Self-Recovery System for LiDAR-Based Autonomous Driving

Ruo.Yun Wang[1], Shih-Fan Chou[1,2], and Ai-Chun Pang[1,2,3]
[1]Department of Computer Science and Information Engineering, National Taiwan University
[2]Research Center for Information Technology Innovation, Academia Sinica
[3]Graduate Institute of Networking and Multimedia, National Taiwan University
Taipei, Taiwan, R.O.C.
E-mail: r04922118@csie.ntu.edu.tw, d00922026@csie.ntu.edu.tw, acpang@csie.ntu.edu.tw

ABSTRACT

For the past few years, many well-known companies and automakers have put a lot of effort into developing self-driving cars (SDCs). The SDC is undoubtedly a future trend for driving and needs various kinds of sensors to detect the nearby environment. Additionally, it uses sensing data in order to plan actions. On most SDCs, LiDAR acts as the main sensor. However, we discovered that the current approach to resolving a LiDAR malfunction is very passive and causes the SDC advantage to be lost. In this paper, we propose two strategies in order to deal with LiDAR failure through V2V Communication. The aim is to recover from the breakdown and safely drive the SDCs to their destination without human support. Finally, we validated the performance of both strategies through simulation and provide insights for wireless networks.

Keywords: V2V communication, self-driving car, LiDAR

1. INTRODUCTION

The Self-Driving Car (SDC), also called autonomous vehicle or driverless vehicle, is no longer a futuristic idea. Since the end of 2014, most car manufacturing companies have been developing their own version of the SDC and investing many funds in its development [1]. Without a driver control, the SDC relies on multiple sensors and internal High-Definition map (HD map) to plan actions. The primary sensor of the SDC is light detection and ranging (LiDAR) which is responsible for determining distances to obstacles and building dynamic 3D point cloud maps of the surrounding environment [2]. However, hardware devices have a limited life-span. The LiDAR life-span is usually 3-5 years and is influenced by the SDC running frequency. LiDAR malfunctioning can cause serious strain on the SDC. By using the remaining sensors, the SDC cannot know the entire information of the nearby environment. The breakdown SDC may execute incorrect actions and cause serious accidents. In order to avoid serious accident, the current approach is emergency stop. However, emergency stop would bring many drawbacks on the SDC delivering service. The negative impacts is critical and needed to be addressed.

As we know, the most important requirement of a delivery service is that the cargo must be delivered to the destination. When a situation occurs that prevents this requirement from being reached, the breakdown SDC needs to wait for another car to carry out the remaining delivery services. However, this approach may cause plenty of traffic problems as follows: (i) *Unpredictable waiting time*: the road rescue time takes at least 30-40 minutes in an urban environment. The number of freight company delivering trucks is the limit and the supporting car which is assigned by the freight company may not be dispatched immediately. The breakdown SDC may cause traffic congestion problems, if it waits while being parked on the road. (ii) *Requiring large human support and losing the advantage of the SDC* : when the supporting car arrives, we need to discharge the goods and transfer them onto the supporting car, reset the delivery path, and tow or drive the breakdown SDC to a repair spot. All the operations are completed by human support staff, and moving the goods on the road consumes time and energy, in addition to being very dangerous. From this two reasons, the current approach is very poor on the SDC delivering service and needs some strategies to improve it.

There are three potential approaches to recover LiDAR failure. One of the potential approach is switch on the backup sensor. However, the cost of LiDAR is very expensive and amounts to approximately \$60,000-\$80,000. In order to enable the SDC to become mainstream and affordable, the cost is a critical point to be addressed. Although this is the simplest approach, from a cost viewpoint, it is infeasible for ubiquitous manufacturing in the future. Another potential approach is utilizing the HD map which is a highly detailed, 3D, computerized map, specifically for SDCs, in order to support safe and more efficient operation [3]. The idea is that the breakdown SDC downloads the HD map in the cloud in order to exchange the internal map, and uses the new map to plan actions and keep running. However, the update frequency happens at a minute scale and the content does not contain dynamic nodes. Therefore, it is infeasible to use the HD map for recovery. The other potential way is V2V support. The concept is that the adjacent SDC with high related sensing data can transfer its information to the breakdown SDC. When the breakdown SDC receives the current information, it can update its internal map and use the new map to plan actions. In Fig. 1, the operation of the SDC is illustrated [4-6]. We aggregate the changing characteristic points into an updating file. The updating file is an LAS file, which is a common format to record the point cloud, and includes information about the changing characteristic points during the past 100 ms, within a radius of 120 m and the point information contains the 3D coordination, point class and point intensity. Considering instantaneity, a neighboring SDC can immediately transfer its information sensing by its sensors through V2V communication. With consideration to traffic fluency, stopping on the road may cause traffic congestion; however, the condition of stopping is that there is no SDC in close proximity to the breakdown SDC. If

