Modelling the Level of Trust in a Cooperative Automated Vehicle Control System

Thomas Rosenstatter[1,2], and Cristofer Englund[1,3]
[1]School of Information Technology, Halmstad University, Sweden
[2]Information Technology & Systems Management, Salzburg University of Applied Sciences, Austria
[3]RISE Viktoria, Göteborg, Sweden

Vehicle-to-Vehicle communication is a key technology for achieving increased perception for automated vehicles, where the communication enables virtual sensing by means of sensors in other vehicles. In addition, this technology also allows detection and recognition of objects that are out-of-sight. This paper presents a trust system that allows a cooperative and automated vehicle to make more reliable and safe decisions. The system evaluates the current situation and generates a trust index indicating the level of trust in the environment, the ego vehicle, and the surrounding vehicles. This research goes beyond secure communication and concerns the verification of the received data on a system level. The results show that the proposed method is capable of correctly identifying various traffic situations and how the trust index is used while manoeuvring in a platoon merge scenario.

***Index Terms*—GCDC 2016, autonomous driving, cooperative driving, Vehicle-to-Vehicle communication, trust, reliability.**

I. INTRODUCTION

Yearly more than 1.2 million fatalities occur on our roads worldwide making traffic accidents to one of the globally leading causes of death [1]. The increasing number of vehicles on public roads and the goal to reduce the environmental impact and improve traffic safety combined with the technological progress leads to research and development in the area of autonomous and cooperative driving. Davila et al. [2] published results from the SARTRE project where they investigated the benefits of platooning systems. Their conclusion was that platooning is safer than manual driving since the vehicle control system and the vehicle dynamics are fully automated. In addition, autonomous vehicles have the potential to increase the comfort for the passengers.

To bring automated vehicles to the market we face considerable safety challenges that may only be overcome by compound research within local awareness, perception and driver support enabled by intelligent vehicular systems [3].

Consequently, software has become the major area of innovation within a vehicle, more than 80 percent of the novelty is achieved by computer systems and their software [4]. The telematics systems of e.g. Daimler and Kia use the Internet for exchanging vehicle status information and calls automatically to the emergency service number in case of an accident [5]. Publicly known projects, such as the self-driving car project[1] from Google, demonstrate the technological progress over the past years.

Automated driving aims to perceive the environment with the on-board vehicle sensors, e. g. Global Navigation Satellite System[2] (GNSS), radar, lidar, and camera systems. Due to the high cost of long range and wide angle sensors and the limitation of the proximity sensors to only being able to detect line-of-sight objects, cooperative driving has turned out to be a reasonable complement. Instead of using expensive high fidelity sensors, cooperative information has the advantage of also perceiving out-of-sight objects via wireless exchange of local information [6]. Consequently, cooperative driving can be the key technology to increase traffic safety and efficiency [7].

One popular application based on Vehicle-to-Vehicle (V2V) communication is platooning, or cooperative adaptive cruise control. For instance, an adaptive cruise control is only following the vehicle in front by measuring the speed of the vehicle and distance to it with the ego (own) vehicle's sensors. It does not significantly increase the efficiency of the entire platoon. With the use of wireless communication to exchange sensor information, e. g. the intended acceleration of the vehicle in front, or the speed, position, and acceleration of the platoon leader, time gaps of less than one second can be achieved [8]. Another field of application is a cooperative interaction to safely cross an intersection [9].

While driving in automated mode the vehicle fully trusts its own sensors. A combination of several sensors in a Sensor Fusion (SF) module [10], [11], [12] gives an accurate representation of the local proximity. In a cooperative system where sensor readings from other vehicles are being shared, the vehicles will require methods to incorporate those signals in their own control system. This paper introduces a Trust System (TS) that evaluates the current traffic situation based on the sensor readings from both the on-board vehicle sensors and the surrounding vehicles to support decision making in the cooperative and automated vehicle.

The TS creates a Trust Index (TI) by considering the quality of the sensor information provided by the own vehicle and other traffic participants describing their behaviour as well as the environment itself. The proposed system is inspired by Aramrattana et al. [13] where dimensions of cooperative driving, ITS and automation are described. The proposed TS is designed to handle the surrounding vehicles (number of actors)

---

[1] https://www.google.com/selfdrivingcar/

[2] Includes the satellite localization systems GPS, Galileo and GLONASS

Cite as "T. Rosenstatter and C. Englund, "Modelling the Level of Trust in a Cooperative Automated Vehicle Control System," in IEEE Transactions on Intelligent Transportation Systems, vol. 19, no. 4, pp. 1237-1247, April 2018, doi: 10.1109/TITS.2017.2749962."

the environment (individual, local or global scope) and the type of driving task (operational, tactical or strategical). The use of this TS allows the decision-making controller to make reliable and safe decisions when interacting with a specific vehicle or operating in a particular environment. Moreover, a prototype of the TS has been tested and evaluated in a Volvo S60 during the Grand Cooperative Driving Challenge (GCDC)[3] 2016 in Helmond, the Netherlands.

Securing the communication between the vehicles and infrastructure, within the vehicle as well as other security mechanisms are inevitable for future vehicles. This approach has to be considered as a model on the system level that supports the decision making module by indicating the trust in the perceived situation.

The reminder of the paper is organized as follows. Section II discusses current research relevant for the proposed model. Section III presents the proposed approach. Section IV describes how the results have been achieved. In Section V, the results of the experiment using the proposed TS are discussed. Finally, Section VI concludes the paper and presents directions of future work.

II. RELATED WORK

Recent research within this field has focused on how to establish trust between agents or vehicles within a Vehicular Ad-Hoc Network (VANET). The authentication of nodes is essential for Vehicle-2-Everything (V2X) communication as well as being able to take counter actions to malicious events and actions. The setup of a trustworthy connection between the nodes at the communication level is the base for further security related applications, such as a TS that evaluates the sensor accuracy and the behaviour of the vehicles. The different types of trust establishing techniques are explained in [14]. Zhang explains in [15] techniques to model trust, such as entity-oriented (e.g. [16] by Minhas et al.), data-oriented (e.g. [17] by Raya et al.), and combined trust models (e.g. VARS in [18]). However, none of these methods deal with the sensor quality, nor the behaviour of the vehicles or nodes. They are focusing on evaluating if nodes communicate the correct events, e. g. slippery road or traffic jam. Models for distributing the trust values between the vehicles are discussed by Agarwal et al. in [19]. Considering the V2V information as a new virtual sensor and estimating a higher accuracy using SF is described in [12]. The result was only verified within a simulation environment. Moreover, Bhargava et al. proposed in [20] a Kalman Filter for calculating a predicted trust. The results show that the computation of the future trust using a Kalman Filter has a problem with time varying trust values. For instance, a constant decrease of the trust value leads to an increasing error of the estimation.

Trust is a common measure in decentralised systems, such as Multi-Agent Systems (MAS). Aras et al. discuss in [21] the relation between trust and uncertainty. The identified sources for uncertainty in MAS are among others, the uncertainty in the observation and the uncertainty when using second-hand information. The authors propose that the trust representation has to reflect the uncertainty and it should allow the use for decision making. One open question is whether it should be represented by a scalar value or be composed of a more complex representation [21].

The contribution of this paper is a model on how to present trust in the own vehicle, the other vehicles, as well as in the environment. Additionally, this model has been tested in an environment with other cooperative vehicles.

