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Enhancement of Vehicle Safety Utilizing Mobile Wireless Communications

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List of Publications

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Conference Papers Corresponding to Thesis

1. T. Osafune, K. Monden, S. Fukuzawa, and S. Matsui, "Performance measurement of mobile ad hoc network for application to Internet-ITS (Intelligent Transportation System)," in *Proc. of IEEE International Symposium on Applications and the Internet*, pp. 25–30, 2004.
2. T. Osafune and L. Yamamoto, "Analysis of an epidemic dissemination protocol for ad hoc networks," in *Proc. of 2005 International Conference on Wireless Networks, Communications and Mobile Computing*, vol. 1, pp. 790–795, 2005.
3. T. Osafune, L. Lin, and M. Lenardi, "Multi-hop vehicular broadcast (MHVB)," in *Proc. of 6th International Conference on ITS Telecommunications*, pp. 757–760, 2006.

Abstract

In recent years, vehicle safety has been rapidly evolved due to the enhancement of Information and Communication Technologies (ICT). One of the examples is Advanced Driving Assistant Systems (ADAS), which help drivers in the driving by the combination of sensing road environment and automatic actuation of brake, accelerator and steering. Another example is Autonomous Driving (AD), which detects surroundings by the sensors such as Radar, LIDAR, GPS, and camera, and autonomously drives by using digital map.

The necessary functions to drive cars can be largely divided into three functions. They are recognition, judgment and operation. Recognition is the function to recognize the environment, and understand if there are any events or objects which require specific driving operation. Judgment is the function to decide what action is necessary based on the information obtained in recognition phase. Operation is the function to take the action decided by the judgment phase. In the case of driving by human, the action can be pressing the brake pedal, turning the steering wheel, and so on.

This thesis focuses on the technologies to realize or support the recognition function by inter-vehicle wireless communications in order to enhance vehicle safety. Especially, the wireless communication protocols are highlighted. As the environment to apply the technology, both general roads and mining sites are considered. Moreover, the vehicle safety depends on not only real-time recognition but also off-line education, which is important to improve the driving behavior to prevent accidents. This thesis also focuses on the correlation between driving behavior and accidental risks.

Firstly, we propose an inter-vehicle communication protocol for general roads. The purpose of this protocol is to exchange information such as location, speed and direction among vehicles, so that they would judge if there is a risk to collide with one another. In order to realize this purpose, the information must be frequently updated. In the case of general roads, vehicle safety would be increased by knowing the information of surrounding vehicles in sub-second. However, the number of surrounding vehicles on the roads varies from time to time, and thus, the number of packets to be transmitted would also vary from time to time. As the result, the technical issue for the inter-vehicle communication protocol is how to realize reliable communications in order to collect the information of surrounding vehicles in sufficiently short duration. We propose the technology to solve the issue by introducing a congestion control mechanism which works in the decentralized environment.

Secondly, we study the possibility to use inter-vehicle communications to enhance the safety in mining sites. In the case of mining sites, different from the general roads, the issue is the specific

environment in the mining site. Namely, the number of vehicles would not be the issue in the mining sites, because the density of heavy equipment such as haul trucks, shovels and excavators are much smaller compared the general roads. So the congestion would not be the issue in the case of mining sites. Meanwhile, the geometric environment such as steep slopes would matter because the angles of such slopes can be 70 degree in the extreme cases. So we primarily studied the actual radio propagation from the antenna attached to the heavy equipment. We also simulated the radio propagation with the extreme geometric conditions. As the results, we have successfully obtained the range where heavy equipment can communicate with each other.

Thirdly, we propose a technology to infer the traffic accident risks from driving data. Here, the driving data means the data obtained by the smartphone to specify the driving. It includes GPS, three-dimensional accelerometers, timestamp and so on. Until now, many analyses about aggressive driving have been reported. However, the direct correlation between aggressive driving and accidental risks has not been studied well. In this thesis, we have analyzed the correlation between driving data and accidental history of the drivers. The purpose is to understand the correlation between aggressive driving and accidental risks. As the result of this research, we have discovered that there are difference regarding the distribution of three driving features between safe drivers and risky drivers.

In summary, in this thesis, we focus on the vehicle safety enhanced by the inter-vehicle communications and driving analysis. The first research is about the inter-vehicle communication protocol which controls the packet congestion in a decentralized manner. The second research is about the applicability of inter-vehicle communications to the mining sites, which environment is quite harsh for the radio propagation. The third research is about the correlation between driving behavior and accidental risks. The objective of this thesis is to contribute to vehicle safety enhancement utilizing information and communication technologies, especially wireless communications.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

In recent years, vehicle safety has been rapidly evolved due to the enhancement of Information and Communication Technologies (ICT). There are many kinds of ICT technologies to be used for the vehicle safety. In the case of Advanced Driving Assistant Systems (ADAS), which help drivers in the driving by the combination of sensing road environment and automatic actuation of brake, accelerator and steering, it uses sensors such as radar and/or stereo camera in order to measure the distance from the preceding car. In the case of Autonomous Driving (AD), which detects surroundings by the sensors not only radar and/or camera, but also GPS device to know the positioning, digital map to understand the geometric information, and LIDAR to understand the surrounding cars and obstacles. It also uses planning technologies to calculate the ideal trajectory for the vehicle to take and control technologies to adjust the position to the ideal trajectory.

One of the first driving assistance systems was the Anti-lock Braking System (ABS), which uses proprioceptive sensors and controls braking system to avoid uncontrolled skidding. Another example as developed driving assistance systems is Electronic Stability Control (ESC). Later, exteroceptive sensors started to be used to acquire external information, including ultrasonic, Radar, LIDAR, camera or Global Navigation Satellite System (GNSS). Due to the development of exteroceptive sensors, recent ADAS such as Automatic Cruise Control (ACC) have been developed [1]. When ACC was firstly introduced, it works only at speeds greater than 50 km/h [2]. However, the current systems have the ability to work at lower speeds. Today, they can automatically follow preceding vehicles even within traffic jam [3]. The most recent technologies enable ADAS to select and control trajectories beyond driver’s requests. By utilizing the combination of devices such as radar and camera and data fusion technology [3], it combines the strength of both technologies. As the new means to understand the surrounding environment, wireless communications are interested. There are many national or European projects such as SIM-TD and DRIVE C2X to conduct the experiment to prove the effect of inter-vehicle communication to vehicle safety.

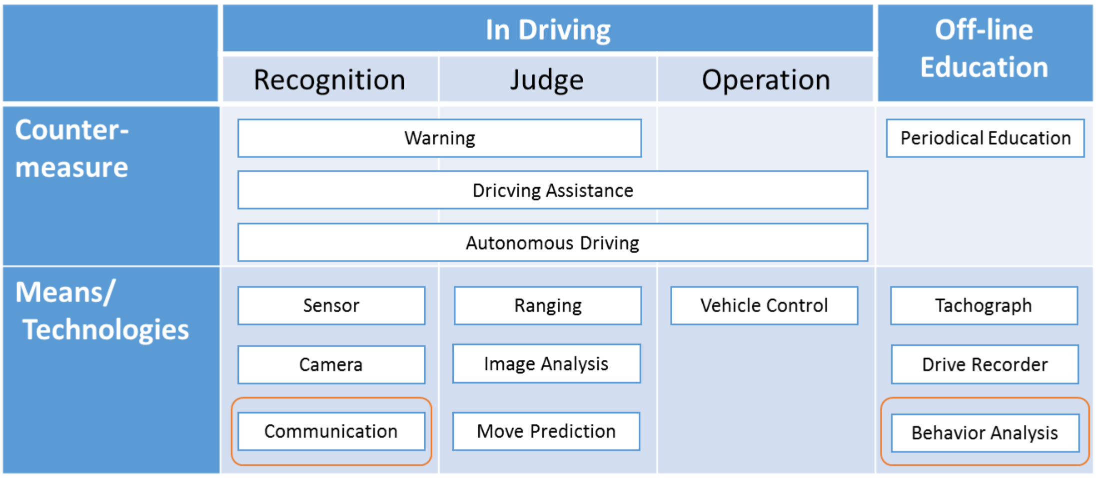


Figure 1.1: Relationship between Driving Functions and Technologies

The necessary functions to drive cars can be largely divided into three functions. They are recognition, judgment and operation. Recognition is the function to recognize the environment, and understand if there are any events or objects which require specific driving operation. Judgment is the function to decide what action is necessary based on the information obtained in recognition phase. Operation is the function to take the action decided by the judgment phase. In the case of driving by human, the action can be pressing the brake pedal, turning the steering wheel, and so on.

The relationship between those functions and the technologies to prevent accidents are mapped in Figure. 1.1. In this figure, not only in-driving technologies, but also off-line education is mapped. Moreover, the categories how to support each functions are listed. They are classified as warning, driving assistance, autonomous driving and periodical education. Each classification consists of plural elemental technologies. For example, the warning system can be realized by the combination of obstacle sensing and ranging, while the driving assistance system can be realized by the combination of image recognition, image analysis and vehicle control in the case of ADAS realized by camera devices.

Even though the technologies for autonomous driving are rapidly growing and partially commercialized, it is speculated that the commercialization of fully autonomous vehicle would take more than 10 years. Currently, human driving with driving assistance is more practical. In these circumstances, warning systems to notify the potential risks to the drivers are regarded as important technologies for its practicality [4], and there are some products with utilizing sensor devices as Lane Departure Warning Systems [5]. On the other hand, although the research of inter-vehicle communications and vehicle-to-infrastructure communications to detect the possibility of collisions among vehicles has progressed and standardized in the standardization body [36][37], the cooperative systems utilizing the communication technologies are not yet commercialized and under evaluation phase [6]. So, one of the focuses of this thesis is the technology to realize or support the recognition function by inter-vehicle wireless communications in order to enhance vehicle safety. Especially, the wireless communication protocols are highlighted. As the environment to apply the technology, both general roads and mining sites are considered. The technical issues in two cases are quite different. In the case of general roads, the technical issue is brought about by the congestion of vehicles. Namely, the traffic congestion causes the wireless network congestion. Meanwhile, in the case of mining site, the harsh environment for wireless communications matter. Namely, the influence of the specific geometry such as steep slope and the size of heavy equipment may block the radio communication among vehicles.

In addition, from practical viewpoint, drivers' behavior in receiving warning must be considered to realize vehicle safety [4]. In the case of commercial vehicles such as trucks, there are commercialized systems which analyze the driving behavior and use them for training and education for the drivers to improve their driving behaviors [7]. Due to the background stated here, we include the technologies analyzing the drivers' behavior in the scope of this these.

