Selected aspects of the road infrastructure in relation to vehicle automation

Dr. Attila Borsos*, Dr. Csaba Koren*, Dr. Emese Makó*, Dr. Dániel Miletics*, Richárd Nagy*

**Széchenyi István University, Győr, Hungary (Tel: 36 96 503 452; e-mail: borsosa@sze.hu)*

Abstract: The development of automated vehicles showed a rapid pace in the recent past, however less attention has been paid to the implications of vehicle automation on safe infrastructure design. This paper gives an introduction to a project addressing this gap. The project entitled "Autonomous vehicles and safe road infrastructure" started recently and will last for five years (June 2019 – May 2024). As a result of several brainstorming sessions five topic areas have been formed as follows: 1) Road design (certain design aspects related to intersections, cross-section and road sections); 2) Detection and perception (road work zones, traffic calming devices, road edges, road markings, and traffic signs); 3) Pavement design (implications of AVs on pavement design); 4) Vulnerable road users (communication and behavioral adaptation); 5) Miscellaneous topics (e.g. traffic conflict analysis, certain aspects of the digital infrastructure). These broad areas have been broken down into specific research tasks. This paper gives an introduction of these research topics.

1. INTRODUCTION

Vehicle automation has shown a rapid development in the past few years. While the vehicle industry seems to be well advanced in automation, the formulation of requirements in relation to the road infrastructure supporting Automated Vehicles (AV) as well as the effects of AVs in the civil and transportation engineering domains have been investigated to a much lesser extent.

In the past few years researchers have started to fill this gap, recently Farah et al. (2018) presented a state of the art on this topic considering both the digital and the physical infrastructure. They also concluded that a considerable research effort exists with respect to the digital infrastructure, while for the physical infrastructure it is scarce. Based on the state of the art, and a brainstorming workshop involving experts from different disciplines in the Netherlands, a detailed mind map was presented and recommendations for future research directions were suggested.

For Hungarian conditions, Egyházy recommended the integration of two fields: on one hand the rapidly evolving IT solutions and on the other hand the "low tech" road design guidelines having many decades of experience (Egyházy, 2019).

A project addressing the connection in between autonomous vehicles and road infrastructure has been recently launched at our department. In the past year several brainstorming events were held and a mind-map of possible research topics has been laid out. These topics were clustered into five groups: road design, detection and perception, pavement design, vulnerable road users and miscellaneous topics. The aim of this paper is to give an introduction of these project ideas.

2. ROAD DESIGN

A lot of rules and parameters of road design guidelines (e.g. curvature, superelevation and sight distances) are based either on vehicle dynamics and/or on human capabilities (e.g. reaction time). Autonomous vehicles are coming soon to our roads. Even though they will coexist with traditional ones for a longer period, thinking about potential savings in road space, required sight distances etc. has started. This section tries to give an overview of potential changes in geometric design rules due to automated vehicles.

2.1 Review of design parameters

The most important factors determining current road design parameters are the physical characteristics of vehicles, vehicle dynamics, traffic volume, physical and mental abilities of the driver, drainage, comfort and safety. With the spread of automated vehicles some of these determinants will change, others will not, or only slightly. Vehicles of the future may also set new requirements for the transport infrastructure.

The most significant difference is expected to be that the sensors replacing the human vision are not located in the same place (inside or outside of the vehicle) and the accuracy of the human eye and the sensors are also different. There are many design parameters that can be explained by the functioning of the human brain and by psychological reasons. No significant change is expected in vehicles or vehicle dynamics, however due to the increasingly stringent environmental regulations and the range requirements for electric vehicles, passenger cars are expected to be smaller and lighter. The research topic focuses on how the aspects listed above will affect the way roads are designed and operated. The goal is to identify design parameters that need to be changed (e.g.: sight distances).

2.2 Intersections

Intersections are a dangerous part of the road network because the paths of different vehicles can cross each other here. Approaching intersections human drivers must collect information about the traffic regulation, positions of other vehicles and decide quickly about entering the junction or not. Intersections represent a special task for AVs, too.

2.2.1 Visibility at intersections

Current visibility requirements at unsignalized intersections are based on speeds on the major road and on accepted gaps by human drivers entering or crossing from the minor road. Autonomous vehicles survey their environment with sensors which are different from the human vision in terms of identifying objects, estimating distances or velocities of other vehicles (Magyari, Koren, 2019).