III. PROPOSED APPROACH

The proposed TS evaluates the current traffic situation by considering different factors, each represented as a partial TI, which are combined into one of the TIs presented in this work, namely the TI about the ego vehicle, surrounding vehicles, and the environment. The generated TIs are broadcasted to all modules of the vehicle's system, which allows, for instance, the decision making module to include this information when making decisions. This Section gives an overview of the vehicle system and data acquisition, followed by the identified factors that influence the decision making and the calculation of the TIs.

A. System Overview

The results of the TS are evaluated using team Halmstad's GCDC competition car, which provides data from the radar, inertial sensor data, and V2X communication for perceiving the environment. The GeoNetworking protocol defined by ETSI [22] is used for communication. The transmission on the physical layer is established using the standard for wireless vehicular communication, IEEE 802.11p [23] and Cooperative Awareness Messages (CAMs) are used to exchange the sensor information of the vehicle between each other [24].

The on-board sensors of the vehicle establish the base for the situation awareness of the ego (own) vehicle. To calculate the relative position to other vehicles, it is necessary to use a positioning system via satellites such as GPS (Global Positioning System) or Galileo. Many GPS devices provide additional information about the measured position, the dimensionless Dilution of Precision (DOP) values. Accuracy describes the absolute position error, whereas the location error is expressed by precision. Horizontal DOP (HDOP) and Vertical DOP (VDOP) characterise the precision of the horizontal or vertical position solution. Milbert discusses in [25] the behaviour of these DOP values [26], [27].

Table I lists the variables including their resolution used in the proposed TS. For a more detailed description of the exchanged information see the ETSI and the i-GAME specifications [28], [29]. HDOP and VDOP values are not included in the afore-mentioned specifications and are thus the only measurements in Table I that are not being exchanged. To perform cooperative manoeuvres the ego vehicle needs to interact with the surrounding vehicles. The most relevant vehicle is the preceding one, which will be named Most Important Object (MIO), according to [29].

Providing other vehicles information about oneself enables the design of more efficient manoeuvres, for example a cooperative adaptive cruise controller that reacts smoother to speed changes using the desired acceleration of the MIO [8].

---

[3] http://gcdc.net/en/

TABLE I: Relevant variables in a VANET environment.

Type	Measurement	Resolution
On-board	speed over ground	0.01 m/s
	longitudinal acceleration	0.1 m/s^2
	desired long. acceleration	0.01 m/s^2
	lateral acceleration	0.1 m/s^2
	yaw rate	0.01 deg/s
Geographical position	latitude	0.1 μdeg
	longitude	0.1 μdeg
	heading	0.1 deg
	HDOP	–
	VDOP	–
With respect to preceding vehicle	bearing	0.002 rad
	range	0.01 m
	range rate	0.01 m/s
	time headway	0.01 s

In this work, a vehicle distance model (VDM) is used that describes how the Kalman Filter, presented by R. E. Kalman in [30], is used. The distance to the preceding vehicle can be obtained by two sensors, the vehicle's front radar and the distance between two geographic positions. Consequently, the distance represented by the two measurements is linear Gaussian distributed and a Kalman Filter can be used for fusing this data. Delays and latency of the two observations can be considered by adapting the variance according to the delay. The relation between speed, acceleration, yaw rate, heading, and position is non-linear. Thus, it is necessary to create a model that represents the relation between these measurements. Here, a vehicle position model (VPM), based on an extended Kalman Filter (EKF), is used for sensor fusion.

B. *Vehicle Distance Model (VDM)*

The VDM combines the distance to the vehicle in front measured by the radar with the distance using the reported geographical position. This model includes safety mechanisms to provide correct, or at least safe, information to the vehicle's control system. Fig. 1 illustrates the model for fusing the distance to the vehicle in front given two different sources. The geographical position can be the raw data provided by the GPS device or an already filtered signal. The *Distance Calculation* block calculates the ellipsoidal distance using the geographical positions of both vehicles and their length. The position of the vehicle is defined as the geometrical centre of the vehicle.

Sensor data from one of the sensors may be absent due to e.g. environmental changes such as driving in a tunnel or on a curvy road, therefore it is important to choose a proper variance for the data and select the distance to the preceding vehicle with respect to these circumstances. This procedure is performed by the *Data Selection* shown in Fig. 1.

The *Data Selection* chooses the measurement(s), adapts the variance, and gives this information to the KF module, which acts as a one dimensional filter [31]. Thus, use cases like driving in a tunnel or losing the radar target on a curve are safely considered. Assuming that the distance calculated using the geographical position is above or below a certain threshold compared to the radar information, the system will consider only the radar distance. This procedure ensures that the vehicle does not crash with the car in front when receiving an incorrect position from the MIO.

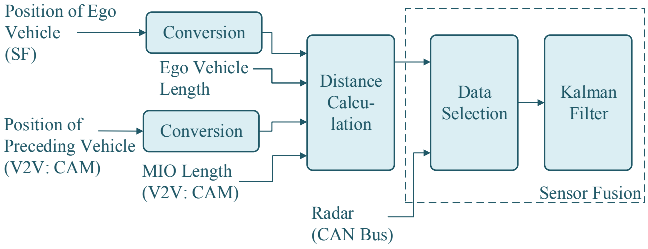


Fig. 1: Vehicle Distance Model - linear sensor fusion.

C. *Vehicle Position Model (VPM)*

The non-linear model, VPM, is applied to both, the ego vehicle's sensor data as well as the sensor data provided via V2V communication by the surrounding vehicles. This model uses the EKF proposed in [32]. However, it has to be highlighted, that the sensor data from the surrounding vehicles cannot be verified with sensors of the ego vehicle.

D. *Potential Factors Influencing the Decision Making*

Automated and cooperative vehicles are introduced to improve traffic safety and efficiency [2], and to reduce greenhouse gases as well as reducing air pollution. However, using other vehicles' information as a basis for decision making in a safety critical system also brings safety and security concerns with it. In an operational environment, all vehicles might not provide equally reliable information and thus, a system that evaluates the received information is necessary.

The vehicular control system needs to adapt to changing situations as well as the environment. It is therefore desirable that the system can rely on the information provided by the surrounding vehicles, in order to make reliable and safe decisions. The factors that may influence the vehicle's driving behaviour or decision making are described below.

a) Sensor Quality: The knowledge about the precision and accuracy of the surrounding vehicles is important to make profound decisions based on this information. Sensor quality is essential when it comes to the data from other vehicles since the ego vehicle may not be able to verify this information with its own sensors. The CAM contains fields describing the accuracy of the measurements, but it might be the case that the sensor, such as the GPS position, is highly dependent on the environment and thus the message field might not be sufficiently updated.

b) Static Environment: Most of the environment along our roads does not change frequently, e. g. tunnels, bridges, and guard rails are considered as static. The environment has a strong impact on our sensors. As an example, the satellite connection of the GPS device is dependent on the environment, due to the reflection of electromagnetic waves between tall buildings within cities.

c) Dynamic Environment: Loss of messages can be an indicator of an environmental change. Other traffic, for example other temporal objects, such as vehicles can influence the radio communication. During tests with a vehicle able to use V2X communication, it was experienced that trucks can block the communication between the preceding vehicle of the truck and the vehicle in the back, due to the physical properties of a truck. Identifying that there is a temporary communication loss caused by another vehicle is necessary in order to be aware of the current situation.

d) Behaviour: The longitudinal and lateral controller design depends on the manufacturer or even on the model of the vehicle. For that reason, it has to be considered how the vehicle behaves or reacts to certain situations and events. For example, a vehicle following another vehicle that has a high velocity fluctuation should be able to compensate these fluctuations to maintain string stability. One more indicator of the behaviour is the observation of the vehicles while they are interacting with each other.