Firstly, we propose an inter-vehicle communication protocol for general roads. The purpose of this protocol is to exchange information such as location, speed and direction among vehicles, so that they would judge if there is a risk to collide with one another. In order to realize this purpose, the information must be frequently updated. In the case of general roads, vehicle safety would be increased by knowing the information of surrounding vehicles in sub-second. However, the number of surrounding vehicles on the roads varies from time to time, and thus, the number of packets to be transmitted would also vary from time to time. As the result, the technical issue for the inter-vehicle communication protocol is how to realize reliable communications in order to collect the information of surrounding vehicles in sufficiently short duration. In order to solve this issue, we propose a congestion control mechanism which works in the decentralized environment as on the general roads.

The congestion control mechanism has been implemented as the simulation codes on NS-2, and the simulation results have been obtained. The feature of the congestion control mechanism can be explained by two steps. The first step is to determine if the traffic congestion has been generated or not. It is determined by counting the number of vehicles in the vicinity. If the number of vehicles is above predetermined threshold, the mechanism judges that the road is congested, and executes the second step. The second step is to control the packet transmission frequency. As is above mentioned, the packet should be transmitted in the sub-second in order to share the updated information of vehicles. Even though it should be updated frequently, the mechanism lessens the frequency to transmit the packet in inversely proportional to the density of the surrounding vehicles in order to mitigate the packet congestion. Thus, the number of packets in a certain spatial point can stay at the steady level. The simulation study revealed that the congestion mechanism can control the packet reception rate of a certain vehicle as desired. At the same time, it is also shown that the information delivery rate stayed higher than 88% in the range of 10 – 100 vehicles / km.

Secondly, we study the possibility to use inter-vehicle communications to enhance the safety in surface mining environment. In the case of mining sites, different from the general roads, the issue is the specific environment in the mining site. Namely, the number of vehicles would not be the issue in the mining sites, because the density of heavy equipment such as the haul trucks, shovels, and excavators are much smaller compared with general roads. So the congestion would not be the issue in the case of mining sites. Meanwhile, the geometric environment such as steep slopes would matter because the angles of such slopes can be 70 degree in the extreme cases. Moreover, the size of heavy equipment also influences the radio propagation among vehicles. So we primarily studied the actual radio propagation from the antenna attached to the heavy equipment. We also simulated the radio propagation with the extreme geometric conditions.

Figure 1.2: Picture of Heavy Equipment

We propose a method that leverages IVC to support drivers' awareness in surface mine. The idea is that we build a radio propagation model for haul trucks, which are the most typical vehicles in surface mine, by accurate ray-tracing. The model is validated in the field experiment, where actual radio signal propagation is measured and compared with the model. Then a mining environment, where steep cliffs due to excavation are often seen, is modeled and we estimate the received signal strength based on the locations of haul trucks and antenna locations. As a result, we point out several blind spots in such environment, which is significant for V2V proximity detection in surface mine.

Thirdly, we propose a technology to infer the traffic accident risks from driving data. Although there are many kinds of devices to obtain driving data such as tachographs and dedicated devices used for usage based insurance, here, it means the driving data means the data obtained by the smartphone to specify the driving.

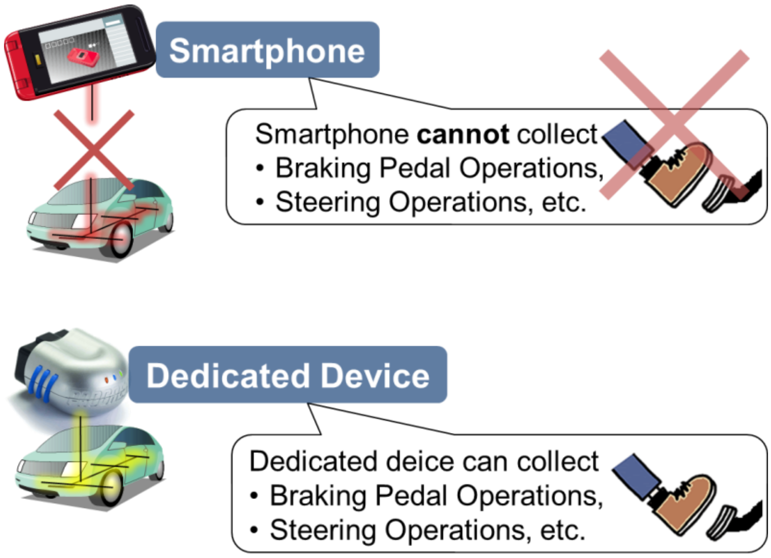


Figure 1.3: Difference of Dedicated Devices and Smartphones

It includes GPS, three-dimensional accelerometers, timestamp, and so on. Until now, many analyses about aggressive driving have been reported. However, the direct correlation between aggressive driving and accidental risk has not been studied well. In this thesis, we have analyzed the correlation between driving data and accidental history of the drivers. The purpose is to understand the correlation between aggressive driving and accidental risks. We have collected driving data for about 15 months from more than 800 drivers using smartphones. These drivers are under contract to car insurance in Japan and categorized into several groups of different ages and genders. The driving data contain each vehicle's GPS positions and accelerations at regular time intervals. Using those data, each driver is labelled by "safe driver" or "risky driver". For this classification, we focus on the history of drivers. In particular, those with 20 or longer years' driving experiences without accident records are labelled as safe drivers and those with more than two accident records as risky ones. As a result, 206 and 24 drivers are categorized into safe and risky ones, respectively. Using these labelled driving data, we have compared the appearance frequency of their aggressive driving behaviors such as sudden acceleration, sudden braking and sudden left/right turns. By statistical significance testing, we have found the threshold values of accelerations to identify the aggressive driving behaviors for unknown data. Based on those results, we have further investigated to obtain a classifier to identify safe and risky drivers. This classifier has been evaluated with the accident histories of drivers, and the accuracy is over 70% in most cases.

In summary, in this thesis, we focus on the vehicle safety enhanced by the inter-vehicle communications and driving analysis. The first research is about the inter-vehicle communication protocol which controls the packet congestion in a decentralized manner. The second research is about the applicability of inter-vehicle communications to the mining sites, which environment is quite harsh for the radio propagation. The third research is about the correlation between driving behavior and accidental risks. The objective of this thesis is to contribute to vehicle safety enhancement utilizing information and communication technologies, especially wireless communications.

This thesis is organized as follows. In Section 2, we address the related works and contributions of our methods. In Section 3, we describe inter-vehicle communication protocol, especially, the congestion control mechanism to prevent wireless network congestion. In Section 4, we describe the results of our experiment and simulation results of how radio would be propagate among heavy equipment in surface mining environment. In Section 5, we propose how to classify the safe drivers and risky drivers from the driving data obtained by the smartphone. Finally, Section 6 concludes this thesis.

Chapter 2

Related Works

2.1 Epidemic Dissemination Protocol for Ad Hoc Networks

In this section, we briefly address the epidemic dissemination protocol for ad hoc networks as the basis of information dissemination in inter-vehicle communication systems. Passive Distributed Indexing (PDI) [9] is a general--purpose distributed lookup method for < key, value > pairs.

The PDI concept was introduced in [9], which also describes the mechanisms for multi-hop query propagation, response and caching of query results. PDI is enhanced in [9] with epidemic dissemination and invalidation techniques for keeping the cache entries coherent.

PDI is designed for mobile networks. It can benefit from node mobility and underlying broadcast mechanisms available for mobile networks for the dissemination of information to peer-to-peer nodes. Each node holds an index cache which is a list of < key, value > pairs. A query is a message from a node that wishes to obtain the value for a given key. Queries are sent in broadcast to all one-hop neighbors of the querying nodes. Responses are also sent in broadcast to all one-hop neighbors of the responding node. This implies that even if a node is not looking for a particular answer to a query, it listens to on-going responses and updates its internal index cache with the observed < key, value > pair. Moreover, nodes moving to other regions in the network carry their values in their local cache and broadcast query responses in the new zone. In this way, popular entries will be disseminated to several nodes. This mechanism is called "epidemic dissemination" because it works like an infectious disease: "infected" nodes "contaminate" other nodes with information they have in their local caches. PDI also supports query propagation over multiple hops. The maximum number of hops, or query TTL (time-to-live), is specified by the inquiring node. Responses may also be forwarded over multiple hops. ORION (Optimized Routing Independent Overlay Network) [10] is another approach to peer-to-peer networking in which a response message navigates through the reverse path taken by the corresponding query message. ORION also provides a method to filter responses along the reverse path, in order to remove redundant responses.

2.2 Classification of Flooding Protocols

Inter-Vehicular Communications (IVCs) are now considered as a way to realize active safety; for example, by providing the position information of each other or the potential danger warning; by wireless communications. A flooding protocol over vehicular ad hoc networks (VANETs) is necessary to efficiently disseminate the information for the sake of active safety applications, such as the positions and the velocities of the vehicles.

Flooding protocols for ad hoc networks are extensively summarized in [11]. It classifies the broadcast techniques for Mobile Ad Hoc NETworks (MANET) [12]-[17] largely into four kinds. The first is (i) simple, flooding, in which all the nodes receiving the broadcast message rebroadcast the packet exactly one time and these rebroadcasts are repeated until all the nodes receive the packet [18][19]. The second is (ii) probability based methods, which are similar to simple flooding except that the node rebroadcasts with a predetermined probability. The third is (iii) area based methods. In order to cover as wide area as possible, the node which can cover larger additional area is chosen as a rebroadcast node. Namely, the farther nodes from the sender preferentially rebroadcast the packet [20]. The fourth broadcast technique is (iv) neighbor knowledge methods. Ideally, Minimum Connected Dominating Set (MCDS) is the set of nodes able to rebroadcast the packet with the least number of packets. However, since the problem of MCDS is known to be NP-hard for general graphs, these methods aim to disseminate the information with as less packet as possible by calculating the localized sub-optimal solution based on the knowledge of neighbors [21] – [26].

There are some works proposed as the flooding protocols dedicated for IVC. In [27], a flooding protocol for IVC is proposed. This protocol belongs to (iii) area based methods with two specific functions, Directional Broadcast and Intersection Broadcast. In Directional Broadcast functions, the authors propose a variant of RTS/CTS applied for broadcasts, so that the broadcast messages could be sent reliably.

In [28], two are proposed, which are categorized in (iv) neighbor knowledge methods. In both of them, a vehicle which wants to transmit a packet to the whole network selects the retransmitter based on the position information after transmitting a position request packet by one hop and acquiring the position information of neighbors as the reply.

In [29], another flooding algorithm is proposed and the performance is evaluated. It is also categorized as (iii) area based methods, and it adopts an approach that the nodes wait a certain wait time before retransmitting a received packet. The wait time is calculated as a function of distance between the sender and the receiver, so that the farther node, from the sender retransmits the packet earlier than the closer nodes. The paper concludes that the proposed protocol suits for the sparse ad hoc networks.