This section will compare current international visibility requirements based on conventional vehicles and those required for autonomous vehicles (Harwood et al., 1995; HRRS, 2004; HA, 1995; FGSV, 2012). Visibility requirements are defined by three vision indicators: distance, angle of view and resolution abilities of autonomous cars and human drivers. These indicators are calculated separately for autonomous vehicles and human drivers for various speeds on the main road and in case of rectangular and 60-degree connection angle.

The aim of this part of the research is to clarify the visibility requirements necessary for AVs at unsignalized crossings. The following four topics will be covered: 1. Requirements for AVs' sensors (distance and speed measurement, angular resolution). 2. Identifying the required sight distances for AVs (level 4). 3. Testing the theoretical parameters. 4. Impacts of the improved parameters on traffic flow. Field measurements and traffic simulations will be used.

2.2.2 Capacity calculation of roundabouts

Besides geometric design it is generally accepted that the presence of pedestrians and bicycles affect the capacity of roundabouts. The capacity calculation of urban roundabouts varies from country to country, some consider crossing pedestrians and/or bicycles, and some do not. The range of conflicting situations to be considered is also a question as they can come in several forms: the effect of crossing bicycle or pedestrian traffic at entry, the effect of crossing bicycle or pedestrian traffic at exit that might result in a spillback, as well as the so-called pseudo conflict caused by the uncertain behavior of the circulating traffic.

Researchers have already investigated how the introduction of AVs could change the operational and safety parameters at roundabouts (Deluka et al., 2018), however less or little attention has been paid to how the above detailed interactions with AVs will exert an influence on capacity.

The capacity calculation prescribed in the current Hungarian guideline (HRRS, 2010) already has several limitations. The aim of this research topic is therefore 1) to update the already existing capacity calculation methods of roundabouts considering all road users and 2) to simulate how this improved method would be effected by AVs at various penetration rates.

2.2.3 Changes in the design of signal-controlled intersections

Geometric design and capacity calculation of signalized intersections, among others the placement of signal heads and stop lines, or headways are based on driver's capabilities (HRRS, 2009). Some design parameters are expected to change with the spread of autonomous vehicles thanks to their improved sensing and communication performance (Sohrweide, 2018). Potential changes are smaller intersection cores (replacement of stop lines), fewer traffic lanes, increased capacity (shorter headways), improved level of service for pedestrians and cyclists (longer green times, pedestrian scrambles), V2I communication, etc. The goal of this part of the research project is the identification of possible changes and analysis of signalized intersections at different penetration levels of AVs.

2.3 Cross section

Cross-sectional design is a very important characteristic of road categories, it has a significant influence on the capacity of road sections and on the effective speed of vehicles. Sufficient capacity is basically achieved through the number of traffic lanes; speed depends on the traffic volume itself, on the road alignment and on lane widths.

2.3.1 Review of traffic lane widths

Current lane widths are determined taking into account the driver's lane keeping capability, vehicle width, and speed. Autonomous vehicles – and any other vehicles equipped with a lane keeping assistant system – are able to follow the axis of the traffic lane much more precisely, so the width of the vehicles is expected to be the most important determining factor of the lane width in the future. The width of the lane however cannot be reduced as long as conventional and automated vehicles share the traffic lane. A reduction in the total width of the road pavement is however questionable (Snyder, 2018) because of the expected growth in the mobility demand (young and elderly people, disabled road users, etc.) The project aims to identify (or define) roads and AV traffic volumes where the road and the traffic can be operated economically with a reduced width of traffic lanes.

2.3.2 Review of level of service (LOS)

Autonomous vehicles are able to move closer to each other (shorter headways, higher density), at a more homogeneous speed, resulting in fewer shockwaves and congestion at higher traffic volumes, and a reduction in delay which is a determining factor of LOS.

Measurement of delays is currently not or only indirectly solved, so traffic design thresholds are linked to specific traffic volumes, which come from traffic counts and – in many cases – estimations. In the future, travel time data of autonomous vehicles may be available in larger quantities and of a better quality because of the improved communication between AVs and the road infrastructure. These data could be directly used for traffic design.

Tracking AVs over time and automatic (not human based) route choice algorithms can make traffic prediction more accurate, privacy questions however can be a barrier in gathering info about specific vehicles. By adding traffic density data (from the distance measured in front of and behind the vehicle) the current GPS and speed-based congestion info (google map, waze, etc.) can be refined.

The space requirements of vehicles and changes in their movement characteristics will affect the currently used passenger car units (PCU) and the fundamental diagrams. The more precise prediction also makes the planning and scheduling of road construction projects easier.