The TS takes the aforementioned factors into account and provides the software modules of the ego vehicle with a TI and a map of the surrounding vehicles. The identification of the surrounding vehicles, especially the MIO, is needed to interact with each other.

E. Trust Index

The TI is designed for a cooperative automated vehicle control system and is a scalar value that indicates the current overall trust. It combines the trust in the environment, in the vehicle itself, and the trust in the surrounding vehicles. An absolute TI was chosen for the reason that such an index is easier to exchange with other vehicles in case of using a distributed database providing TIs of other vehicles.

To combine different TIs into one integrated index that describes the overall trust in both the environment and the vehicles, a weighted average is proposed. The formula for estimating the weighted average TI is described in Equation 1.

$$TI = \frac{\sum_{n=0}^{N} w_n \cdot TI_n}{\sum_{n=0}^{N} w_n}, \tag{1}$$

where

TI is the combined TI,
N is the total number of TIs,
w_n is the weight for that specific TI, and
TI_n is the index of a certain TI.

The proposed four TIs are TI_{ego}, TI_{mio}, TI_{env}, and TI_{v_i}. TI_{ego} describes the trust in the ego vehicle according to sensor quality gathered from the VPM, including the knowledge about the DOP values gathered from the GPS device. TI_{mio} represents the trust in the preceding vehicle by combining the sensor quality and the behaviour of the vehicle. The trust in the environment is represented by TI_{env} and the trust in the vehicle i is described by TI_{v_i}. Fig. 2 illustrates the partial TIs and their sources that are combined into one index.

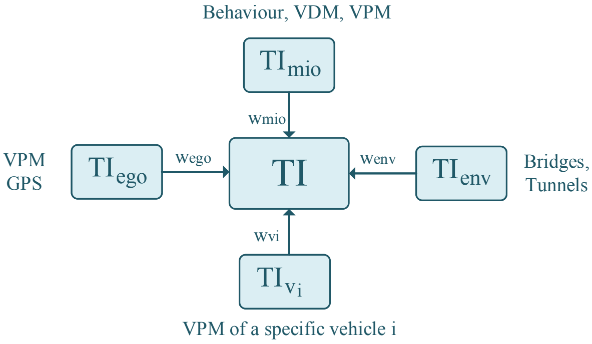


Fig. 2: Composition of TI.

1) Trust Index TI_{ego}

This TI indicates the trust of the ego vehicle based on its own sensor data. Validating the own trust in the sensor quality is essential in order to create reliable awareness. If the system is not able to trust its own sensor data, the system will not be able to perceive the environment correctly and thus the passenger's safety of the ego and the surrounding vehicles would be at risk. The EKF of the VPM provides the Kalman gain K_k at each time step and reflects how much "trust" it puts into both the predicted state and the new measurement. The DOP values provided by the GPS device indicate the precision of the position.

Fig. 3 illustrates the process of computing TI_{ego}. The first step is to compute a partial TI that contains the quality of the measured position according to the previously mentioned DOP values. These dimensionless values can be infinitely large [33]. Consequently, it is necessary to set a limit that indicates a highly imprecise measurement. This limit is set by the constant C, since a reliable geographical position is a prerequisite for cooperative driving. The limit of $C = 25$ is based on an experiment with disadvantageous weather conditions, namely intense rain and clouded sky, where platooning was still possible. This condition was set to $TI_{gps} = 0.5$. The Position DOP (PDOP) value is a combination of the former DOP values and used for further computation [33]. Equation 2 provides the formulas for calculating TI_{ego}. The first step is to compute the PDOP value and normalise it with a maximum value, constant C. Next, the Kalman gain is evaluated by calculating the mean of the diagonal of K_k, which contains the factor

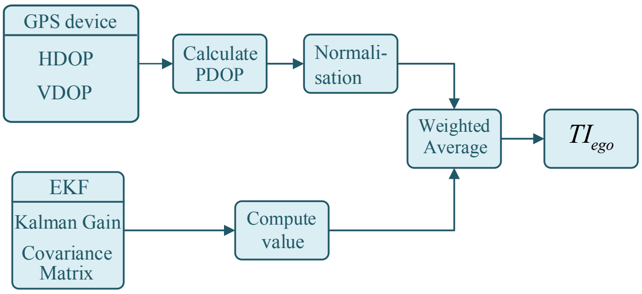


Fig. 3: Composition of TI_{ego}.

of “trust” for each measurement. The overall TI of the ego vehicle representing the quality of the sensors is achieved by applying a weighted average of the indices describing the EKF and the GPS quality.

Each measurement described by the VPM has the same weight for calculating TI_{VPM} described in Equation 2c. A higher weight for the position accuracy is not necessary since the quality of the geographical position itself is already considered in TI_{gps}.

$$\text{PDOP} = \sqrt{\text{HDOP}^2 + \text{VDOP}^2} \tag{2a}$$

$$TI_{gps} = \begin{cases} 0 & \text{if PDOP} > C \\ 1 - \frac{\text{PDOP}}{C} & \text{otherwise} \end{cases} \tag{2b}$$

$$TI_{VPM} = \frac{\sum_{i=1}^{N} K_k(i,i)}{N} \tag{2c}$$

$$TI_{ego} = \frac{w_{gps} \cdot TI_{gps} + w_{VPM} \cdot TI_{VPM}}{w_{gps} + w_{VPM}} \tag{2d}$$

2) Trust Index TI_{mio}

TI_{mio} and TI_{v_i} are both combining trust in the measurement quality and trust in the behaviour of the other vehicles. A definition of correct or wrong behaviour is highly complex since one can consider many factors that help to define behaviour. A survey of the factors expressing the behaviour of a vehicle is shown in this Section.

Vehicle behaviour can be described through observing historical data generated by the vehicle while driving. Fig. 4 illustrates the identified factors that help to conclude about the vehicular behaviour. The current velocity provides information about the cautiousness of the driver or automated system.

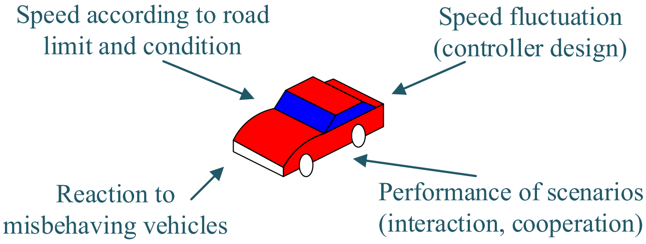


Fig. 4: Factors describing the behaviour of a vehicle.

The system of other vehicles might do something wrong or unexpected due to lack of perception. Vehicles have to react properly even if other road users make mistakes.

The interaction with the surrounding traffic is important for cooperative driving. The main requirement for cooperative driving is using a common interaction protocol.

a) Speed Fluctuation: The stability of the speed of the MIO can be considered by analysing the speed profile. A condition for using the velocity profile of the MIO is a second sensor that is able to measure the speed of the preceding vehicle. A front radar is able to detect the distance and calculate the range rate to any obstacles in front. The range rate is defined in [34] as the rate of the change of the distance to the obstacle as defined in Equation 3a.

$$\dot{R} = \frac{dR}{dt} \tag{3a}$$

$$v_{mio} = v_{ego} + \dot{R}, \tag{3b}$$

where

R is range or distance to the detected obstacle,
$\dot{R}$ is range rate, and
v is the velocity of the MIO or ego vehicle.