2.3 Protocols for Decentralized Congestion Control

There are three major approaches for DCC over vehicular cooperative systems. The first is Transmission Power Control (TPC), and the second is Transmission Rate Control (TRC), and the third is to use both TPC and TRC. The capability of TPC and TRC is required in ETSI standard [41] as individual functions, and these three approaches are currently being proposed.

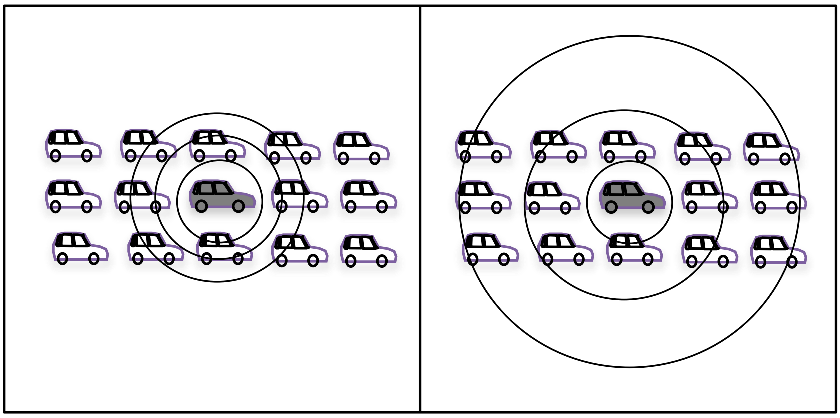


Figure 2.1: Schematic of different radio ranges, showing difference in the number of vehicles

Figure 3.1 shows the schematic figures to help understand the difference between TPC and TRC. In this figure, the size of the outer circle denotes radio range, and the space between circles denotes the transmission interval for both left and right parts. TPC, depicted on the left side, decreases the number of vehicles to receive the packets by decreasing the size of the outer circle. On the other hand, TRC, depicted on the right side, decreases the number of packets to be received by increasing the transmission interval, which means decreasing the transmission rate.

As a TPC mechanism, Distributed Fair Transmit Power Adjustment for Vehicular environments (D-FPAV) [42] is proposed. This method controls the transmission power for each beacon packet in order to limit the load in the wireless channel to less than the Maximum Beaconing Load (MBL) and give fair opportunities of channel access to each vehicle. For this purpose, D-FPAV decides each vehicle’s transmission power dependent on predictions of application-layer traffic of all the vehicles in the carrier sense range. The simulation study reveals that D-FPAV can achieve higher probability of message reception within the range of 150 m than communication without D-FPAV, and that the channel access time is 1.7 ms on average, which is shorter than 20 ms in the case without D-FPAV. These results suggest that D-FPAV, by reducing the transmission power, efficiently controls congestion, and consequently produces a lesser packet reception rate by avoiding communication with unnecessary vehicles.

As TRC mechanisms, Periodically Uploaded Load Sensitive Adaptive Rate (PULSAR) is proposed in [43], and Multi Hop Vehicular Broadcast (MHVB) is proposed in [44][45]. The approach of PULSAR is that the transmission power is fixed first. The reason why transmission power can be fixed as constant is that the average packet Inter-Reception Time (IRT), i.e., the average amount of time between two subsequently received messages for a sender-receiver pair, does not depend on transmission power. After fixing the transmission power, PULSAR varies transmission rate to adjust Channel Busy Rate (CBR) of the wireless channel to 0.6. The reason is that the number of packets received successfully by neighbor vehicles is maximized when CBR is around 0.6 as reported in [46]. The simulation results were shown for a dynamic highway scenario, where two groups of vehicles move bi-directionally from either side. They reveal that the transmission interval varies dynamically according to the density of vehicles, always keeping CBR less than 0.6 even under very high density. PULSAR tackles the issue of how much the wireless channel can be utilized, taking CBR as the unique criteria of congestion control.

Multi-Hop Vehicular Broadcast (MHVB) was first proposed in [44] and enhanced functionality was proposed later in [45]. The fundamental objective of this protocol is to disseminate vehicle information efficiently to surrounding vehicles in a multi-hop manner and at the same time to control network congestion. In order to perform congestion control, MHVB firstly detects vehicle traffic congestion based on the number of surrounding vehicles. When there are more vehicles than predefined thresholds, it judges the degree of accident risk as the next step. For example, it judges the vehicles on the head or tail of traffic as risky, and the vehicles in the midst of traffic as less risky. Once a vehicle is judged as less risky, the transmission rate is changed inversely proportional to the number of surrounding vehicles, so that the total number of packets sent would be constant. On the other hand, the vehicles judged as risky keep the transmission rate of beacon packets as default, so that they can notify their existence and status to surrounding vehicles with sufficient frequency.

As mechanisms using both TPC and TRC, a joint power / rate congestion control algorithm is proposed in [47]. The combined power and rate control algorithm consists of three phases: channel monitoring, load change estimation and action. The channel monitoring phase extracts the number of neighbors in the surrounding area by observing channel busy time. Based on the number of neighbors, the algorithm computes the new transmission power and transmission rate to be used during the next predefined interval in the phase of load change estimation, in order not to violate the channel busy time threshold.

The common objective of the above-mentioned congestion control approaches is to keep the utilization of a channel at a certain level. However, to the best of our knowledge, there are no related works aiming to control the number of packets received on an OBU in order to specify the performance requirement of a communication apparatus.

2.4 Inter-Vehicle Communication in Surface Mine

2.4.1 Proximity Warning System

As introduced in Section I, safety guidelines for drivers have been regulated so far, which are not effective for human errors and in extreme situations [65]. Meanwhile, a lot of efforts have been dedicated to building reliable alert systems. These systems aim at warning in the detection of deviation from the scheduled routes and/or overspeed.

An equipment operating assistance system utilizing Google Earth is proposed in [57], [58], [66]. In this system, the locations of each surface mining equipment are obtained by GPS. This information is shared to be displayed on a 3D map, via a wireless mesh network that consists of base stations placed in the mine. In [60], a system utilizing polyvinyl poles at the roadside is proposed to pursue high accuracy of location detection. The system is based on laser range and bearing sensors that measure the relative distance to standard polyvinyl chloride poles located at roadside. [62] employs 433MHz band for communication. The system aims at collision avoidance among vehicles, workers and obstacles within the range of 10 to 20 meters. Once it detects an object in the vicinity, it gives a warning to equipment operators. However, these systems in [57], [58], [60], [66] require outdoor infrastructure such as base stations and poles. In a harsh environment like mines, the installation and maintenance cost of those devices are not ignorable. [62] is similar to our approach, but our focus is to analyze wireless signal propagation characteristics to leverage Wi-Fi for proximity awareness with various entities and under various situations that affect communication. Meanwhile, reliable signal propagation is assumed in [62].

2.4.2 Radio Propagation Model for Inter-Vehicle Communication

As discussed in [67], inter-vehicle communication models can be categorized into (i) the deterministic models with geometric information such as [68], [69], (ii) the statistical models with geometric information such as [70] and (iii) the statistical models without geometric information such as [71]. In [68], the authors have designed a geometry-based efficient propagation model for inter-vehicle communication, which uses the frames of stationary objects such as buildings and foliage as well as mobile objects such as surrounding vehicles. It also considers two types of communication links, line of sight (LOS) and non-LOS. This model employs deterministic calculation of the large-scale signal variations, whereas the stochastic calculation is introduced for small-scale signal variations based on the number and size of surrounding objects. In [69], the authors establish a ray-tracing-based model for 5.2GHz radio propagation among vehicles incorporating traffic flow, roadside trees and traffic signs. Both papers have successfully established the models based on real measurement. In [70], a statistical model that is applicable to a local area has been developed by using the probability distributions of the received envelope and phase, spatial-time correlation function and the power spectral density of the complex envelope. In [71], the authors have measured the received signal at driving vehicles and built the models to represent various situations in cities.

2.4.3 C. Our Contributions

Our objective is to understand how Wi-Fi radio propagation is affected by haul truck bodies and geography in order to leverage low cost, off-the-shelf Wi-Fi technologies in mine safety applications. In this perspective, all the propagation models introduced above are for light vehicles with a typical size of 4.5m x 1.8m x 1.5m or similar. On the contrary, those of haul trucks in the mines are around 15m x 10m x 8m or larger, approximately 80 times larger than light vehicles in volume. Moreover, the geometric environments in mines are quite different from cities. We believe this is the first approach to model Wi-Fi propagation in mine environment, considering haul truck bodies under harsh environment in mines.

2.5 Driving Behavior Analysis

Smartphone-based telematics systems are becoming popular as they are open and low-cost alternatives for expensive dedicated sensors and communications. As introduced earlier, some car insurance companies such as Aviva [93] and StateFarm [94] have introduced smartphone-based systems to identify safe and risky drivers to build more reasonable price systems where lower insurance fees are offered to safer drivers.

There have been several studies on leveraging smartphones as a means of observing driving behavior. Nowadays, every smartphone is equipped with plural sensors and devices such as a global positioning system (GPS) device, inertial sensors and a camera. It has been reported in the past literature that GPS locations can be used to infer the time series of speed profiles with less than 4 km/h errors [77]. In [78], cameras are utilized to detect dangerous driving such as drowsy and distracted driving and lane weaving. They are also used to detect eyelid closure together with other sensors calculating drivers' vigilance indexes [79]. Acceleration sensors have been intensively focused on, where comparative studies are conducted with IMUs in [80], [96]. In particular, it has been addressed in [80] that significant correlations are found between accelerations measured by smartphones and IMUs, but smartphones are more false-positive to critical driving events such as sudden acceleration, braking and turn. Some other studies discuss how to detect driving events by Symbolic Aggregate Approximation (SAX) [81] and driving styles by Dynamic Time Warping (DTW) [82]. These analytical approaches of driver behavior are also presented for similar but different application domains such as efficient driving support to reduce fuel consumption [83], road condition monitoring [84], [95] and assessment of drivers [85].

The analyses of driver behavior for safety have been intensively studied so far [86]-[88], [97]-[101]. Ref. [86] proposes a novel system that uses DTW and smartphone based sensor-fusion to detect aggressive turns, acceleration and braking, which are typically regarded as risky driving behavior. The authors of [87], [91] have proposed a vehicle driver profiling mechanism, which scores driving behavior based on the Fuzzy Inference System (FIS). It reveals that the mechanism can classify driving styles into 3 categories: normal, moderate and aggressive. In [88], the authors have constructed an in-vehicle sensing platform to build an aggressive driving style model. They have collected driving data for 3 weeks from 22 drivers, whose record of traffic violation and the result of Manchester Driving Questionnaire (DBQ) are given. Machine learning techniques are used to build a driver model to estimate the driving styles. Their models can classify drivers into the aggressive and non-aggressive categories with 90.5% accuracy using smartphones, OBD2 and IMU.

