with the limitations of the spreading of autonomous vehicles. They noted that increasing the level of automation could significantly reduce the environmental impact of our transportation systems; however, legal barriers will limit the spread of full automation for a long time.

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Our study is based on the basic concept of connected transport systems, which assumes that transport system components located close to each other in space and time can form an ad-hoc network The components of these networks collect, receive, and transmit information about their own state, perceived environmental characteristics, and other system users (Dinh Van et al., 2020). Of course, in addition to vehicles, other road users (such as pedestrians) can connect to the network. After defining the basic model, the research aims to simplify the models of highly automated transport systems that are suitable for safety assessment (Török, 2020) of critical scenarios, including various safety aspects (Zhu and Ukkusuri, 2015; Szalay et al., 2017).

2. Methodology

We have to emphasize that this section describes the outcomes of a long and complex research project. The derived basic model and the introduced simplification methods are introduced in the cited articles (Pauer and Török, 2021; 2022); accordingly, this paper focuses on concluding the most relevant safety aspects of the entire research process.

A detailed literature review was conducted in the first phase of the research. Subsequently, a basic linear model was developed, which is suitable for examining the safety issues of autonomous transport systems (Derenda et al., 2018). As a first step, we conducted a literature review of methods for safety evaluation of critical scenarios for linear models describing highly automated transport systems (Daganzo, 1994–1995;Peeta and Ziliaskopoulos, 2001; Török, 2011). Based on this, we identified the essential development directions that provide an opportunity to simplify the models consisting of a large number of equations. The main goal of the linear model is, in addition to the parameters suitable for system-level traffic optimization, to provide the possibility to map certain vehicle-level critical dynamic conditions (Pauer and Török, 2021). In this process, the simple representation of the system is a priority, in order to create an opportunity for fast, reliable, and safe operation (Pauer and Török, 2022). The simplification of the conditions related to velocity and acceleration is a primary research task, as the constraint functions associated with them are generally non-linear. Among the system-level security conditions, it is advisable to highlight:

– constraints of the prohibition regarding the dangerous crossings of traffic flows;

– representation of the directions allowed by the traffic rules.

The most important safety conditions at the vehicle level are:

– linear representation of the maximum permitted speed limit;

– linear representation of the maximum allowable acceleration limit;

– linear representation of the maximum deceleration limit.

Subsequently, we simplified the procedure for the safety assessment of the critical scenarios (Szalay, 2021; Nyerges and Szalay, 2017) of the developed linear model. In the course of simplification, particular attention had to be paid to the equations for safety-critical aspects, considering the relationship between the indicators used to describe the efficiency and safety of systems. In the second phase of the research, some scenarios affecting the system with a high level of risk were identified, as well as possible forms of malicious intervention for the system, such as:

– the effect of random failures of certain components;

– modeling the behavior of a system component to maximize the adverse effects of an intentional accident.

By representing the developed scenario variants in the system, it is possible to examine the impact of the examined cases and analyze the risks and vulnerabilities related to the system.

3. Results

3.1 The linear model

To make the real-time management processes of vehicle traffic more efficient (Szabó and Sipos, 2020), some operations based on static information are performed offline, thus making it possible to reduce the complexity of real-time calculations. Following the above, the speed values required to travel between the network node pairs are determined based on node distances. Thus, the vehicle speed between two given points per time unit can be defined. In addition, the distance between

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the network nodes is used to calculate the required rate of vehicle speed change when traveling through a specific node triplet.

In the next step, the basic criteria for traffic safety were defined. If these requirements (Table 1) are not fulfilled, safety cannot be guaranteed.

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Table 1. Criteria for traffic safety

Considered safety criteria
Only one component can be in one position at a time.
A component can only be in one position at a time.
The trajectories of components at the same time must not cross each other.
Vehicles must not exceed the speed limit.
The acceleration of vehicles shall not exceed the predefined acceleration limit.
The deceleration of vehicles shall not exceed the predefined deceleration limit.

3.2 Safety indicators

The safety level of the current system processes could be evaluated through real-time indicators. Accordingly, we need indicators that can be used to measure the risk posed by the processes. Thus, the factors that significantly affect the severity or probability of accidents related to the transport system must be examined (Sipos et al., 2021; Jima and Sipos, 2022). The different characteristics of vehicle speed, acceleration, and intersecting movements are key factors. In this context, the following considerations shall be taken into account.

1. Kinetic energy depends squarely on the speed, so a higher risk can characterize the system in which the components move at a faster speed.
2. System homogeneity improves system safety, so a system in which:
   a) the speed values of components vary less, can be considered safer (the specific vehicles apply similar speed levels);
   b) the speed of specific components changes less (the speed profiles of the particular vehicles are less variable over time – vehicles accelerate and decelerate less) can be considered safer.
3. The potential conflict of intersecting movements results in critical situations. Therefore, in the case of successive movements, a relationship between their temporal distance and the probability of accidents can be assumed. Consequently, a system is considered safer than another at a given unit of time if the sum of the time distances between system components is larger.

3.3 Random failure

In the case of random failures, specific risk scenarios should be analyzed separately, taking into account the severity of the potential accident and the probability of its occurrence. This approach allows us to identify cases classified as hazardous regarding accident risk and, if possible, prefer safer scenarios where appropriate.

3.4 Intentional Malicious Intervention

The safety and security of the connected systems of the future will depend heavily on the reliability of wireless communication between components. Accordingly, basic communication parameters such as latency or packet reception rate will significantly determine the security of future systems. Based on these considerations, for example, the intentional malicious modification of these parameters may increase the risk level in the system.

Accordingly, from the viewpoint of cyber security, cases in which the initial scenario is considered secure, but the change/modification in network performance indicators leads to dangerous scenarios can be classified as high-risk.

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4. Conclusion

In our interdisciplinary research, we aimed to investigate the field of intelligent transport systems.

The following basic safety requirements have been defined for highly connected and automated traffic management systems:

1. One location can be occupied by only one system component at a given time step.
2. One system component can only be located in one position at a given time step.
3. System components are not allowed to have intersecting movements at a given time step.
4. System components are not allowed to apply higher velocity than the speed limit.
5. System components are not allowed to apply higher acceleration than the acceleration limit.
6. System components are not allowed to apply higher deceleration than the deceleration limit.

As the described model can define several suboptimal assignment alternatives regarding the possible combinations of input variables, we can distinguish between scenarios that are sensitive to safety or cybersecurity parameters.

To select the safety and cybersecurity sensitive suboptimal feasible solutions, we recommend using the following indicators:

1. Severity indicator represents the kinetic energy, which depends squarely on the speed. Accordingly, higher risk can characterize the system in which the components move at a faster speed.
2. System homogeneity indicator assumes that homogeneity improves system safety. Accordingly, if
   a. the standard deviation of the velocities in a system is smaller, then this system can be considered safer than another system, the variance of the velocities of its components is larger;
   b. the standard deviations of the velocity of certain components are smaller in a system, then this system can be considered safer than another system, in which the variances of the velocity of the certain components are larger.
3. Crossing movements can cause critical events; hence, in the case of successive movements, a dependency between the temporal distances and the collision risk can be expected. In the light of this, we consider a system safer than another at a given unit of time if the sum of the time distance between system components is larger.

We must realize that in addition to increasing efforts to improve efficiency, we must also pay more and more attention to safety. On the one hand, these efforts are inevitable to ensure the required safety level of highly automated transport systems. On the other hand, high complexity systems can only achieve the expected safety-enhancing effect if a careful safety preparation procedure supports the system development process.

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