Equation 3b shows the calculation of the preceding vehicle’s speed considering the speed of the ego vehicle and the range rate $\dot{R}$ of the MIO. The range rate in m/s provides information about the change of the distance in metres. The formula is only valid if the preceding vehicle is moving in the same direction as the ego vehicle. This requirement is fulfilled while the vehicles are driving on a straight road however it might be invalid in curves.

b) Interaction: This TI is GCDC specific, but can be applied to other interaction protocols as well. The communication between the vehicles during a scenario can be observed as long as they are within communication range of the ego vehicle. The highway scenario, scenario 1, of GCDC 2016 relies on the correct pairing of the vehicles in order to perform a safe merge from one lane to the other. The pairing procedure is described in the i-GAME deliverable 3.2 [29] and in [35]. The lack of interoperability can be a cause for wrong interactions. Observing a wrong pairing of the MIO, or another vehicle around the ego vehicle, can be used for consideration in both TI_{mio} and TI_{v_i}.

Another measure to validate the correct implementation of the interaction protocol is the observation of the Safe-to-Merge (STOM) message. Vehicles that have paired up correctly are making a gap relative to their pairing partner. As soon as the vehicle that is making a gap for a merging vehicle decides that the gap is large enough to merge, it sends out a STOM message. Observing the created gap when the STOM message is sent can be used to verify the trust in the vehicle when interacting with other vehicles. Future scenarios for cooperative and automated driving may provide more accurate measures to be considered in a TI.

c) Recommended Speed: The speed of the preceding vehicle indicates how safe it is driving. Considering the weather and the road conditions in combination with the knowledge about the current speed limit allows to conclude a recommended speed for safe driving.

d) Reaction to misbehaving vehicles: The reliability of the vehicle’s control system is important and should be considered in the TI computation for each vehicle. The ego vehicle has to know, if the vehicle is not able to react to misbehaving vehicles properly, because the safety of the passengers in the vehicle itself and the surrounding vehicles might be at risk. Analysing the behaviour of all vehicles and evaluating the reaction of the surrounding vehicles needs significant computational power and different types of sensors are required.

e) Composition of TI_{mio}*:* Fig. 5 illustrates the measures that can be considered in TI_{mio}. *Interaction* can be used to signal how well the vehicle cooperates with others, e. g. if it pairs and sends STOMs correctly. The degree of the speed fluctuation is mapped using a predefined table and represented as the factor *Speed Fluctuation*. Taking into account the factors weather, road condition, and current speed limit, allows the computation of the recommended speed using inference. A comparison of this recommendation and the actual speed of the preceding vehicle is mapped to the partial TI *Speed*. The VDM and VPM described in Sections III-B and III-C provide information about the sensor quality of the vehicle in front. The reaction to misbehaving vehicles is expressed as the sixth factor to be considered for TI_{mio}.

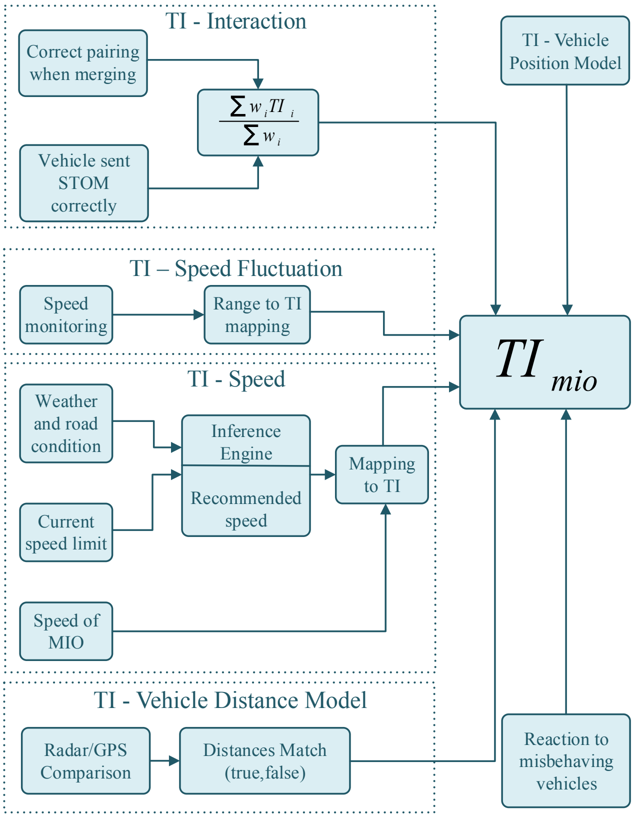


Fig. 5: Composition of TI_{mio}.

Fig. 4 illustrates the factors that potentially influence the TI. Moreover, Fig. 5 shows the composition of TI_{mio}. Since the competition car was not able to perceive all the mentioned measures, such as the current speed limit, road condition, and the observation of the reaction to misbehaving vehicles, this work focuses on the following four factors: the result of the VDM and VPM using an EKF, the speed fluctuation, and the performance when interacting with other vehicles.

3) Trust Index TI_{env}

The environment is categorised into static and dynamic. Roads, tunnels, bridges and the information about rural or urban areas are considered as static. Changes in the dynamic environment may be communication disturbances due to vehicles that block the radio waves e. g. a truck. Research about algorithms deciding what should be forwarded by the truck in order to enable the communication for all vehicles within a certain range is ongoing. Larsson proposes in [36] a performance centric forwarding algorithm.

Deciding whether being in an urban or rural environment can be made using several different methods. One method is to use a map of a navigation software. Another approach is using the PDOP value which is provided by the GPS device. By considering this precision information, it can be deduced if the vehicle is driving in a city, tunnel, under a bridge or on a highway. A less precise geographic position is common in cities, due to the reflection of the electromagnetic waves by buildings. An indicator that the vehicle is driving in a tunnel is the lack of position updates and high HDOP and VDOP values.

The knowledge of the environment, such as the information that the vehicle is in a city, is important. The situation awareness has to be increased when driving in cities, due to dense traffic, bicyclists, pedestrians and other vulnerable road users.

TI_{env} considers the PDOP value for indicating the trust in the environment. Moreover, TI_{env} is being stored in a database for prospective use. The mapping of a TI_{env} perceived in the past is accomplished using circles of a certain size, e. g. 5 metres.

4) Trust Index TI_{v_i}

This TI is similar to TI_{mio}. A system with enough resources for computation can observe and evaluate the interaction of the surrounding vehicles with each other. Moreover, more sensors and different types of sensors are needed in order to evaluate the precision of the other vehicle's information.

Another challenge is the calculation of a TI considering observations made by other vehicles. More sensors can increase the perception of the ego vehicle, but they can only be used to a certain extent. The system has to rely on the V2V information in case a vehicle cannot be perceived with the own sensors. For example, the distance between two vehicles can be compared with the calculated distance using the geographic position and the reported distance to the MIO.

F. V2V Perception

The perception range of the vehicle is strongly dependent on its level of automation. A fully autonomous vehicle has to make all decisions on its own as the driver is not in the control loop anymore. Thus, it needs to detect obstacles, other vehicles, pedestrians, traffic lights, speed limits, lanes markings and road conditions. The system used to evaluate the proposed concept has a limited perception and a longitudinal controller whereas the lateral control is performed manually. This restriction decreases the number of sensors needed to be able to drive automatically.

A map of the surrounding vehicles is essential for fulfilling the interaction of the scenarios described in [29]. The system needs to identify the vehicle in the front right/left as well as the vehicle behind on the right lane. To generate a map that fulfils this requirement with the available sensors, the system has to rely on the reported vehicle position provided via V2V communication, because only the position of the vehicle in front can be verified with the built-in radar. This approach has been chosen for the reason that the ego vehicle used for the TS has a limited perception. Vehicles with a more advanced perception should rely on their own sensors and consider the correctness of the information provided via V2V communication in the vehicle specific TI, TI_{v_i}.