Compared with the above mentioned approaches, our contributions are summarized as follows. Firstly, we tackle to clarify the correlation between drivers' accident history and smartphones' inertial sensor readings. We assume that smartphone-based systems may attract more participants than dedicated systems and are therefore able to provide analytical results that are valuable to such future open systems. Secondly, we have collected over one year's driving data (about 15 months) from more than 800 drivers. This large-scale dataset increases the confidence of our approach, and we have discovered the statistically-significant driving behavior which correlates drivers' accident history. As far as we know, none of the existing approaches has both significant features.

Chapter 3

Effect of Decentralized Congestion Control on Cooperative Systems

3.1 Introduction

Cooperative systems using Vehicle-to-Vehicle (V2V) communications or Vehicle-to-Infrastructure (V2I) communications, or in general V2X communications, are now investigated worldwide. In some parts of the world, it has even reached pre-deployment phase under various pilot projects [1][32]. The purpose of these systems is to make road traffic safer and an important requirement to realize this is to enable vehicles to dynamically exchange the status information with other nearby vehicles. This status information typically includes geographical position, velocity and direction. As these systems deal with road safety, maintaining stable wireless intercommunication among them has become a prime requirement in order to guarantee information exchange between all vehicles. To this extent, standardization activities are actively pursued in globally renowned standardization bodies, such as IEEE [33][34][35], ETSI [36][37] and ARIB[38].

One of the current standardization trends is realizing separate safety applications based on periodic messages. These messages are called Cooperative Awareness Message (CAM) [36]in Europe and Basic Safety Message (BSM) [34] in the United States. Every vehicle participating in the cooperative system periodically broadcasts the messages to nearby vehicles, thereby constantly making them aware of its position and velocity. The nearby vehicles receiving these messages can judge if they have a potential risk with the vehicle.

There are two major technical issues to be solved before deploying these messages into practice. One is communication security as pointed out in [39]. As these messages influence vehicular safety, there must be a mechanism to prevent these messages from being tampered with and to protect privacy information. In [40], the authors proposed a message verification mechanism through a hardware security module which protects the on-board unit and the communication. This module can successfully verify 436 messages per second.

The second major issue is the risk that the radio channel could be easily saturated if no network congestion control is at work. As pointed out in[41], it is known that network congestion occurs even in simple scenarios. As cooperative systems involve decentralized communication, congestion control mechanisms operate in a decentralized way, and hence are known as Decentralized Congestion Control (DCC).

Congestion affects wireless communication in two ways. Firstly, it causes packet loss, which leads to uncertainty in information exchange among vehicles. Secondly, the performance of the communication apparatus, called on-board unit (OBU) may become unpredictable although it should guarantee a certain level of performance for service provision. The number of packets that can be processed per second by OBU is a possible metric to assess the performance level achieved by OBU.

This chapter focuses on the second issue which is rarely studied in the prior art. For this purpose, this chapter presents a decentralized mechanism of controlling the maximum number of packets delivered to OBU. A novel DCC method introducing a new criteria, Packet Reception Rate (PRR), is proposed and evaluated under simple road scenarios (e.g. uniform vehicle distribution in a single road) in simulation.

The remainder of this chapter is organized as follows. Section 3.2 provides a description of the proposed protocol. In order to evaluate the proposed protocol, the network simulator NS-2 is used. The configuration detail for the simulation is explained in Section 3.3. Section 3.4 shows the simulation results, varying the density of vehicles to emulate the network congestion, with discussion in Section 3.5. Summary and concluding remarks are provided in section 3.6.

3.2 Wireless Communication Systems for Cooperative Systems

The upcoming cooperative systems both in the US and in Europe rely on the IEEE 802.11p standard, a revision of Wireless LAN standard (IEEE 802.11) for V2X communications requiring low latency. The medium access control (MAC) protocol of IEEE802.11p is carrier sense multiple access with collision avoidance (CSMA/CA). The standard for V2V communications in Japan [112] is also based on CSMA, while V2I communications are managed on the time division multiple access (TDMA) basis. The CSMA has well-known drawbacks; it causes collisions on the channel as well as unbounded delay before channel access in congested situations [106]. This issue makes a considerable impact on the road safety applications based on periodic messages, requiring reliable and low-latency awareness of surrounding vehicles.

Due to these problems, some papers proposed to use a self-organizing time division multiple access (STDMA) scheme [107][108][109][110], which is in commercial use in system as automatic identification system (AIS) for collision avoidance between ships [111]. Thanks to the deterministic channel access control mechanism, STDMA shows better results in terms of communication reliability as well as latency. However, the main drawback is that it requires strict time synchronization through a global navigation satellite system (GNSS), which may cause cost increase of the apparatus. On the contrary, the apparatus with CSMA is expected to be developed with much lower cost, due to its straightforward implementation with ready-to-use wireless LAN technologies. Therefore, despite of such technical drawbacks, CSMA has been adopted as the standards for the first phase of cooperative systems in the world.

Another approach to overcome the above-mentioned issues of CSMA is DCC. The primary feature of DCC compared to STDMA approach is the incorporation of the CSMA mechanism with parameter control. By flexibly managing transmission intervals, transmission power and others on top of CSMA, congestion can be avoided even in the crowded situations. Therefore DCC mechanism can be applied to the next-generation cooperative systems in the world, where CSMA is adopted as PHY/MAC layer protocols.

The motivation of this study is to address the technical challenges towards commercial deployment. For this reason, this thesis targets the standard compliant wireless communication systems, and therefore the latter approach (i.e., DCC over CSMA) is studied.

3.3 Protocols for DCC

3.3.1 Issues to be solved

In this section, the problem to be solved by the congestion control algorithm is defined. The major requirements come from the fact that it is used for vehicle safety applications. Because the congestion control algorithm is implemented as a part of a beacon protocol for cooperative systems, it must achieve the requirements necessary for traffic safety applications as summarized in [36]. Among traffic safety applications, Car-to-Car Communication Consortium (C2C-CC) defines "Day-1" applications. They consist of 10 applications, which are to be put into practice from the beginning of deployment. These applications were chosen based on the consensus of several stakeholders such as automobile companies, road operators, traffic authorities, and academic institutes. They were also fetched through opinion polls of various conferences related to Intelligent Transport Systems (ITS). The applications are listed below:

- Emergency Vehicle Warning
- Emergency Brake Light
- Stationary Vehicle Warning V2C Rescue Signal
- Traffic Jam Ahead Warning
- In Vehicle Signage (speed management)
- Hazardous Location Warning
- Contextual Speed Limit
- Road Work Warning
- Green Light Optimal Speed Advisory

These applications require the underlying beacon protocols to satisfy their common requirement which is summarized into the following two criteria.

(1) Information propagation distance

The information of a certain vehicle should be forwarded up to the other vehicles located in a distance $DIST_F$ from the vehicle.

(2) Information freshness

The information of a certain vehicle should be received by the other vehicles within a time delay T_D after its generation at the originating vehicle.

The mission of beacon protocols is to maintain the situation that all vehicles can receive the information of all surrounding vehicles within the distance of $DIST_F$ from their own position within the time of T_D, in order to enable them to grasp surrounding traffic situations and judge the risk of potential traffic accidents. The above criteria are considered important for effective functioning of the "Day-1" applications. Additionally, there are two other requirements for cooperative systems to properly function in reality.

(1) Use of limited wireless channel

Because cooperative systems work over wireless communication, there is limitation of wireless data rate D_R. In the case of cooperative systems, IEEE802.11p is regarded as the worldwide standard, which has data rate ranging between 3 – 27Mbps dependent on the type of modulation. This requirement does not only mean that the amount of data rate at a certain spatial point should be less than the data rate, but also mean that the hidden terminal problem [49] in an ad hoc network [50] under the data rate should be taken into account, especially under high network utilization.

(2) Performance requirements for communication apparatus

In order to bring cooperative systems to realization, performance requirements for communication apparatus should be specified. In the case of co-operative systems, unlike other IT systems which serve in a best effort manner, each application process should be able to handle all in-bound data within a predefined time. In order to evaluate the performance, a performance parameter defined as Packet Reception Rate (PRR) is introduced, which directly reflects the performance criteria for processing on a communication apparatus such as cryptographic processing.

As a summary, the challenge for the beacon protocol can be stated as follows.

Given any collection of vehicles located on the road, the information of a certain vehicle should be passed to other vehicles within the distance of $DIST_F$, within the time of T_D, under D_R specified by wireless channel, controlling PRR less than predefined threshold for each vehicle.

Ideal information dissemination of beacon protocols satisfying the above-mentioned requirements is illustrated in Figure 3.1. The vertical axis is success rate, which indicates the ratio of at least one data reception from other vehicles within time T_D. The horizontal axis is distance between sending vehicle and receiving vehicle. Reflecting the requirements, the success rate should be 100% until the distance of $DIST_F$. The success rate may become zero after $DIST_F$, which means that a vehicle does not need to receive other vehicle information further than $DIST_F$ to satisfy application requirements. The reason why the success rate further $DIST_F$ is zero in the ideal case is that unnecessary information should not be received, so that the communication apparatus does not consume unnecessary wireless bandwidth and processing resources. From a practical viewpoint, it is not essential to be zero for the distances greater than $DIST_F$. It is just an ideal scenario and in reality the information dissemination depends on the presence of vehicles at the edge of radio communication coverage of a sending vehicle.

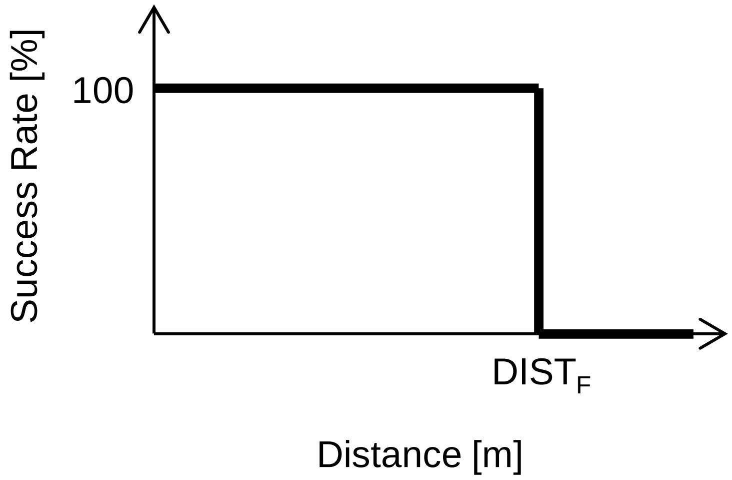


Figure 3.1: Ideal characteristic for information dissemination

The challenge for beacon protocols is to make information dissemination as close as the ideal situation, though it is impossible to perfectly realize it. Note that the challenge in reality includes not only wireless communication but also information processing capability on the OBU.