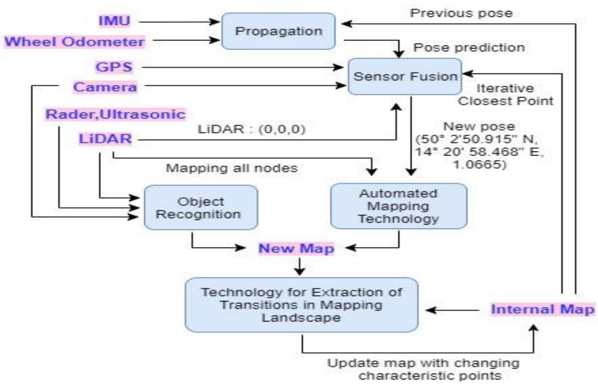


Figure 1 The operation of the SDC

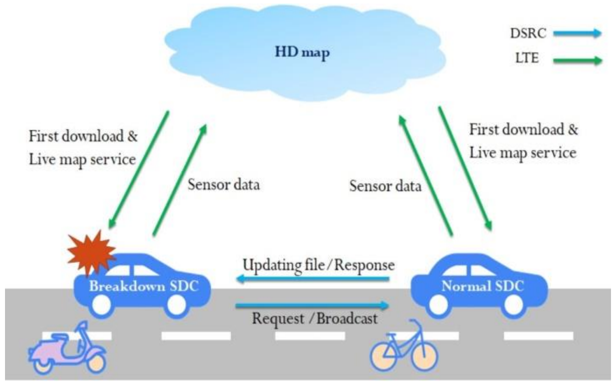


Figure 2 System Model

there is no other SDC travelling close to the break-down SDC, the probability of traffic congestion is low. We consider that using V2V support is the most suitable way to recover from LiDAR failure in the SDC, with consideration to information instantaneity and traffic flow. Below, we will design a recovery system based on V2V support.

In this paper, we propose a self-recovery system for LiDAR malfunction on the SDC through V2V communication. The objective is to minimize the total time of the breakdown SDC costs the drive from the departure to the destination. The contributions of this paper are summarized as follows. Firstly, we show the scenario about major sensor of the SDC malfunctions on delivering service and prove it is a critical problem. Secondly, we propose strategies to recover the failure through V2V communication and let breakdown car arrive at the destination with its own. The way would consider safety, traffic congestion and avoid collision. Finally, due to the simulation, we evaluate the method and give insight to wireless networks.

The rest of this paper is organized as follows. In section 2, we describe the system model and problem formulation. In section 3, we present the solution design. In section 4, the simulation results are presented and the performance evaluations are discussed. Finally, we conclude the thesis in section 5.

2. SYSTEM MODEL AND PROBLEM FORMULATION

2.1 System Model

The system model is shown in Fig. 2. In this system, there are numerous vehicles including normal SDC, breakdown SDC, bikes, and motorcycles travel-ling on the road in an urban environment. The SDCs downloads the HD map, from departure to destination, before starting to drive. When the LiDAR on the SDC breakdowns, the SDC will immediately broadcast to its nearby SDCs, in order to notify them about the situation, and then it will stop. When the nearby SDCs receive the message, they transmit the updating file to the breakdown SDC. After the breakdown, the SDC receives the updating file, and uses it to update the internal map and even apply the data to updating the HD map in the cloud, while continuing its travel to the destination. During the trip, the HD map in the cloud still provides live map services for all SDCs regardless of whether the SDC is normal or breakdown. We use the Dedicated Short Range Communication (DSRC), also known as IEEE 802.11p, which is a suite of standards for communication between vehicles, and uses LTE to communicate between vehicles and the cloud. Our requirements of this system is as follows. Firstly, the breakdown SDC must arrive to the destination. Secondly, the breakdown SDC should avoid collision during the trip