2.4 Road sections

Under this subsection a selected number of project ideas in relation to the design of road sections are described.

2.4.1 Tidal lanes

Tidal lanes (or reversible traffic lanes) make a more efficient use of the cross-sectional space of the road possible, especially on suburban roads with significant commuter traffic. Their economical operation needs a number of factors to be considered at present: location of the junctions (section lengths between them), permissible/required traffic directions of the junction, signal coordination, traffic volumes, change and indication of directions. Some of these factors can be changed in the future: indication can be simpler (V2I communication), multiple lanes may be reversible, etc. This research topic focuses on the potential of tidal lanes in a "smart" environment, trying to answer the question: What conditions have to be provided for wider application of tidal lanes in the presence of AVs?

2.4.2 Speed profiles and speed advice

Speed plays a crucial role in road safety (Mocsári, 2012). The design speed of the road, the posted speed limit, the actual speed and the speed considering vehicle dynamics are not equal in many cases. How can we guarantee that autonomous vehicles choose safe speeds? Often, safe speeds on a particular road section are not indicated by local speed limits. Neither does the image provided by the sensors provide sufficient information. The research focuses on where and what type of information should be provided for autonomous vehicles about safe speeds.

2.4.3 Overtaking sections

On 2x1 lane roads sections suitable for safe overtaking shall be provided as a percentage of the length of the road. The required percentages are specified in the design guidelines (HRRS, 2008). The length of overtaking sections also plays a role in the capacity and the level of service of a given road, but it is also one of the major sources of accident risk on our highways. Overtaking sections (to be designated in the prescribed proportions) often do not provide safe passing possibility and may even deceive the driver (overtaking in large radius curves). The need for overtaking possibilities is explained by the inhomogeneous distribution of vehicle speeds. Automated vehicles however are expected to choose much more homogeneous speeds: they will aim to reach the speed limit and not to exceed it. The vehicles of the future will travel efficiently even in longer platoons, and the need for overtaking is expected to decrease (but not completely eliminated by slower vehicles on the road e.g.). The research focuses on the possible reduction of the length of designated overtaking sections (especially in hazardous areas) and on specifying the conditions under which a "no overtaking" road category may be defined.

3. DETECTION, PERCEPTION

Autonomous vehicles collect a lot of information helping them to prepare decisions in different situations. These cars survey their environment with sensors which are different from the human vision in terms of identifying objects, estimating distances or velocity of other vehicles.

3.1 Road work zones

Due to the large variety of the arrangement of temporary road work zones, their identification is a complicated task for humans, and it can be assumed that it is difficult for AVs too. The goal of this research is to identify the information given by various arrangements of temporary closures to drivers and automated vehicles. A further goal is to find appropriate measures to help AVs to safely recognize these situations and to identify the appropriate actions. In some cases, the right action could be that the human driver takes over control of the situation and at the end of the work zone, the human driver can give back control to the vehicle.

Preliminary research has shown that the use of continuous row of traffic cones, large panels of traffic signs and lighting arrows are very effective to inform the driver about the traffic situation. In these situations, signs with many texts and contradictory messages should be avoided.

The research method will be to collect many pictures and videos of various situations and to analyze them by humans and by picture recognition software. Good and bed solutions will be identified.

3.2 Traffic calming devices

In urban areas, a number of various traffic calming devices are used, like chicanes, middle islands, curb extensions, speed humps etc. Some of them, especially speed humps are difficult to recognize for humans, and it can be assumed that it is difficult for AVs, too. Figure 1 shows an example of a moderately complex situation. The goal of this research is to identify the information given by various arrangements of traffic calming devices to drivers and AVs. A further goal is to find appropriate measures to help AVs to recognize these situations and to identify the right actions, including the appropriate speed at each of these devices.

The research method will be to collect many pictures and videos of various situations and to analyze them by humans and by picture recognition software in terms of recognizability. Speed measurements and acceleration measurements will be taken to select the right speed. Good and bed solutions will be identified.

Fig. 1. A sophisticated traffic calming device

3.3 Road edges

In built-up areas, road or traffic lane edges have layouts which are different from usual continuous painted lane markings, like raised or dropped curbs, or pavements of different material (e.g. cobblestone) or color etc. Usually these devices cause no difficulty for humans to be recognized, but they might be difficult for AVs (Fig. 2). The goal of this research is to identify the information given by various arrangements of road edges to AVs. A further goal is to find appropriate measures to help AVs to recognize these situations and to identify the right actions, including the appropriate distance from these devices.

Fig. 2. Where is the edge of the traffic lane?