3.3.2 Functions of MHVB

The primary objective of this study is to control the number of packets received by decentralized congestion control under the influence of the hidden terminal problem, which makes a congestion control mechanism unstable. This thesis adopts TRC as a base mechanism for achieving congestion control in MHVB. In addition to congestion control, MHVB is designed to satisfy the requirements presented in the previous section. The details of MHVB functions and its improvement for above-mentioned objectives are described.

3.3.2.1 Multi-hop information dissemination based on distance from the source vehicle

Safety-critical applications require information dissemination up to the distance of $DIST_F$ from a vehicle, although radio range under practical conditions on roads may be shorter. This is because the radio range varies depending on physical conditions such as the existence of buildings and the shape of roads. Regardless of the surroundings, MHVB disseminates information up to $DIST_F$ by using intermediate forwarders.

The function works as follows. Once a vehicle receives a packet transmitted by another vehicle, it checks the contents of the packet. The packet format of MHVB is illustrated in Figure 3.3.

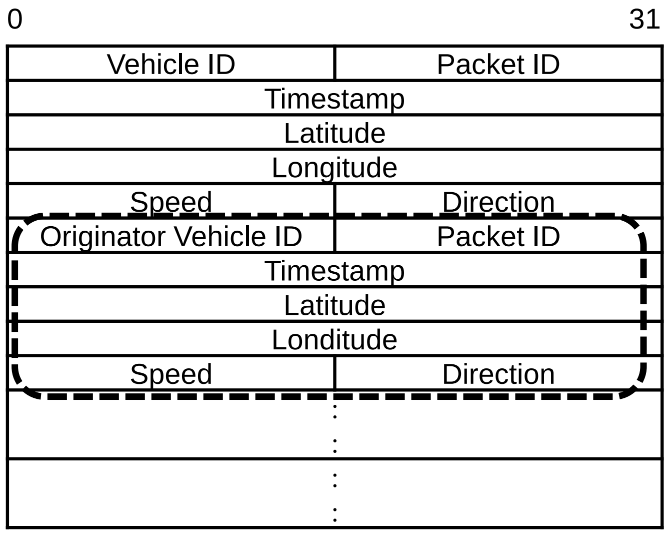


Figure 3.2: MHVB packet format

The packet format can be essentially divided into two main parts. The first part contains information of the sender, which is the vehicle that transmitted the packet. It starts from “Vehicle ID” to “Direction” in Figure 3.2. This part is essential for all the packets of MHVB. The meaning of each field is described in Table 3.1.

Table 3.1: Meaning of each field in MHVB packet

Field Name	Meaning
Vehicle ID	Identifier of the vehicle
Packet ID	Identifier of the packet transmitted by the vehicle
Timestamp	Time of data generation
Latitude	Coordinates of the position of the vehicle at time of data generation
Longitude	
Speed	Speed of the vehicle
Direction	Driving direction of the vehicle

The second part is the information of an originator, which is another vehicle than the sender. More specifically, the part enclosed in the dotted line was once received by the sender and retransmitted in a multi-hop manner. MHVB packets can contain plural sets of originator information in a single packet i.e., the multi-hop in MHVB means not forwarding a packet as it is, but transmitting a packet containing plural sets of information of other vehicles received before. Thus, MHVB can disseminate the data of one or more vehicles in a multi-hop manner.

3.3.2.2 Backfire

In the case of multi-hop information dissemination, redundant information may be sent because plural vehicles may send the same information by retransmitting it. Backfire is the mechanism to suppress such redundant information dissemination.

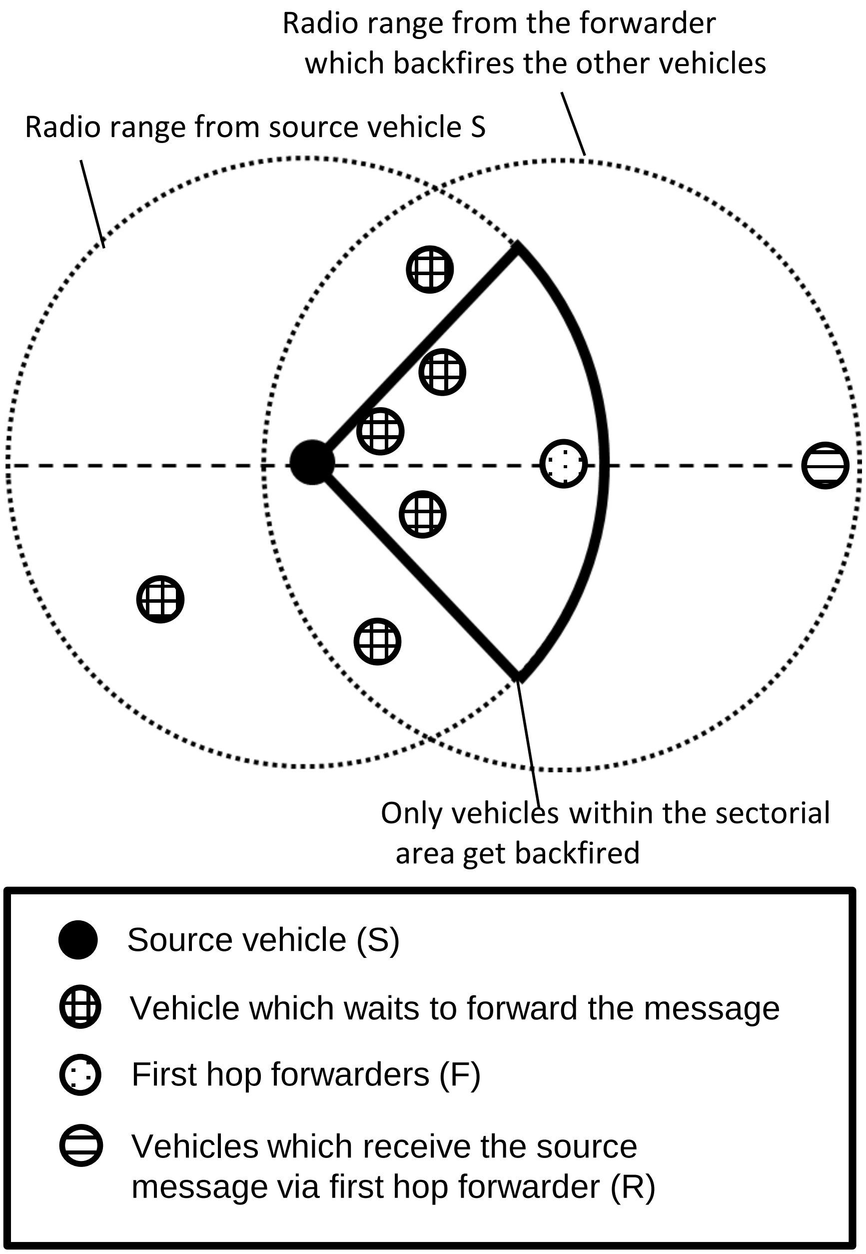


Figure 3.3: Backfire mechanism

Figure 3.3 illustrates how the backfire mechanism works. When a packet is transmitted, the vehicles within the radio range of the source vehicle will receive the packet. On receiving it, each vehicle calculates a waiting time WT_d for the set of information at a distance d from the sender to relay the packet and store the data and its WT_d in the memory. Thus a distance-based contention mechanism relative to the transmitting vehicle is induced in the forwarding stage among the receiving vehicles.

$$WT_d = WT_{\max} \times \left(1 - \frac{d}{R}\right) \quad \text{(eq.1)}$$

In the above equation (eq.1), WT_{max} is the predefined maximum waiting time, and R is the theoretical radio range. When the vehicle transmits a packet, it checks this waiting time for every set of information and decides if the packet should include the information set. If a vehicle overhears the same set of information from other vehicle, then it cancels the waiting time and stops retransmitting the information set. This is known as "backfire". From eq.1, it can be inferred that a farther located vehicle is preferred to send the information set earlier so that the vehicles located in-between the originator and the farther vehicle cancel their respective retransmission. Note that the actual timing of packet transmission is controlled in the function of congestion control.

3.3.2.3 Congestion Control

For efficient utilization of bandwidth available in the channel, MHVB adjusts the interval of beacon packet transmission in accordance to the density of neighboring vehicles. In the case of cooperative systems, network traffic congestion occurs when there are many vehicles within the radio range of a vehicle. This situation can typically occur in a traffic jam. In order to avoid network congestion during a traffic jam, the congestion control mechanism of MHVB functions in two steps. The first step is to check if the vehicle is located in a traffic jam, and the second step is to determine the interval of packet transmission.

Step 1: In order to check if the vehicle traffic is jammed, the number of vehicles within radio range is estimated by counting the number of Vehicle ID included in MHVB packets received in the past one second. If the number of vehicles NV exceeds a predefined threshold NV_{max}, it also checks if the number of vehicles forward exceeds another predefined threshold NV_f and if the number of vehicles backward exceeds yet another predefined threshold NV_b, in order to judge if its location is in the midst of traffic jam.

Step 2: If the vehicle is located in the midst of a traffic jam, it changes its transmission interval proportional to the number of vehicles in its radio range. The interval T_{int} is calculated as in eq.2, where T_{def} denotes default transmission interval and NV denotes number of vehicles in radio range. As a result, the transmission interval is calculated as shown in Figure 3.4.

$$T_{\text{int}} = T_{def} \times \frac{NV}{NV_{\max}} \quad \text{(eq.2)}$$

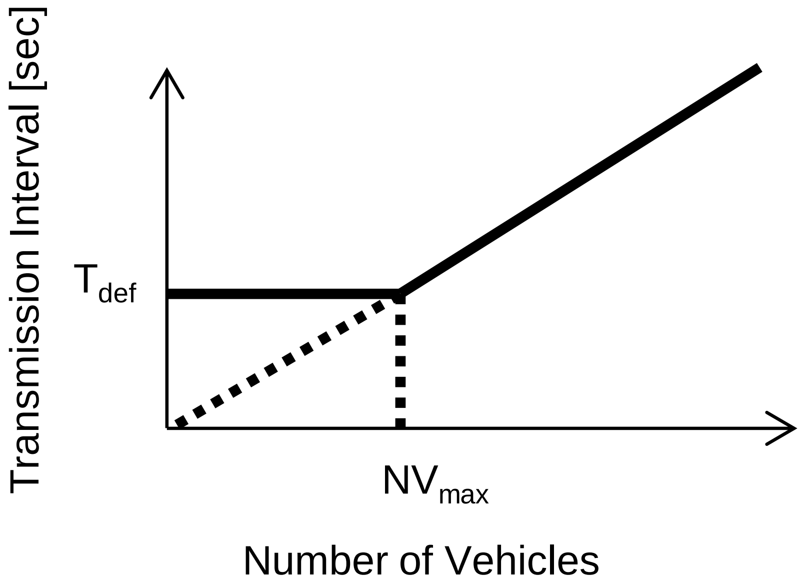


Figure 3.4: Variation of transmission interval w.r.t. number of vehicles, where T_{def} is default interval.