As shown in Table I, the set V consists of all kinds of the vehicles in the system. Before SDCs start, the system initiates some flags to record their current states. It sets $F_{breakdown}$, F_{stop} and F_{resume} to zero. Let $N_{neighbor}$ denote the number of neighboring normal SDC for the breakdown SDC. The definition of collision is that when moving, the breakdown SDC cannot obtain the updating file and the distance between the front of the vehicle is smaller than the smallest safe distance; thereby, collision occurs. Equation (1) specifies the smallest safe distance d_{safe} for the breakdown SDC in V, where g and u are the gravitational acceleration and the coefficient of asphalt road friction, respectively.

$$d_{safe} = \frac{v^2}{2 \times g \times u} + 0.2 \times v \qquad (1)$$

We calculated angle in order to determine the relative position of the breakdown SDC and other vehicles. Equation (2) specifies the angle between the breakdown SDC and the neighboring vehicle to de-termine whether the vehicle is in the front of the breakdown SDC, where A' represents the previous location of the breakdown SDC and B represents the location of another vehicle. The angle θ is a vector from A to A' and a vector from B to A. When it is over the threshold, then it means B is in front of A.

$$\theta = \left| \measuredangle(\overrightarrow{A'A}, \overrightarrow{AB}) \right| \qquad (2)$$

Various metrics have been proposed in order to evaluate the design method in this system. These metrics can be classified into two aspects by separat-ing the recovery efficiency for the breakdown SDC, and the impact on the wireless network. For the breakdown SDC, we use two evaluation metrics. The first one is *total time*. The total time of the breakdown SDC, costs the drive from the departure to the destination. The second metric is the *collision rate*, which is the rate of breakdown SDC collisions that occur during the trip. The collision rate represents the ratio of the number of collisions to the total number of estimated times. For the wireless network, we used four evaluation metrics. The first one is *broadcast overhead*, which is the total number of broadcast packets transmitted during the trip in order to recover the system; the second one is the *Broadcast burst*, which is the maximum broadcast overhead in a unit of time. The third one is the *Transmission overhead*, which is the total amount of times that the normal SDCs transmits its updating files to the breakdown SDC during the trip, for the purpose of system recovery; The fouth one is *transmission burst* which is the maximum transmission overhead in a unit of time. The unit of time is set to 100 ms, since the synchronization interval of the DSRC channel is 100 ms and the period of transmission and broadcast is also 100 ms.

2.2 Problem Formulation

Our objective is to minimize the total time $time$ subject to the constraint $r_c < 5\%$. Input is the set V and outputs are $time$, $trans$, $broadcast$, $burst_t$ and $burst_b$. We have some assumptions for the problem as follows. Firstly, normal SDCs, bikes and motorcycles do not crash with the breakdown SDC. Secondly, the quality of the DSRC channel is good which means that the channel is not congested. Finally, the path loss about the radio shadow caused by obstacles does not severely influence the transmission. The notations are summarized in Table 1.

TABLE 1 SUMMARY OF NOTATION

Symbol	Definition
$\boldsymbol{V}$	The set of the vehicles
$\boldsymbol{F_{stop}}$	The flag of stop state for the breakdown SDC
$\boldsymbol{F_{breakdown}}$	The flag of breakdown state for the SDC
$\boldsymbol{F_{resume}}$	The flag of resume state for the breakdown SDC
$\boldsymbol{N_{neighbor}}$	The number of neighboring normal SDC
$\boldsymbol{r_c}$	The collision rate of the breakdown SDC
$\boldsymbol{d_{safe}}$	The smallest safety distance
$\boldsymbol{d_{neighbor}}$	The distance of neighbor
$\boldsymbol{d_{min}}$	The shortest distance between the breakdown SDC and its neighbor
$\boldsymbol{burst_t}$	Transmission burst
$\boldsymbol{burst_b}$	Broadcast burst
$\boldsymbol{trans}$	Transmission overhead
$\boldsymbol{time}$	Total time
$\boldsymbol{broadcast}$	Broadcast overhead
$\boldsymbol{u}$	The coefficient of asphalt road friction
$\boldsymbol{g}$	Gravitational acceleration
$\boldsymbol{v}$	The speed of vehicle
$\boldsymbol{\theta}$	The angle determine whether the vehicle is in the front of the breakdown SDC