The research method will be to collect many pictures and videos of various situations and to analyze them by humans and by picture recognition software in terms of recognizability. Measurements will be taken to assess the distance kept by vehicles from various types of road edges. Good and bed solutions will be identified. Virtual reality situations will be tested.

3.4 Road markings and traffic signs

As it is highlighted by Lu (2018) at the beginning of the transition period (it may be considered that it has already started and lasts until no conventional vehicles are on the roads) the operation of AVs requires reliable recognition and understanding of road markings and traffic signs. The signage system should be unambiguous and homogeneous and tailored to AVs. These principles are declared also in the Vienna Convention on Road Signs and Signals of 1968 (UN, 1968) and in the 2019/1936 EU Directive (EU, 2019).

AVs encounter difficulties in harsh weather conditions (extreme rainfall, snow, fog) (Sohrweide, 2018) due to restricted recognizability of pavement marking and traffic signs. Traffic sign recognition is already one of the assistant systems offered by some car manufacturers and recent researches show improving results in terms of accuracy (99%<) of such systems (Aziz et al., 2018), however processing complex, multiple-sign situations are poorly discussed (Fig. 3).

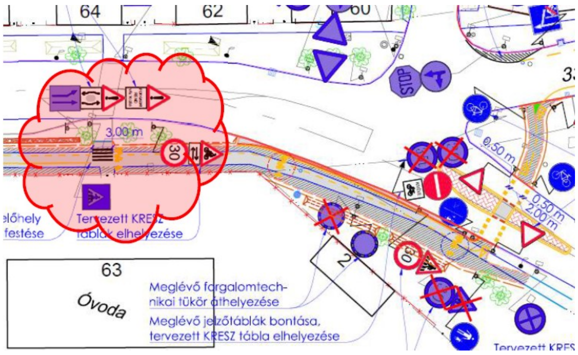

Fig. 3. Example of complex situations with multiple traffic signs

3.4.1 Extra information at dangerous locations

In terms of road markings, the research focuses on how additional information placed in the continuously monitored pavement markings can help the safe operation of autonomous vehicles. For instance, the implementation (length, frequency, etc.) of dashed lines, the width of the lines and the ending/shape of the lines may give additional information to the self-driving vehicle. This additional information can be such as indication of the traffic lane in which the AV is located, indication of the correct direction (e.g. dashed lines ending in an arrow to avoid wrong-way driving) and speed advice. These "codes" hidden in the pavement markings could be read by advanced sensors of self-driving vehicles, but some solutions can be useful for conventional drivers, as well.

The research also aims to analyze the possibility of using traffic signs developed specifically for AVs. As a first step QR-code based traffic signs will be tested.

3.4.2 Visibility under various weather conditions

Adverse weather conditions (heavy rain, snowfall, snow/ice covered pavement, fog) impair the visibility of road markings and traffic signs. This research topic focuses on the extent to which different weather conditions influence the visibility of pavement markings and the means by which the adverse effects can be reduced.

4. PAVEMENT DESIGN

Extending the lifetime of road pavement and service level sustainability over time depends on several factors. Our current design process takes into account, among other parameters, the number of unit axes passed, cross-sectional design, local weather conditions, pavement structure and properties of the road pavement materials. Pavement design will be significantly affected by the arrival of autonomous vehicles on the roads. This effect is clearly dependent on the level of automation and it is increasing as it grows, some of the input parameters will probably change, weights may shift, and other new parameters need to be addressed.

4.1 Effect of axle lateral wandering

The first question that several authors have addressed (Noorvand et al., 2017; Chen et al., 2019) is the axle lateral wandering with the appearance of autonomous vehicles. Because the autonomous vehicles wheel path is expected to be much more accurate than that of human-driven vehicles, load distribution may be more concentrated.

A study (Noorvand et al., 2017) deals with the effect of channeled traffic, which, in the framework of the accelerated pavement testing procedure, has 25-45% greater rutting on sections where vehicles follow the same track compared to those where lateral wandering had a normal distribution (Fig. 4).