In the context of network architecture, this congestion control mechanism is realized by the cross layer design principle. In Step 1, the number of vehicles is estimated based on the Vehicle ID included in the packets of MHVB, residing at the network layer (Layer 3 of the OSI reference model). On the other hand, the transmission interval control in Step 2 should be realized at the media access layer (Layer 2 of the OSI reference model). In order to address this gap, as depicted in Figure 3.5, the information on the number of vehicles is provided by the MHVB protocol to the vertical layer, and the transmission interval control function obtains it from the vertical layer. The same concept can be seen in the ETSI standard on the DCC [106]. In the ETSI TC ITS reference architecture, the management layer plays a role of the above-mentioned vertical layer.

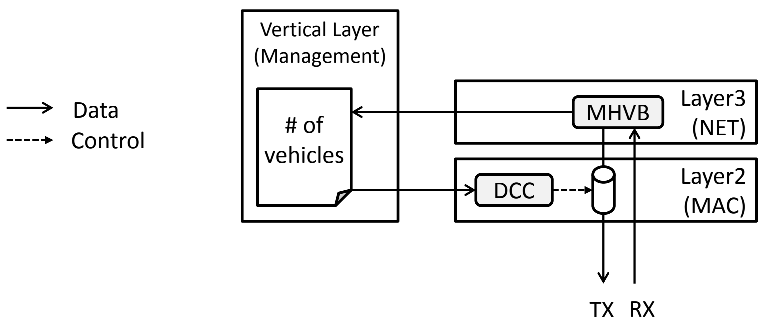


Figure 3.5: Cross layer design for DCC

3.3.2.4 Improvement of current MHVB w.r.t. previous versions

As described in section 2.3.1, the packet length of original MHVB [45][46] varies dependent on the number of vehicles included in a packet. Namely, the higher the density of vehicles is, the longer the packet length becomes. Because the longer packet easily causes packet collisions on the air by the hidden-terminal problem, we limit the packet length PL to 142 Bytes for this study. As a result, the effect of information propagation by multi-hop manner decreases, while the packet loss rate by packet collision also decreases.

3.4 Evaluation

In this section, the effect of the congestion control mechanism in MHVB is evaluated. A theoretical analysis is given followed by simulation results by using the network simulator NS-2.

3.4.1 Theoretical Analysis

The objective of this thesis is to control the packet reception rate PRR less than a targeted threshold for each vehicle. Suppose that there is no packet loss brought about by CSMA/CA and hidden terminal problem. PRR of a focused vehicle is ideally calculated as eq.3, where the summation is taken for each vehicle in the radio range and PTR_i stands for packet transmission rate of the i-th vehicle.

$$PRR = \sum_i PTR_i \quad \text{(eq. 3)}$$

Here the real packet reception is affected by packet loss and packet collisions in the air. Within this thesis, the PRR expressed in the formula above is called “Ideal PRR”, while the packet reception rate at a certain vehicle is called “Actual PRR”.

In order to control PRR, MHVB controls PTR_i, namely the packet transmission rate of the i-th vehicle by changing the packet transmission interval upon congestion.

3.4.2 Simulation Environment

Simulation studies were performed using the network simulator NS-2 to investigate whether the proposed congestion control scheme satisfies the objective. The simulation parameters and MHVB parameters are shown in Table 3.2 and Table 3.3, respectively.

Table 3.2: Simulation parameters

Parameter	Value
NS-2 version	2.35
Mobility scenario	Single lane model
Data rate	6 Mbps
Radio range	350m
Carrier Frequency	5.9 GHz
Interface type	802.11p
Simulation time	100s
Density of vehicles	10-140 per km

Table 3.3: MHVB parameters

Parameter	Value
T_{def}	0.1 sec
WT_{max}	0.1 sec
$DIST_f$	400 m
T_D	0.3
PRR_{target}	100 / 200 / 300 / 400 pps
NV_{max}	10 / 20 / 30 / 40
NV_f	5
NV_b	5
PL	142 Byte

The parameter PRR_{target} means the targeted PRR value of entire communication system. Actually, targeted PRR is controlled by the value of NV_{max} and T_{def}. The relationship between them is as follows.

$$PRR_{target} = \frac{NV_{max}}{T_{def}} \quad \text{(eq.4)}$$

3.5 Simulation Results

In this section, the simulation results for different target PRRs are presented followed by the result of preliminary study is illustrated in Figure 3.6.

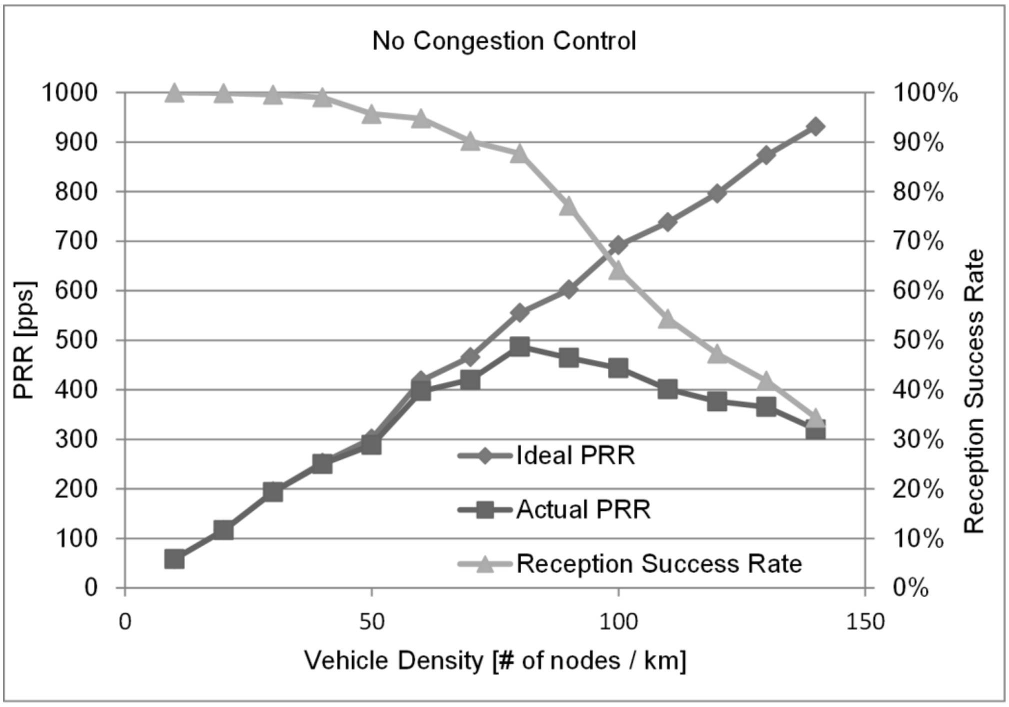


Figure 3.6: PRR and Reception Success Rate w.r.t vehicle density (no congestion control)

This preliminary result shows how PRR behaves with regard to vehicle density in the absence of congestion control function. Ideal PRR is calculated from the number of packets transmitted from the vehicles within the radio range in the simulation, i.e., the average number of packets to be potentially received by a single vehicle per second. Actual PRR indicates the average number of packets actually received by a single vehicle per second.

Without congestion control, Ideal PRR increases up to 932 pps at 140 vehicles / km proportionally to vehicle density, while Actual PRR has a peak 468 pps at 80 vehicles / km. The fact that Ideal PRR continues to increase proportionally implies that the vehicles can send out beacon packets without the effect of CSMA/CA. On the other hand, a vehicle cannot receive all the packets because of the effect of hidden terminal problem. The reception success rate, which is introduced by Actual PRR / Ideal PRR, stays higher than 90% for smaller vehicle density than 70 vehicles / km, while it decreases down to 34% when the vehicle density is 140 vehicles / km.

The detail of the reasoning is explained together with Table 3.4. It shows the experimental results and the breakdown of packet losses analyzed from the simulation results. In this table, “Vehicle in RR” means the number of vehicles in radio range from the viewpoint of a certain vehicle, which can be calculated from the mean interval between two adjacent vehicles and radio range. “Tx Loss” means the percentage of packets not being transmitted with respect to the “Ideal PTR” defined in eq. 5. Because T_{def} in this simulation is defined as 0.1 sec, Ideal PTR corresponds to 10 times of “Vehicle in RR”. “Rx Loss” means the percentage of packets not being received with respect to Ideal PTR. “Tx Loss” and “Rx Loss” are expressed as eq. 6 and eq. 7, respectively.

$$\text{Ideal PTR} = \text{Vehicle in RR} / T_{def} \quad \text{(eq. 5)}$$
$$\text{Tx Loss} = (\text{Ideal PRR} - \text{Ideal PTR}) / \text{Ideal PTR} \quad \text{(eq. 6)}$$
$$\text{Rx Loss} = (\text{Actual PRR} - \text{Ideal PTR}) / \text{Ideal PTR} \quad \text{(eq. 7)}$$

Please note that Ideal PRR in Table 3.4 is always close to Ideal PTR, namely the 10 times of Vehicle in RR, and that the Tx Loss is uncorrelated to the vehicle density. In general, the reasons for Tx Loss can be classified into two types. The first is transmission buffer overflow caused by CSMA/CA on MAC layer, and the second is that the upper layer does not send a packet for any reason. Considering the fact that utilization of wireless channel with vehicle density 140 is around 1.1 Mbps, and that Tx Loss stays constant irrelevant of vehicle density, it should be ascribed to the upper layer not transmitting a packet. Actually, MHVB has a function to add a jitter in the transmission interval in order to avoid continuous packet collisions caused by the hidden terminal problem.

It is also notable that the Rx Loss increases according to an increase in vehicle density. In general, the reasons why a packet in the air cannot be received by a vehicle can be classified into two types in the case of wireless communication. The first is the packet collision, and the second is too low signal-to-noise ratio (S/N). Because the effect of low S/N can be negligible in this simulation, the major reason of Rx Loss can be interpreted as the loss caused by the hidden terminal problem.