The identification of the surrounding vehicle's position can be determined by considering the lane in which the vehicle is currently driving in or by computing the relative angles to the vehicles with the shortest distance. Both approaches are computed and further on combined with each other in order to achieve a more robust identification of the vehicle's relative position.

a) Lane: The CAM as well as the i-GAME Cooperative Lane Change messages (iCLCMs) contain a field describing the lane in which the vehicle is currently driving. The CAM lane is an integer in the range of -1 to 14. -1 refers to a position outside of the road, 0 is the hard shoulder and 1 is the outermost driving lane [28]. By taking the lane position of the vehicle into account, the algorithm is more robust against misidentified vehicles.

b) Angles: Considering only the relative angles of the vehicles and their distance provides a more robust identification of vehicles that are sending an incorrect or no lane ID. The downside of only using this algorithm for identifying the relative position of the surrounding vehicles is the risk of misclassification of vehicles when driving in a curve.

A method that combines both proposed algorithms takes the advantages of both. Vehicles in the GCDC 2016 mostly sent the correct lane ID and therefore, this algorithm is used as a base. In case a vehicle is identified at another position by the map that considers only the angles and the distance, this field is also updated in the overall map. This approach allows false positives, as it possible that one vehicle is identified at two places, for instance front-left and front.

Fig. 6 illustrates the ego vehicle and the relative position description of the surrounding vehicles. The first letter contains the information if the car is in the front of the vehicle or behind it, while the other letter indicates left or right. The blue areas indicate the angle range that is used for classifying the position of the vehicles.

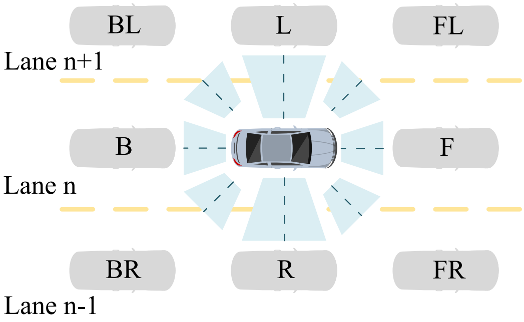


Fig. 6: Illustration of the map and the classification of the surrounding vehicles.

IV. EXPERIMENTAL INVESTIGATIONS

The developed TS is evaluated with data from the highway scenario of the GCDC, because this scenario relies the most on the interaction with other vehicles via V2V communication. This Section introduces the car, the GCDC highway scenario, and the parameters used for this experiment.

A. Car Setup

The proposed system has been implemented in a Volvo S60 provided by Volvo Car Corporation and tested and evaluated during and after the GCDC 2016. Java[4] was chosen as the primary programming language for realising the different functionalities of the car from team Halmstad. The communication between the modules of the system was achieved with Lightweight Communications and Marshalling (LCM)[5]. The benefit of using LCM is the ease of replaying log data and the real time observation of the exchanged data.

The competition car was equipped with antennas for the differential GPS and for the wireless communication. In addition to the antennas, there were two lights indicating whether the vehicle is in automated (green light) or manual (red light) mode.

The power is provided via a 12 V to 220 V power converter which is attached to an uninterruptible power supply. The communication between the devices is established with a wireless router. The V2X communication with the other vehicles and infrastructure is provided by the Alix System Board alix2d3[6]. To ensure a certain accuracy of the geographical position in the range of $+/-10$ cm in standstill, a differential GPS device is needed. The dSPACE MicroAutoBox, provided by Fengco Real Time Control AB, is used as the interface between the system and the car. Furthermore, the MicroAutoBox executes the low-level longitudinal controller. The system of the competition vehicle is executed on a computer, which is located in the front passenger seat.

B. Highway scenario

The highway scenario took place on the highway A270 between Eindhoven and Helmond in the Netherlands. Due to speed limitations of some participating vehicles, this scenario was split into two heats, one high speed and one low speed. In the high speed heat, the vehicles in the right lane, lane B, were driving with a speed of 60 km/h and the vehicles on the left lane, lane A, were driving at 80 km/h. In the low-speed heats the speed of the vehicles in lane A was 45 km/h and in lane B 40 km/h.

The highway scenario is split into four phases, pace making, parallel pairing, sequential pairing, and the merging phase. Fig. 7 illustrates phase III of the highway scenario, when the pairing between the vehicles is completed [29], [35].

---

[4] https://java.com/en/
[5] https://lcm-proj.github.io/
[6] http://pcengines.ch/alix2d3.htm

a) I: Pace Making: At the beginning, the OPCs are bringing the vehicles into the right position. As soon as the vehicles are correctly positioned, a roadwork message is sent to all participants. The roadwork message implies a roadwork on a certain lane (lane A) and the reduction of all vehicles' speed to 40 km/h.

b) II: Parallel Pairing: A merge request triggers the so-called *B2A* pairing, which means that the vehicles on the right lane are setting their forward pair, the vehicle on the front-left, in the iCLCM message. This pairing is performed in parallel by all vehicles. Additionally, their forward partner acknowledges the pairing by setting them as its backward pair. When the *B2A* pairing is done, the vehicles in lane B create a gap so that their forward partner can merge in front of it.

c) III: Sequential Pairing: After a certain time, the lead vehicle on the left lane pairs up with the vehicle on the front-right and creates a gap. The front-right vehicle is identified as the MIO of the backward pair. As soon as the gap is large enough, the backward pair of the lead vehicle sends out a STOM message indicating that the gap is large enough for the lead vehicle to merge.

d) IV: Merging done: After merging, the lead vehicle adapts its parameters to the right platoon and the new lead vehicle on the left lane can start with the *A2B* pairing.

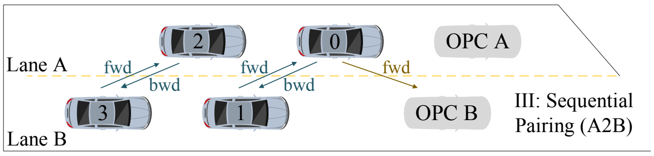


Fig. 7: Phase III of the GCDC highway scenario (reproduced from [29, p. 8]).

During the competition, one case was experienced, where the communication to all vehicles in front of two trucks driving next to each other on two adjacent lanes was blocked due to their physical properties. The only available information about the vehicles in front is the MIO information transmitted by the trucks via the iCLCM message. With this information, the system of the vehicle has the knowledge that another vehicle is in front of its MIO with a certain distance. Other information, such as the preceding vehicle of the MIO of the truck cannot be gathered and thus an increased situation awareness is necessary for a correct evaluation of the situation.

C. Parameter Settings

The data gathered during the competition has been logged according to the requirements of the competition shown in [37] and with the use of *lcm-log*. The generated LCM logs can be played with the *lcm-logplayer*. Moreover, the logs were created for each module individually as a separate file containing only the received or transmitted data. Thus, it is possible to playback the log of the TS containing all information that the TS received. The use of recorded data was chosen for the reason that it is data from a real situation, which includes the interaction with other vehicles, sensor inaccuracies, and communication delays.