3. METHOD DESIGN

3.1 Decision

As the name implies, the concept of the Decision strategy is that the breakdown SDC is active, in order to decide which normal SDCs should transmit the updating file to it. The procedure is as follows. (i) when the breakdown occurs, the SDC immediately broadcasts to nearby vehicles in order to notify that $F_{breakdown} = 1$, its location , and stop on the road and set $F_{stop} = 1$; (ii) when the nearby normal SDCs obtain the broadcast message, they calculate the distance between the breakdown SDC. If the distance is lower than $d_{neighbor}$, they send the distance to the breakdown SDC. (iii) When the breakdown SDC obtains these distances, it chooses a normal SDC with d_{min} and notifies it in order to send its file. (iv) When the chosen SDC gets the message, it sends its updating files to the breakdown SDC. (v) When the breakdown SDC receives the updating file, it uses the file and resumes its travel on the road and sets $F_{stop} = 0$, $F_{resume} = 1$; (vi) if $N_{neighbor} = 0$ or the breakdown SDC cannot receive any updating file to use, the breakdown SDC still stop on the road and set $F_{stop} = 1$, $F_{resume} = 0$. The broadcast to notify the nearby SDC in step i is periodic. In order to reduce the transmission overhead, the normal SDC cannot send its updating file to the breakdown SDC when the breakdown SDC is waiting for the traffic light.

3.2 Non-Decision

Unlike Decision, the concept of the Non-Decision strategy is that the breakdown SDC does not decide which normal SDC should transmit its updating file to it. The procedure is as follows. (i) when breakdown occurs, the breakdown SDC immediately broadcasts to nearby vehicles to notify them that $F_{breakdown} = 1$, its location, and stops on the road and sets $F_{stop} = 1$; (ii) when the nearby normal SDCs receive the broadcast message, they calculate the distance between the breakdown SDC. If the distance is lower than $d_{neighbor}$, they send their files to the breakdown SDC; (iii) when the breakdown SDC receives these files, it merges their files for use, and resumes to run on the road and sets $F_{stop} = 0$, $F_{resume} = 1$; (iv) if $N_{neighbor} = 0$ or the breakdown SDC cannot get any updating file to use, the breakdown SDC still stops on the road and set $F_{stop} = 1$, $F_{resume} = 0$. The broadcast for notifying the nearby normal SDC in step i is event triggered. When the number of received updating files is lower than the previous unit of time or the state of the breakdown SDC is “stopping”, the breakdown SDC rebroadcasts the message in order to inform its nearby vehicles. It uses the same Decision strategy in order to reduce transmission overhead.

4. SIMULATION

4.1 Simulation Environment

The map was downloaded from OpenStreetMap (OSM), which is an open world map. Simulation of Urban Mobility (SUMO), which is a free and open traffic simulation suite, was used as the traffic simulator. The simulation was developed in MATLAB. The simulation environment consisted of one square kilometer of the Taipei City Zhongzheng District, which has one breakdown SDC, some normal SDCs, bikes, and motorcycles. The number of SDCs within the area have a density of 100, 200, or 300, and correspond to the same number of bikes plus motorcycles. The average density within one square kilometer in the urban environment is 200.The value of 100 represents the off-peak hour, and 300 represents the rush hour. The odometer of the breakdown SDC, from departure to destination, is 1.5 km and breakdown SDC breakdown after travelling 150 m from departure. The simulation settings are summarized in Table 2.

4.2 Simulation Results

For each density, we created one hundred different routes. Each route has the same path and odometer for the breakdown SDC, and a random path for other vehicles. In Fig. 3(a), we show the total time for two methods, normal mode, and emergency stop for each density. The normal mode represents that the breakdown SDC does not breakdown during the trip. Emergency stop is the current approach. The results of these four ways are the average of one hundred routes for each density on the map. We can observe that the performance of both methods for these densities is similar. Although the total time of both methods is higher than the normal mode, the gap between them is small, and does not exceed 5% based on the total time of the normal mode. By using the current approach the total time would be very high, in comparison to other methods. This includes road rescue time of approximately 30 minutes, discharge and carry time of approximately 10 minutes, and remaining trip time. The Decision and Non-Decision approaches can improve the total time by at least 88-90%. For the normal mode, when the density is bigger, the total time is higher due to the traffic flow. For other approaches, we observed that the total time for a density of 100 is the longest. Since this wastes a lot of time for waiting, vehicles travel into the neighboring area. We also observe that the total time for the density of 300 was longer than that 200 due to the traffic flow.

The collision rate is shown in Fig. 3(b). The results were obtained by the estimated number of routes, with collisions occurring in one hundred routes. We observed that the collision rates of both methods were similar, and did not exceed our 5 percent constrain. Actually, the collision rate would be lower than the results due to support from remaining sensors such as camera and radar.