Table 3.4: Breakdown of packet losses w.r.t. vehicle density

Vehicle Density	Vehicle in RR	Ideal PRR	Actual PRR	Tx Loss	Rx Loss	Collision Loss
10	6	58.2947368	58.2947368	2.84%	2.84%	0.00%
20	12	116.652632	116.515789	2.79%	2.90%	0.11%
30	20	194.484211	193.653684	2.76%	3.17%	0.42%
40	26	252.708271	250.242857	2.80%	3.75%	0.95%
50	34	330.180263	306.683552	2.89%	9.80%	6.91%
60	40	388.231579	377.181578	2.94%	5.70%	2.76%
70	48	465.898565	420.168421	2.94%	12.46%	9.53%
80	54	524.215385	468.295141	2.92%	13.28%	10.36%
90	62	602.215789	464.499624	2.87%	25.08%	22.21%
100	68	660.338158	429.921381	2.89%	36.78%	33.88%
110	76	738.070588	401.240866	2.89%	47.21%	44.32%
120	82	796.195014	376.415512	2.90%	54.10%	51.19%
130	90	873.331579	365.276578	2.96%	59.41%	56.45%
140	96	931.65933	319.891387	2.95%	66.68%	63.73%

Because the target of this study is congestion control to suppress the number of packets received on an OBU, the simulation is performed varying PRR_{target} values from 100 up to 400 pps, which is smaller than the maximum Actual PRR in Table 3.4. This is also in line with the maximum message verification speed of automotive Hardware Security Modules (HSM) [39] which provides secure hardware extension to the ECUs of a vehicle in order to prevent manipulation and misuse of information exchanged among vehicles.

Figure 3.7 illustrates the comparison among different PRR_{target} values with regard to vehicle density. As expected theoretically, the behavior for each PRR_{target} value is almost the same for vehicle density smaller than 20 vehicles / km. This is because MHVB judges that the traffic is not congested and the congestion control function is not invoked. As a result, Actual PRR increases proportionally to the vehicle density.

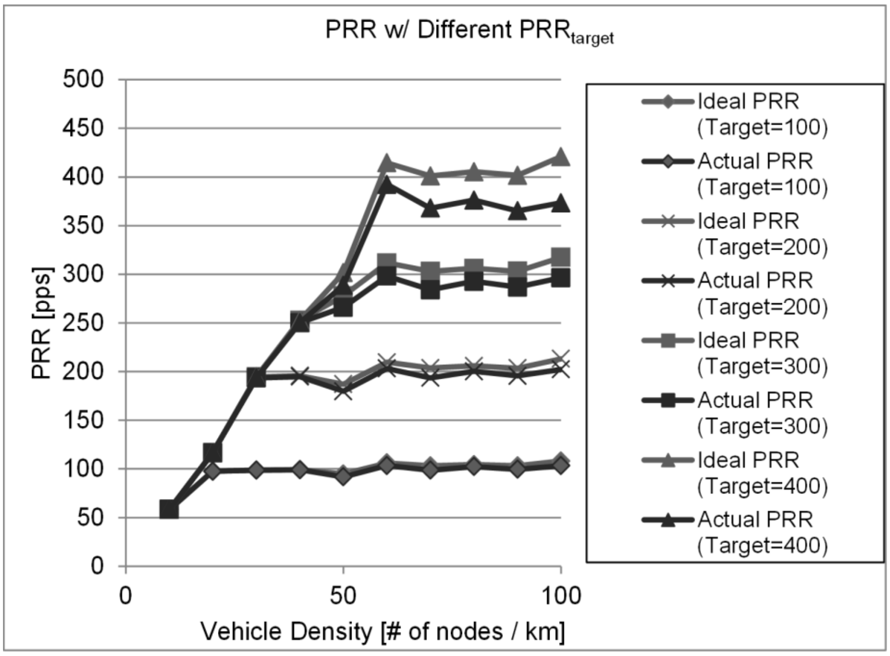


Figure 3.7: Comparison among different target PRRs w.r.t vehicle density

On the other hand, the behavior of each PRR_{target} value becomes different for larger vehicle density than 20 vehicles / km. This is because MHVB judges the traffic congestion according to each PRR_{target} value. Once it detects traffic congestion at a certain vehicle density, the congestion control function is invoked and the PRR stays constant irrespective of any further increase in the vehicle density.

Figure 3.8 illustrates the simulation results on reception success rate with regard to vehicle density and different PRR_{target} values (100, 200, 300, 400 and none). As the result of congestion control, reception success rate with PRR_{target} is much higher than the result of no congestion control, which is denoted as No PRR_{target} in the figure.

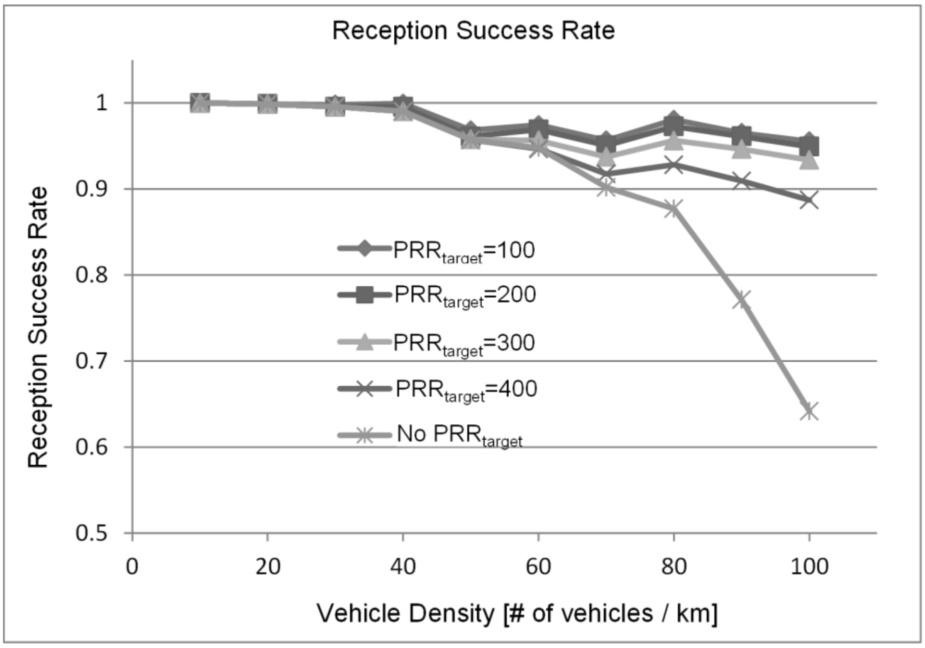


Figure 3.8: Reception Success Rate w.r.t vehicle density (PRR_{Target}=100, 200, 300, 400, none)

For more detailed discussion, the breakdown of packet loss with respect to PRR_{target} values is shown in Table 3.5. Unlike the definition of "Tx Loss" and "Rx Loss" in Table 3.4, those in Table 3.5 are calculated by eq. 8 and eq. 9. The negative value of Tx Loss means Ideal PRR, which is sum of packet transmission rate for surrounding vehicles, is more than PRRtarget.

$$\text{Tx Loss} = (\text{Ideal PRR} - PRR_{target}) / PRR_{target} \quad \text{(eq. 8)}$$

$$\text{Rx Loss} = (\text{Actual PRR} - PRR_{target}) / PRR_{target} \quad \text{(eq. 9)}$$

Because the same discussion as Table 3.4 can be applied to Table 3.5, the collision loss can again be ascribed to the hidden terminal problem. Taking the case of PRR_{target} being equal to 400 as

Table 3.5: Breakdown of packet losses w.r.t. PRRtarget (vehicle density = 100)

PRR_{target}	Vehicle in RR	Ideal PRR	Actual PRR	Tx Loss	Rx Loss	Collision Loss
100	68	108.0804754	103.2709677	-8.08%	-3.27%	4.74%
200	68	213.1151104	202.2974533	-6.56%	-1.15%	5.41%
300	68	317.4702886	296.4370119	-5.82%	1.19%	7.01%
400	68	420.8179966	373.373854	-5.16%	5.32%	10.48%
None	68	660.3381579	429.9213816	2.89%	36.78%	33.88%

an example, when the vehicle is exposed to 400 pps, 10.48% is lost due to packet collisions. This is around one third of the number without congestion control. In the case of PRR_{target} being 100, the collision loss is suppressed to 4.74%. This means that the congestion control works relatively well, because of less packet loss thanks to less network utilization.

3.6 Discussion

In this section, we consider a microscopic network status for investigating the results.

Firstly, we consider the reason why the negative Tx Loss Values are observed for all PRR_{target}. The negative Tx Value means that a vehicle miscounts the number of vehicles in radio range and transmits MHVB packets more frequently than it should. The reason can be explained by the relationship between how the packet transmission interval is calculated and collision loss. In the case of PRR_{target}= 100, the transmission interval T_{int} is calculated as 0.68 second from eq. 2 and eq. 4, if there is no packet loss. As stated in section 2.3.3, a vehicle counts the number of vehicles in radio range by counting the number of Vehicle ID included in MHVB packets received in the past one second. Once packet collision occurs with T_{int} being 0.68 second, there might not be a next chance to receive a packet containing the same Vehicle ID within a second. Considering the fact that the 4.74% collision loss is observed and that Ideal PRR is 8.08% higher than PRR_{target}, it is speculated that a vehicle does not have information of average 8.08% of vehicles in the radio range within a second, due to 4.74% collision loss. Namely, the vehicle transmits 8.08% more packets because it cannot count all the surrounding vehicles properly. On the other hand, in the case of PRR_{target} = 400, the same calculation leads to T_{int} = 0.165 second, and there are average 6.06 times opportunities to receive a vehicle ID within a second. Although the collision rate is estimated as 10.48%, more frequent opportunities results in higher probability to receive the Vehicle ID within a second. This is why the difference between Ideal PRR and PRR_{target} is smaller than the case of PRR_{target} = 100.

Secondly, we consider how collision occurs. Figure 3.9 depicts the schematic figure of hidden terminals from the viewpoint of a vehicle located at the center in the figure. Suppose that the focused vehicle tries to receive a packet from another vehicle. It is obvious that the number of hidden terminals, which are not covered by the radio range of another, is more when another is farther. In the case of 100 vehicles / km, the number of hidden terminals is 34 at maximum and 1 at minimum, which lead to 34 times difference on the probability of collision loss by a coarse approximation. Namely, the packet of a farther vehicle is selectively lost due to collision loss.

The microscopic view in the case of PRR_{target} = 400 can be summarized as follows from the viewpoint of a vehicle.

- It transmits packets around every 0.165 seconds.
- Around 10% of packets transmitted by the surrounding vehicles are lost because of packet collision caused by hidden terminal problem.
- It fails to receive around 5% of surrounding vehicle information within a second, but most of them are expected to be relatively farther.