The weights of the TIs were chosen manually to demonstrate the general idea of the TS. All TIs, except TI_{ego}, have the same weight. TI_{ego} has a higher weight because it describes the trust in the ego vehicle. Equation 4 shows the specific weights. It should be noted that the only appearance of TI_{v_i} is TI_{fwd} and has thus been weighted with the same weight as TI_{mio}.

$$w_{mio} = w_{v_i} = w_{env} = 3; \quad w_{ego} = 5; \tag{4}$$

Moreover, the adjusted weights for TI_{ego} described in Section III-E1 are listed in Equation 5.

$$w_{gps} = 0.25; \quad w_{VPM} = 0.75; \tag{5}$$

V. RESULTS

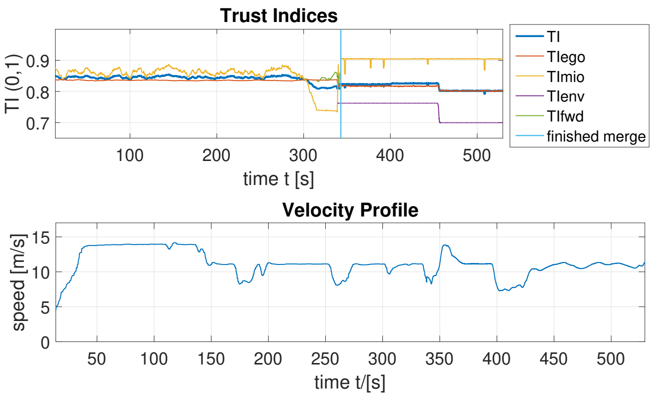
The results are shown as graphs illustrating the TI during different heats and different placements of the vehicle within the two platoons. The partial TIs are depicted in the same plots to show the composition and highlight the influences of each component. The generation of the TI has been simplified due to the limited performance of the system of the competition car. To ease visibility in the plots, the TIs have been filtered with a moving average filter with a twelve second window, which has been experimentally selected.

A. Vehicle merges into right lane

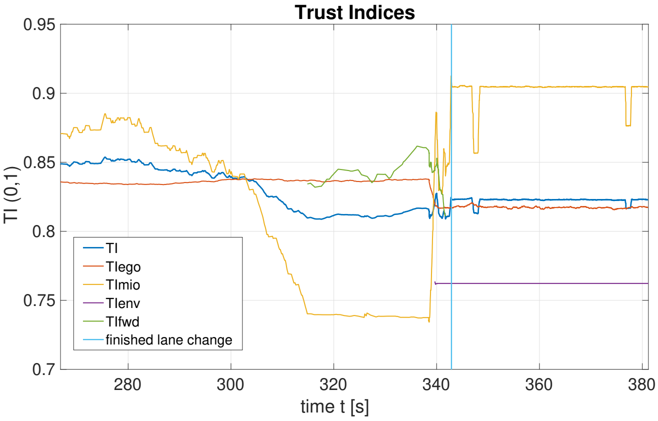
Fig. 8a illustrates the TI and the speed profile of the test vehicle during a low-speed heat. The speed profile is shown for the sake of completeness and omitted in further figures. The behaviour of TI_{ego} is stable with a value at around 0.84 until the vehicle merges. A level between 0.8 and 0.9 indicates for the decision making algorithm that the information of the ego, the other vehicles, and the environment is reliable and that the vehicle can decrease or keep its distance to the MIO. Whenever the TS does not have the necessary information to calculate a partial TI, it will omit it in the TI calculation. In a future implementation one may mark certain information sources as mandatory or optional. This way, the lack of information would be also considered in the TIs.

TI_{ego} decreases as soon as the TS has more information about its geographic position, which is shown by the appearance of TI_{env} that considers also the precision information (PDOP value) gathered from the GPS device. The late appearance of the PDOP value is caused by the GPS device that never provided this information in this area (until $t = 340$ in Fig. 8a). It shows the influence of the knowledge about the environment on TI_{env} and TI_{ego}. TI_{env} is calculated by using the current PDOP value or a TI_{env} from the area close to the vehicle that was perceived in the past. Moreover, TI_{env} decreases at second 460 due to a change in the environment – trees covered the road and caused a decrease of the GPS precision.

Comparing TI_{mio} before and after the merge shows that there are different vehicles in front of the ego vehicle. It also indicates that the MIO after the merge is more reliable compared to the preceding vehicle before the merge. The vertical blue line indicates the time when the merge to the right

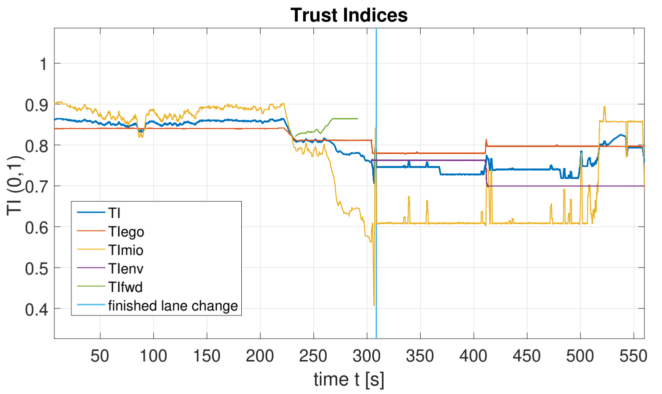


(a) TI and speed profile.

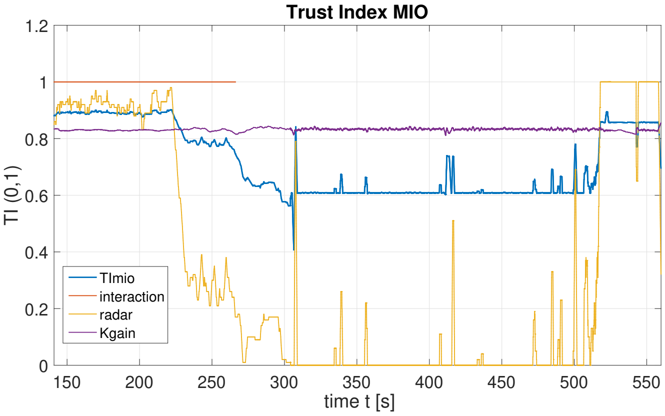


(b) TI during the merge.

Fig. 8: Experiment I: Highway scenario starting from the left lane.



(a) Behaviour of the TI



(b) Composition of TI_{mio}.

Fig. 9: Experiment II: Highway scenario starting from right lane.

lane has finished. It can also be seen that TI_{mio} is decreasing while the merge is being performed because the system cannot detect the correct MIO during that phase and thus the radar match is negative.

The forward partner is only set within the *B2A* and the merging phase. TI_{fwd} describes the trust in the forward partner and is thus only calculated within these phases. This TI originates from TI_{v_i}.

An extract of the TI during the merge from second 250 to 380 can be found in Fig. 8b. It shows TI_{fwd} in more detail and it also illustrates the behaviour of TI_{mio} during the merge.

The decreased TI during the merge can be used to inform the decision making module that it has to decrease its trust into the current situation. However, the lane change has to be treated as a special case, since the car has to keep its speed in order to not interfere with the interaction protocol. Furthermore, the trust in the new preceding vehicle is stable with a value of around 0.9, because the match between radar distance and geographical position is more accurate than with the previous MIO. This information can be used to maintain safety while decreasing the time headway or the distance to the preceding vehicle when this vehicle provides reliable data, i.e. has a high TI.

B. *Making gap for vehicle to merge*

In the highway scenario, when the vehicle starts in the right lane, it does not need to change the lane. It creates a gap with respect to its forward partner on the left lane and sends out a STOM message as soon as the gap is large enough for the forward partner to merge.

Fig. 9 depicts the composition and behaviour of the TI and TI_{mio}. TI_{ego} shown in Fig. 9a is also stable and changes when the PDOP value occurs. The behaviour of TI_{fwd} is similar to the one presented in Fig. 8a. First, TI_{fwd} is lower and increases with the experience gathered about the vehicle. It shows also the same behaviour during the merge. As soon as the vehicle, in this case the forward partner, changes the lane, TI_{mio} is decreasing significantly due to the change of the ego vehicle's preceding car. Furthermore, the new MIO has a lower TI compared to the previous one. This is caused by a continuous misidentification of the MIO. Due to this misidentification, the observed values with the radar and the reported data via V2V communication do not match, the TI decreases. The reason for this continuous misidentification is a low accuracy of the received geographical position. It was experienced that the new preceding vehicle had provided delayed position data and thus the system could not identify it correctly.