For the broadcast overhead in Fig. 3(c), we also averaged one hundred routes for each density on the map. The broadcast overhead of Decision was much higher than that of Non-Decision. Apparently, the reason was that the Decision strategy is periodic instead of event triggered, like Non-Decision. When the density was higher, the number of nearby SDCs was bigger and the broadcast overhead was also higher. However, the gap between the broadcast overhead of Non-Decision on different densities was small, since the timing of broadcast was event triggered. In the broadcast overhead, we only know the total number of broadcast packets during the trip

TABLE 2 PARAMETER SETTING

Parameter	Description	value
$maxSpeed_{SDC}$	Max speed of SDC	16 m/s
$maxSpeed_{motor}$	Max speed of motorcycle	16 m/s
$maxSpeed_{bike}$	Max speed of bike	6 m/s
$d_{neighbor}$	The distance of neighbor	80 m
d_{LiDAR}	The scanning range of LiDAR	120 m
d_{DSRC}	The transmission range of DSRC	300 m
$f_{broadcast}$	The frequency of broadcast	100 ms
f_{trans}	The frequency of transmitting updating file	100 ms
$s_{broadcast}$	The size of broadcast packet	100 bytes
s_{update}	The size of updating file	53 KB
L_v	The most longest length of vehicle	18 m
D	Data rate	27 Mbps
δ	The threshold of the θ	90^o
u	The coefficient of asphalt road friction	0.8
g	Gravitational acceleration	9.8 m/s^2

and it is hard to observe the effect on the wireless network. Therefore, we should focus on the broadcast overhead in a unit of time and analyze the load of the channel.

For the broadcast burst in Table 3, we just aim at the Decision strategy. The reason is that Non-Decision only sends one broadcast packet in a unit of time, at most, and the impact on the wireless network is low. The results include the average of the maximum number of broadcast packets in a unit of time for about one hundred routes with different density. The maximum of these is the maximum number of broadcast packets in one unit of time. When the density is higher, the number of nearby SDCs is bigger and the result is higher, we would directly focus on the maximum value of 27 pkts in order to discuss whether the DSRC channel can sustain the number in one unit of time. For the default alternating access, the remaining time of transmitting 27 pkts is 46 ms [7]. With consideration to CSMA/CA, we need 5.058 ms to send 27 pkts, and the time is far less than 46 ms. It can be seen that the maximum broadcast burst can also be sustained by the DSRC channel.

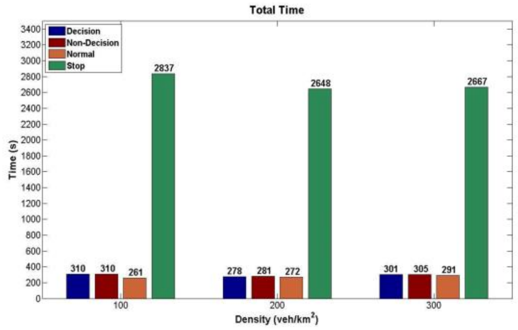
For the transmission overhead in Fig. 3(d), we also average one hundred routes for each density. The transmission overhead of Non-Decision was much higher than that of Decision, since the Non-Decision strategy is that all neighbors transfer their files to the breakdown SDC instead of selecting the closest SDC, like Decision. When the density is higher, the number of nearby SDCs is larger and the transmission overhead of Non-Decision is also higher. However, the gap between the transmission overhead of Decision on different densities is small. The reason is that, regardless of the number of neighbors, the breakdown SDC only selects the closest SDC to transfer the file. In the transmission overhead, we are difficult to observe the effect on the wireless

TABLE 3 DECISION : BROADCAST BURST

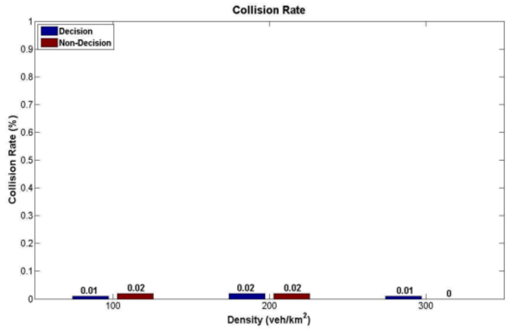
Density (veh/km^2)	Average ($pkts$)	Max ($pkts$)
100	13	23
200	19	25
300	20	27