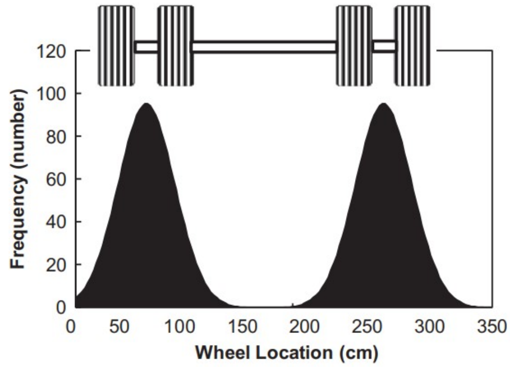

Fig. 4. Probability distributions of normally distributed non-autonomous trucks (Noorvand et al., 2017)

A possible scenario with the emergence of AVs is much narrower roads and less pavement, where reinforcing the track structure will become necessary. The additional destructive effect of the increase in load should be examined in the Hungarian environment, paying special attention to the difference between straight and curved sections.

Another possible effect of AVs on pavement design is the operating speed and the clearance between vehicles (Harvey et al., 2000). Vehicle speed affects the contact time between the wheel and the road surface. Thus, the process can be designed and optimized for specific load frequency sensitivity. Load frequency significantly affects which deformation occurs, elastic or permanent, therefore, this topic is also very important if we have the ability to influence the flow of traffic. It follows from the above that autonomous vehicles are capable of accelerating and decelerating at predetermined parameters under controlled conditions. In this way, the surface stresses transmitted to the road pavement can be optimized.

One can also expect that there will be fewer stops at intersections. AVs have a better control mechanism in urban areas, combined with advanced traffic lights that can be used to reduce the frequency of vehicle stops at intersections. As a result, the occurrence of longitudinal stress is reduced leading to a smaller likelihood of permanent deformation.

4.2 Effect of 2D and 3D sensors

The input parameters of our current design processes are provided by expert assessment and are not based on real-time information. Conversely, if we can design a roadway structure in which the sensors provide up-to-date road status, it will significantly influence our design process. Yang (2014) and Xu et al. (2015) provide a very good basis for these effects. The research focuses on two main issues, one of which is the best positioning of the sensors for accurate communication. Another aspect is the effect of sensors on the road pavement.

This research aims to provide answers to the following questions:

What physical parameters must the sensors have to be built into the road pavement?

What physical parameters are detected by the built-in sensor that can be used to help road pavement design?

At what installation density can the road pavement provide the expected load-bearing capacity and satisfy other performance measures?

Does the shape and size of the sensor affect the low and high temperature behavior of the track structure?

4.3 Wheel spray effect

Several studies (Kabanovs et al., 2019; Kumar et al., 2012) point to the importance of examining wheel spray formation. It is an important issue not only because of the tire-pavement interaction but also has an impact on the reliability of in-vehicle sensors. We have to test the confidence limits of in-vehicle sensors as a function of the degree of water fog formation taking into account the vehicle's tire and asphalt type.

5. VULNERABLE ROAD USERS

Automated vehicle technology has mainly focused on the detection and recognition of pedestrians and cyclists by the vehicle and even though good progress has been made, many difficulties are yet to be overcome (e.g. reliable operation in adverse weather conditions) (Vissers et al., 2016).

Behavior of pedestrians and cyclists is also crucial for safe interactions between automated vehicles and pedestrians/cyclists. According to some studies (Lagström et al., 2015; Lundgren et al., 2017) pedestrians and cyclists were found to appreciate messages and/or signals from the car indicating whether the car has detected them and what it intends to do. However, which exact messages need to be brought about and the method of communicating them are not yet settled and this requires further study.

One of the questions concerns the safe interaction of automated cars with pedestrians and cyclists, and in particular how pedestrians and cyclists react to automated vehicles and whether this would affect their expectations and their behavior.

5.1 AV and pedestrian communication

A few studies looked into the effects of different communication cues on the interaction between pedestrians, cyclists and motorized vehicles. Several studies have demonstrated the effect of eye contact between a pedestrian who wants to cross and an approaching car driver.

Will there be new communication needs to warrant safe interactions with automated vehicles?

In this research, we would like to investigate how pedestrians are willing to cross the street at designated crossings when the driver of the approaching car is not communicating with the pedestrians (inattentive or showing uncommon driver behavior). An automated vehicle (or a dummy vehicle that pretends it is an AV) is going to inform the pedestrian about its mode and intentions using a LED-surface on the car hood displaying different communication patterns. Pedestrians will be notified by lights and in some cases even by auditory signals when they are seen by the approaching 'automated vehicle'. Several LED communicating patterns with and without auditory signals will be set individually as cases of the trial on public roads.

Will those communication tools help pedestrians understand the intentions of the automated vehicles? Which combination of the tools is the most adequate for this purpose? Those questions will be answered under this research topic

5.2 AV and bicycle communication

Cyclists may have incorrect expectations of the behavior of automated vehicles in interactions with them, which could bring extra risks in traffic.