Fig. 9b depicts the partial TIs used to calculate TI_{mio}. For a better illustration of the TIs, the same moving average filter has been applied. This filter is the reason why the TI of the radar is not binary. The forward partner becomes the new MIO after the merge. Since TI_{fwd} only uses the VPM for calculating this index, TI_{mio} does not necessarily match with TI_{fwd}. The behaviour of TI_{mio} is strongly influenced by the result of the radar match. After the merge, from second 300 to 510, the measured radar distance differs from the distance using the geographical position. The evaluation of the radar match is performed within the VDM of the system of the car as described in Section III-B.

The identification of measurement mismatches by comparing the own sensor data of the ego vehicle with the reported data is important for situation awareness. The implemented controller did not have any problems with following this vehicle in a platoon because the system relies, for safety reasons, in such cases on the radar information. The decreased TI_{mio} tells the other modules of the system that the reported data can not be fully trusted.

The graph shows that the trust in the new MIO after the merge is about 0.6. Comparing the overall TI of the system highlights that the situation awareness has to be increased. A possible reaction to this behaviour can be an increased time headway or distance to the preceding vehicle. An overall TI of less than 0.5 means that the TS has evidence for not trusting this vehicle and the gap to the preceding vehicle has to be increased.

C. Unreliable Geographical Position

The proposed system has to rely to a certain extent on the geographical position provided by the other vehicles because the system is only able to verify the position of the preceding vehicle and the VPM is not capable of improving the position of highly inaccurate position data or unreliable data. One case was experienced in the course of the GCDC where the intended forward partner provided unreliable position information.

The introduced TS is able to improve the geographical position of a vehicle by considering the inertial sensor information, but it cannot improve the position of highly inaccurate measurements that provide changes in the position from $+/-80$ metres. Fig. 10 illustrates such a situation. The position of the competition car is plotted in blue as a reference. The red curve shows the position of the forward partner. As can be seen, the geographical position of the other participant's vehicle is fluctuating to a large extent. Unfortunately the source of the disturbance is not known and could not be investigated. From experience the characteristics of the disturbance indicate that it may be caused by synchronization problems with the Real Time Kinematic (RTK) base station.

Vehicles which provide such an unreliable position cannot be identified with the current implementation of the proposed TS. This is caused by the competition car's limited perception with its own sensors. For computational reasons, only vehicles that behave properly to a certain extent are monitored, i.e. vehicles with large fluctuations in position can not be followed with the use of the VDM.

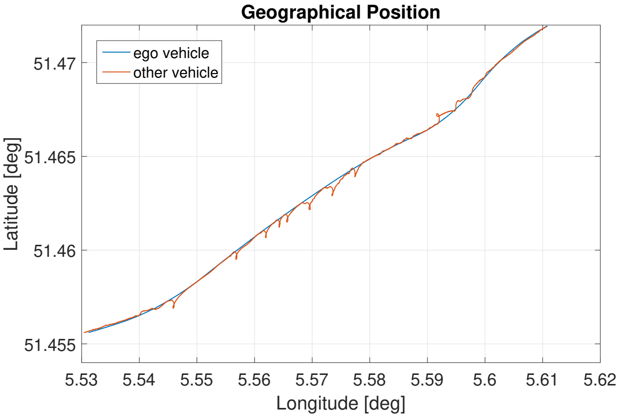


Fig. 10: Unreliable/Inaccurate geographical position

VI. CONCLUSION

This paper presents a Trust System (TS) capable of perceiving the local environment and generate a Trust Index (TI) describing the overall reliability of both the on-board vehicle sensor data as well as the data received through V2V communication. The TS perceives the vehicle's local environment and generates a TI indicating the system's level of trust in the sensor readings and their reliability at any given time instant. The TI is within the range 0 to 1, and takes several factors into account e.g. the environment itself, the ego vehicle, the other vehicles, and in particular the preceding vehicle. The TI is broadcasted to the modules of the vehicle's system to inform them about the current situation and allow them to consider it when taking actions.

The evaluation of the sensor accuracy of the ego vehicle and the other vehicles is performed with the vehicle distance model (VDM) and the vehicle position model (VPM). The VDM describes the relation between the distance measured with a radar and the distance based on the provided geographical position. A kinematic model of the vehicle in combination with an EKF has been implemented in the VPM. The TS generates the TI based on various factors that can influence the situation awareness.

The results of the TS are illustrated and discussed. The behaviour of the TI in various situations shows the correct identification of situations, where the preceding vehicle has a lower reliability and thus a lower TI is assigned to the vehicle. A discussion about the possible influences of the proposed TS in decision making is also given and indicates that, to maintain safety while the TI is low, the TS can suggest to increase the time headway to the preceding vehicle or reduce the own vehicle's speed. The overall TI consists of several partial TIs, future work may include adaptive weighing of these TIs in different situations. This can be achieved through further testing in various situations.

ACKNOWLEDGMENT

The authors would like to thank the i-GAME project for preparing and organising GCDC 2016, the Swedish CoAct project and institutions for supporting us organisationally

and financially, and our sponsors including Fengco, TASS International, and Volvo Cars.

REFERENCES

[1] World Health Organization (WHO), *Global Status Report on Road Safety 2015*. Geneva: WHO Press, 2015.

[2] A. Davila and M. Nombela, "Platooning - safe and eco-friendly mobility." *SAE Technical Paper 2012-01-0488*, 2012.

[3] J. Dokic, B. Müller, and G. Meyer, "European roadmap smart systems for automated driving," *European Technology Platform on Smart Systems Integration*, 2015.

[4] R. N. Charette, "This Car Runs on Code," 2009. [Online]. Available: http://spectrum.ieee.org/transportation/systems/this-car-runs-on-code

[5] T. Bijlsma, S. de Kievit, J. van de Sluis, E. van Nunen, I. Passchier, and E. Luiijf, "Security challenges for cooperative and interconnected mobility systems," in *International Workshop on Critical Information Infrastructures Security*. Springer, 2013, pp. 1–15.

[6] S.-W. Kim, Z. J. Chong, B. Qin, X. Shen, Z. Cheng, W. Liu, and M. H. Ang, "Cooperative perception for autonomous vehicle control on the road: Motivation and experimental results," *IEEE International Conference on Intelligent Robots and Systems*, pp. 5059–5066, 2013.

[7] S. W. Kim, B. Qin, Z. J. Chong, X. Shen, W. Liu, M. H. Ang, E. Frazzoli, and D. Rus, "Multivehicle Cooperative Driving Using Cooperative Perception: Design and Experimental Validation," *IEEE Transactions on Intelligent Transportation Systems*, vol. 16, no. 2, pp. 663–680, 2015.

[8] J. Ploeg, B. T. Scheepers, E. van Nunen, N. van de Wouw, and H. Nijmeijer, "Design and experimental evaluation of cooperative adaptive cruise control," *2011 14th International IEEE Conference on Intelligent Transportation Systems (ITSC)*, no. June 2016, pp. 260–265, 2011.

[9] L. Chen and C. Englund, "Cooperative Intersection Management: A Survey," *IEEE Transactions on Intelligent Transportation Systems*, vol. 17, no. 2, pp. 570–586, 2016.