TABLE 4 NON-DECISION : TRANSMISSION BURST

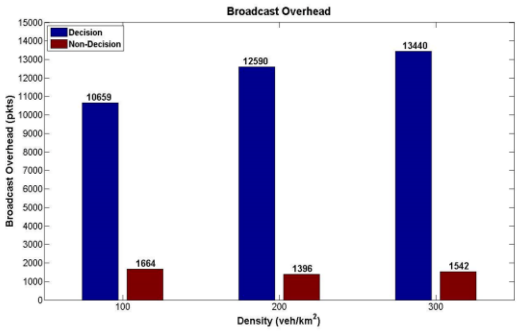
Density (veh/km^2)	Average ($times$)	Max ($tims$)
100	11	21
200	17	23
300	18	25



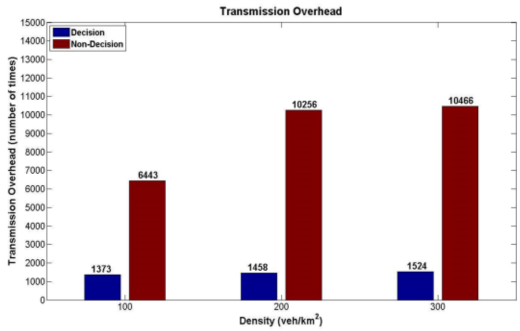
(a) Total Time



(b) Collision Rate



(c) Broadcast Overhead



(d) Transmission Overhead

Figure 3 Simulation Results

network. Therefore, we would focus on the transmission overhead in one unit of time and analyze the load of the channel.

For the transmission burst in Table 4, we just aimed at the Non-Decision strategy. The reason was that Decision only sends one updating file, at most, in one unit of time, and the impact on the wireless network is low. The data include the average of the maximum number of transmission times in one unit of time, which is approximately one hundred routes with different density, with their maximum being the maximum number of transmission times in one unit of time. When the density was higher, the number of nearby SDCs was bigger. We would analyze whether these transmission bursts could be loaded by the SCH. In the DSRC, this enabled the use of four SCHs in parallel [7]. For the default alternating access, each SCH existed for 46 ms, in order to transfer the files, and we could only transmit 8 files in one unit of time. Apparently, this was not enough; therefore, we adjusted to immediate access, which allowed channel switching at any time. For immediate access, each SCH existed for 80 ms, and could transmit 20 files in one unit of time. However, if the transmission burst exceeded 20, it had still occurred packet loss.

In summary, for the total time and collision rate, the performance of the two methods was similar. For the impact on the wireless network, Decision is better than Non-Decision. Non-Decision is not ideal and is more applicable at low density.

5. Conclusion

In this thesis, we investigated the reaction of the SDC after LiDAR malfunction, and discovered that it was currently very poor. Consequently, the advantages of the SDC are being lost. Therefore, we proposed two strategies in order to recover LiDAR breakdown for the SDC. Both strategies apply information transfer from the nearby SDC through V2V Communication. We validated both strategies by simulation and found that they were able to reach our targets. Additionally, we analyzed their effect on the wireless network.

References

[1] T.Jiang, S.Petrovic, U.Ayyer, A.Tolani, and S.Husain. “Self-Driving Cars : Disruptive or Incremental” In UC Berkeley engineering leadership professional program, 2015, pp.3–22.

[2] Velodyne LiDAR 2017. Available at http://velodynelidar.com

[3] K.Massow et al. “Deriving HD maps for highly automated driving from vehicular probe data” In IEEE International Conference on Intelligent Transportation Systems, 2016, pp.1745–1752.

[4] K.Jo, J.Kim, D.Kim, C.Jang, and M.Sunwoo. “Development of Autonomous Car—Part I: Distributed System Architecture and Development Process” In IEEE Trans-actions on Industrial Electronics, volume 61, 2014, pp.7131–7140.

[5] RAND Corporation. “Autonomous Vehicle Technology - A Guide for Policymakers”, 2016, pp.1–214.

[6] S.Bauer, Y.Alkhorshid, and G.Wanielik. “Using High-Definition maps for precise urban vehicle localization” In IEEE International Conference on Intelligent Transportation Systems, 2016, pp. 492–497.

[7] IEEE Standard for Wireless Access in Vehicular Environments (WAVE) – Networking Services. In IEEE Std 1609.3-2016, pp. 1–160, April 2016