Cyclists communicate with car drivers very similarly to pedestrians at crossings. Eye contact, hand gestures, non-verbal communication have significant role for cyclists, as well. Nevertheless, their speed is much higher than pedestrian's even in urban environment. Moreover, the priority rules at designated bicycle crossings differ, in some cases the cyclists have to yield in other cases the motor vehicles have to yield to cyclists. It creates some uncertainty at designated bicycle crossings compared to designated pedestrian crossings.

In this research the LED-display and the auditory signal introduced under the previous section will be applied for investigating the communication between the driver of an automated vehicle and the cyclists at designated bicycle crossings.

5.3 Effect of pedestrians' behavioral adaption on road capacity

Autonomous vehicles will prioritize the safety of pedestrians (and other vulnerable road users) over traffic flow. As a result, pedestrians would receive all of the benefits of automated vehicles and would interrupt traffic flow, while the technology is rendered increasingly unattractive to drivers (Botello et al., 2019).

To what extent will the capacity of the different road categories be affected by the interactions of pedestrians and automated vehicles? Would pedestrians' crossing maneuvers be restricted to designated pedestrian crossings?

In this research topic we are going to examine the effects of pedestrian - automated vehicle interactions by means of traffic simulations.

6. MISCELLANEOUS TOPICS

Under this section a selection of miscellaneous project ideas is given.

6.1 Dynamic road data and RSUs

Roadside units (RSU) can serve as a communication device for vehicular networks providing vehicle-to-infrastructure (V2I) connectivity to nearby vehicles. These devices can provide a detailed coverage of the road environment and offer a wide range of use-cases (some of the latest are control loss warning, emergency vehicle alert, forward collision warning, intersection movement assist, tailgating advisory, slow vehicle warning (Commsignia, 2020).

From the side of the infrastructure the question is what criteria determine the localization of RSUs as well as what kind of information they need to provide. As for the latter, the provision of dynamic road data is crucial, especially when it gets to temporary conditions such as road works, pavement condition, weather circumstances etc.

6.2 Traffic conflict analysis using AV data

This research topic is specifically traffic safety oriented. It originates from the idea of using so-called surrogate measures of safety instead of historic crash data for traffic safety analyses. The use of non-crash events have gained a great deal of attention especially due to the rapid improvement of sensing technologies facilitating the collection of trajectory data. Over the years, a vast number of indicators of surrogate safety have been developed to investigate traffic safety (Mahmud et al., 2017), these indicators mostly express the proximity to a crash either in time or space. This research topic aims to use such data extracted from AVs that have already driven in actual traffic conditions. By analyzing this dataset it would be possible to analyze specific surrogate indicators for interactions between conventional and automated vehicles.

6.3 Standardized road and traffic base map

A correct, detailed and up-to-date traffic map is needed to help AVs on public roads. The traffic map has to contain road geometry and objects regulating traffic, like traffic signs and signals, pedestrian crossings, etc.

The Hungarian national road authority has a uniform data collection system, however, for municipal roads there is no uniform data base. Mapping responsibility is based on a decree (GKM, 2004) which regulates the elements to be registered but does not contain the mapping methods. Therefore, the basic data which would be necessary for AVs vary by municipalities. Differences between countries can also cause difficulties for AV developers.

The research question in this section is: what kind of road and traffic data are needed to assist AVs? It will be investigated how the available road and traffic registries can be standardized.

6.4. Defining traffic situations to be investigated

This topic collects recommendations for various traffic situations for ZalaZone Proving Ground to be investigated. These situations will be based on the research topics detailed in this paper in relation to the road infrastructure. A possible traffic situation to be investigated is shown in Figure 6.

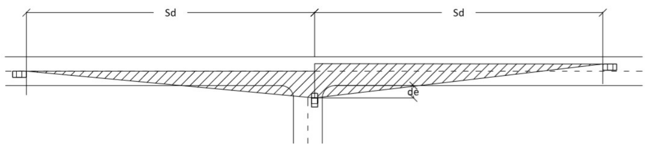

Fig. 6. Example of a simple traffic situation to be investigated

6. CONCLUSIONS

This paper summarized the research proposals coming from several brainstorming sessions that were held as part of a project on autonomous vehicles and safe road infrastructure. These sessions were attended by infrastructure researchers, infrastructure operators, autonomous vehicle developers and IT technologists. A selection of the research proposals in this paper are already in an initial phase or will be launched in the near future. Several MSc and PhD research topics were defined for present and future students.

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