[10] R. Kianfar, B. Augusto, A. Ebadighajari, U. Hakeem, J. Nilsson, A. Raza, R. S. Tabar, N. V. Irukulapati, C. Englund, P. Falcone, S. Papanastasiou, L. Svensson, and H. Wymeersch, "Design and Experimental Validation of a Cooperative Driving System in the Grand Cooperative Driving Challenge," *Intelligent Transportation Systems, IEEE Transactions on*, vol. 13, no. 3, pp. 994–1007, sep 2012.

[11] K. Lidström, K. Sjöberg, U. Holmberg, J. Andersson, F. Bergh, M. Bjäde, and S. Mak, "A Modular CACC System Integration and Design," 2012.

[12] M. Röckl, J. Gacnik, and J. Schomerus, "Integration of Car-2-Car Communication as a Virtual Sensor in Automotive Sensor Fusion for Advanced Driver Assistance Systems," in *Proceedings. FISITA*, no. 1. Munich, Germany: Springer Automotive Media, 2008, pp. 2008–2008.

[13] M. Aramrattana, T. Larsson, J. Jansson, and C. Englund, "Dimensions of cooperative driving, its and automation," in *2015 IEEE Intelligent Vehicles Symposium (IV)*, June 2015, pp. 144–149.

[14] P. Wex, J. Breuer, A. Held, T. Leinmuller, and L. Delgrossi, "Trust Issues for Vehicular Ad Hoc Networks," *VTC Spring 2008 - IEEE Vehicular Technology Conference*, pp. 2800–2804, 2008.

[15] J. Zhang, "A survey on trust management for VANETs," *Proceedings - International Conference on Advanced Information Networking and Applications, AINA*, pp. 105–112, 2011.

[16] U. F. Minhas, J. Zhang, T. Tran, and R. Cohen, "Towards expanded trust management for agents in vehicular ad-hoc networks," *International Journal of Computational Intelligence Theory and Practice (IJCITP)*, vol. 5, no. 1, 2010.

[17] M. Raya, P. Papadimitratos, V. D. Gligor, and J. P. Hubaux, "On Data-Centric Trust Establishment in Ephemeral Ad Hoc Networks," *IEEE INFOCOM 2008*, pp. 1912–1920, 2008.

[18] F. Dötzer, L. Fischer, and P. Magiera, "VARS: A vehicle ad-hoc network reputation system," *Proceedings - 6th IEEE International Symposium on a World of Wireless Mobile and Multimedia Networks, WoWMoM 2005*, pp. 454–456, 2005.

[19] P. Agarwal and N. Bhardwaj, "A Review on Trust Model in Vehicular Ad Hoc Network," *International Journal of Grid and Distributed Computing*, vol. 9, no. 4, pp. 325–334, 2016.

[20] A. Bhargava, S. Verma, and B. K. Chaurasia, "Kalman filter for trust estimation in VANETs," in *2015 IEEE UP Section Conference on Electrical Computer and Electronics, UPCON 2015*, 2015.

[21] H. Aras, C. Beckstein, S. Buchegger, P. Dittrich, T. Hubauer, F. Klan, B. Knig-Ries, and O. Wolfson, "Uncertainty and trust," in *Univ. of Illinois, Dagstuhl Seminar Proceedings*, vol. 8421, 2009.

[22] ETSI (European Telecommunications Standards Institute), "Intelligent Transport Systems (ITS); Vehicular Communications; GeoNetworking; Part 3: Network architecture," *ETSI TS 102 636-3*, vol. 1, pp. 1–23, 2010.

[23] L. Chen and C. Englund, "Cooperative ITS - EU standards to accelerate cooperative mobility," in *The 3rd International Conference on Connected Vehicles & Expo (ICCVE 2014)*, 2014, pp. 681–686.

[24] ETSI (European Telecommunications Standards Institute), "Vehicular Communications ; Basic Set of Applications ; Part 2 : Specification of Cooperative," *ETSI TS 102 637-2*, vol. 1, pp. 1–18, 2011.

[25] D. MILBERT, "Dilution of precision revisited," *Navigation*, vol. 55, no. 1, pp. 67–81, 2008. [Online]. Available: http://dx.doi.org/10.1002/j.2161-4296.2008.tb00419.x

[26] E. Kaplan and C. Hegarty, *Understanding GPS: Principles and Applications*. Artech House, 2005.

[27] R. Yarlagadda, I. Ali, N. Al-Dhahir, and J. Hershey, "Gps gdop metric," *IEE Proceedings - Radar, Sonar and Navigation*, vol. 147, no. 5, pp. 259–264, Oct 2000.

[28] ETSI (European Telecommunications Standards Institute), "Intelligent Transport Systems (ITS); Users and applications requirements; Part 2: Applications and facilities layer common data dictionary," *ETSI TS 102 894-2*, vol. 1, pp. 1–78, 2013.

[29] J. van de Sluis, L. Chen, and L. Garcia-Sol, "DEL_i-GAME_D3.2 Proposal for extended message set for supervised automated driving," i-game gcdc, Tech. Rep., 2015.

[30] R. E. Kalman, "A New Approach to Linear Filtering and Prediction Problems," *Journal of Basic Engineering*, vol. 82, no. 1, p. 35, 1960.

[31] R. Faragher, "Understanding the basis of the kalman filter via a simple and intuitive derivation," *IEEE Signal Processing Magazine*, vol. 29, no. 5, pp. 128–132, 2012.

[32] N. Magnusson and T. Odenman, "Improving absolute position estimates of an automotive vehicle using GPS in sensor fusion," Master's thesis, Chalmers University of Technology, 2012.

[33] R. B. Langley, "Dilution of Precision," *GPS World*, vol. 10, no. May, pp. 52–59, 1999.

[34] B. S. Bourgeois, "Using Range and Range Rate for Relative Navigation," Naval Research Laboratory Marine, Mississippi, Tech. Rep., 2007.

[35] C. Englund, L. Chen, J. Ploeg, E. Semsar-Kazerooni, A. Voronov, H. H. Bengtsson, and J. Didoff, "The grand cooperative driving challenge 2016: boosting the introduction of cooperative automated vehicles," *IEEE Wireless Communications*, vol. 23, no. 4, pp. 146–152, August 2016.

[36] M. Larsson, *Methods to Improve V2V Communications in Platoons of Heavy Duty Vehicles*. Halmstad University Press, 2016.

[37] H. Salunkhe, H. H. van Huysduynen, B. Nijssen, and J. Terken, "DEL_i-GAME_D7.1 GCDC judging criteria and their evaluation (Final)," i-game gcdc, Tech. Rep., 2016.

Thomas Rosenstatter Thomas Rosenstatter pursues a Ph.D. in vehicular security at the Chalmers University of Technology in Gothenburg, Sweden. He completed his Master studies in Embedded and Intelligent Systems at the Halmstad University, Sweden, in 2016. Additionally, he received a Diplom-Ingenieur from the Salzburg University of Applied Sciences, Austria in the same year. Thomas participated in the Grand Cooperative Driving Challenge 2016 as part of Team Halmstad. His research interests are security and software architecture.

Dr. Cristofer Englund received his Ph.D. in electrical engineering from Chalmers University of Technology, Gothenburg, Sweden in 2007. Currently he holds a research managerial position within cooperative systems at RISE Viktoria, Gothenburg, Sweden. He is also research director of the Traffic Systems competence area at SAFER, Vehicle and Traffic Safety Centre at Chalmers University of Technology. In addition, he holds an adjunct senior lecturer position at Halmstad University, Sweden within information technology. His research interests include automated driving, machine learning, and data mining.