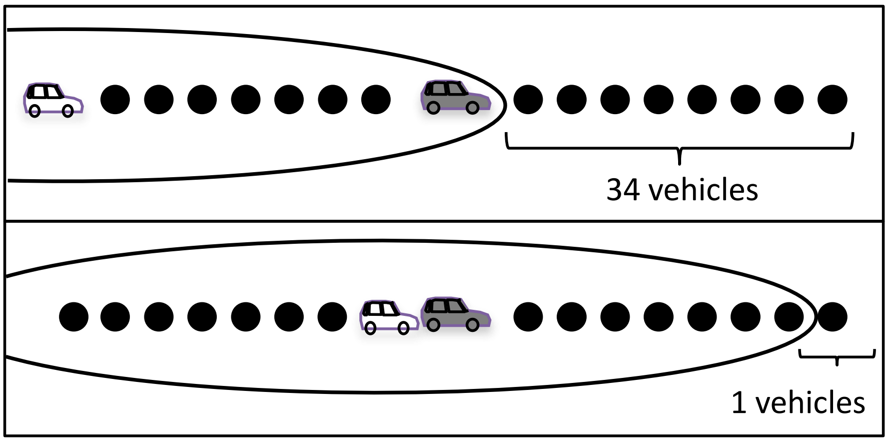


Figure 3.9: Schematic of relative position between two vehicles and hidden terminals.

3.7 Concluding Remarks

In this thesis, the effects of a decentralized congestion control (DCC) mechanism over cooperative systems were studied using MHVB protocol. Packet Reception Rate (PRR) was introduced as a criterion to evaluate the effects of DCC. The simulation study revealed that the congestion mechanism of MHVB can control PRR as desired. At the same time, it was also shown that the information delivery rate stayed higher than 88% in the range of 10 – 100 vehicles / km up to target PRR of 400. The collision loss was reduced to one third compared to no congestion control.

The microscopic network status under DCC was considered. The situation of the target PRR equal to 400 satisfies performance requirements introduced from the constraints of cryptographic processing, and the requirements for vehicular safety communications at a certain level.

In this research work, two issues came up which necessitate further investigation as future work. The first is to reduce the errors of PRR from PRR target value. The PRR at higher PRR target values tends to fluctuate because of collision loss brought about by hidden terminal problem. Although the hidden terminal problem itself may be inevitable, further investigation for possible ways to overcome its uncertainty is necessary in order to improve the stability of the PRR. The second is more quantitative analysis to find out to how much extent the application requirement is satisfied. Although we believe our proposal satisfies the application requirements for vehicular safety at a certain level, more quantitative analysis reflecting the non-application requirements, such as the maximum number of vehicles to be connected and the packet length taking into account the security standard in future, should be presented. Because they are under discussion in the community and not yet standardized, they remain open issue currently.

Chapter 4

Vehicle Proximity Awareness by Inter-Vehicle Communication for Surface Mine Operation Safety

4.1 Introduction

Although the safety assurance in surface mining is significant, the risk management in mines is not still well-designed compared to that in public road cases. A lot of efforts have been dedicated to establish effective regulations so far. For example, Earth Moving Equipment Safety Round Table (EMERST) was established in 2006 to promote and accelerate the development and adaptation of leading practice designs of mining equipment to minimize safety risks. The U.S. Department of Labor's Mine Safety and Health Administration (MSHA), which works to prevent death, illness, and injury from mining, summarized the safety standards for surface haulage as a proposed rule [50]. However, the largest proportion of accidents is caused by human factor such as operator fatigue and carelessness, which is not easy to prevent by rules only.

Figure 4.1: Collision Accident Scene

Fundamentally, this comes from too large size of ultra-heavy vehicles, where human perception does not work correctly. For example, a heavy truck allowing 10 tons payloads is 7.6m length, 2.5m width and 3.3m height, while a typical ultraheavy haul truck in mine has 15.5m length, 9.6m width and 7.5m height, which is about 17.5 times larger in volume. Therefore, there are a lot of blind angles around the vehicles and it is usually impossible for drivers and in-vehicle operators to recognize the surrounding situations. Not only the unexpected size of vehicles, but also the severe environment makes the drivers' awareness worse. For example, air and weather conditions in surface mine are usually much severer due to dense fog and dust. In such situations, the range of sight is often limited to only 10 to 20 meters, which is quite dangerous to drive such huge vehicles. Consequently, those severe conditions directly cause a variety of accidents. Ultraheavy vehicles accidentally contact workers and light vehicles, or those vehicles collide with each other [51]–[53]. In particular, collision between huge vehicles causes tragic results, as shown in Figure 4. 1.

In order to avoid contact between vehicles and workers, alert systems using RF-ID or millimeter wave technologies have been developed so far [55], [56]. However, the range of RF-ID is limited to 10 to 20 meters and millimeter wave is too expensive to detect all directions, so both of them cannot directly be applied to collision warning systems among ultra-heavy vehicles. In addition, RF-based approaches such as cellular-based systems and sensor-based detection [57]–[64] have been developed and utilized where locations of vehicles are exchanged via wireless communication. These are effective in relatively small-scale mining sites, but they need particular effort to cover the large mine site, which is widely spread over fields and mountains. Sensor-based approaches always have the issue of installation and maintenance cost, where each sensor requires a power supply and needs periodical maintenance. Inter-vehicle communication (IVC) is a promising, cost-effective approach in terms of the installation and maintenance. Two approaching vehicles within a certain range can communicate with each other to exchange their location information. Our partner company has actually installed 2.4 GHz Wi-Fi antenna to haul truck and the communication system is ready to use in the real field. However, unlike IVC between normal vehicles, there are several issues to be addressed. Firstly, the vehicles themselves considerably affect the RF signal propagation as they are like huge iron blocks. Therefore, directions, location of antennas, and even loaded iron sensitively degrade availability of communication. Secondly, all the mine-specific geography such as height level difference and cliffs affect communication, which often causes unexpected blind angles. Considering these issues, we recognize that Wi-Fi based IVC is not a perfect solution. Nevertheless, focusing on their strong merits in terms of cost-effectiveness and easy-maintenance, it is worth being deployed with proper understanding of their characteristics. In this perspective, we address the issues to leverage Wi-Fi based IVC to support drivers' awareness in surface mine. The idea is that we build a radio propagation model for haul trucks, which are the most typical vehicles in surface mine, by accurate ray-tracing. The model is validated in the field experiment, where actual radio signal propagation is measured and compared with the model. Then a mining environment, where steep cliffs due to excavation are often seen, is modeled and we estimate the received signal strength based on the locations of haul trucks and antenna locations. As a result, we can show that a haul truck can communicate with haul trucks approaching while it is difficult to detect haul trucks going away by IVC.

4.2 Characteristics of IVC in Mine and Factors That Affect Communication

In this chapter, we explain propagation characteristics of radio wave for IVC in mining environments. Firstly, we consider the effects of haul truck bodies and payloads as shown in the Fig. 2 on radio wave propagation. Radio waves are affected by the phenomena of diffraction, reflection and attenuation caused by the haul truck bodies and payloads. In particular, the payload might often be higher than the haul truck as shown in Figure 4. 2. This means that a haul truck with a payload have different propagation characteristics compared with the truck without payloads. As a result, radio propagation between two haul trucks has directional propagation characteristics according to a positional relation between two physical antennas mounted on the haul tracks and installation positions of the antennas even if the antennas have omnidirectional characteristics. Besides, the position of the antenna on haul tracks is limited unlike passenger cars. For example, the antenna is usually installed at left-front position because it is difficult to install the antenna at the rear-part of the haul trucks. Consequently, the effects of haul truck bodies and their payloads on radio wave propagation depend on the direction of each haul truck. For example, if two haul trucks have antennas at left-front position and move in opposite directions, the effects caused by the haul truck bodies and payloads on radio wave propagation could be large because the bodies and payloads are located between the antennas. From the above, in order to measure the effect of them to radio wave propagation, we model a haul truck as a combination of the presence of payloads (represented by a binary variable $p = f0; 1g$), antenna position (represented by a) and direction of each haul truck (represented by d,d').

Figure 4.2: Haul Truck with Payload (Photo from Our Partner Company)

Table 4.1: Dimensions and Materials of Haul Truck Body and Payloads

Size	15.49m length x 9.6m width x 7.52m Height
Material	iron
Payload	iron
Payload	Height rooftop+2m

Secondly, we consider the effects of terrain in mine contain cliffs and roads with different height levels on radio wave propagation. The terrain of the open pit mine becomes like an earthenware mortar and has stair-casing roads in order to mine the deep underground mineral. Furthermore, there are ramps that connect the two roads at different levels. Due to the road design criteria of a typical open pit mine moat [72], the angle of the cliffs in mines can be up to 75 degrees and the road height difference between two adjacent levels usually becomes 15m, which is much higher than the vehicle height and corresponds to the height of four or five-storybuildings. Furthermore, it is reported in several literatures that due to mis-driving and other accidental events, ultraheavy vehicles may slide down on steep slopes to lower levels and collide with vehicles there. This increases the potential risks of collisions or other serious accidents, and awareness is essential to alert such risks to drivers. Therefore, we must consider awareness between different levels and the effects of terrain characteristics in mine on radio waves. From the above, we model a mine environment as a combination of a terrain (represented by g) and a positional relation of two haul trucks (represented by l, l′).

4.3 Propagation Model Design

Radio emitted from a physical antenna attached to a haul truck is influenced by reflection and diffraction by its body and payloads. As a result, even though the physical antenna has omni-directional characteristics, the truck body itself can be regarded as a virtual directional antenna with directional propagation characteristics. We call it *antenna model*, which we obtain using the ray tracing method [73] to pursue the reality.

Then, in order to take environmental factors into account, we have simulated communication between two haul trucks at different coordinates with same/different antenna positions and payloads so that applications can easily estimate the ranges of communications for given situations. We have used the Scenargie simulator [74] with the fast urban module and the high fidelity module (the ray tracing module) for this purpose. Scenargie is a powerful simulator which has a framework to enable design and analyze wireless communications in realistic environments.

4.3.1 Obtaining Antenna Model by Ray Tracing

The dimensions and the materials of haul trucks and its payloads used in our study are shown in Table 4.1. We assume piled iron as a payload whose peak height is 2m higher than the rooftop height. We note that through several preliminary experiments, it is known that modeling the too-detailed form of the body does not contribute to increasing the accuracy. Thus, we constructed 3D model of the haul truck and its payloads by several cube objects in Scenargie. The specification of the antenna is shown in Table II. The two mount positions of antenna, "Left-front" and "Middle-front" are used in the following simulation experiments.

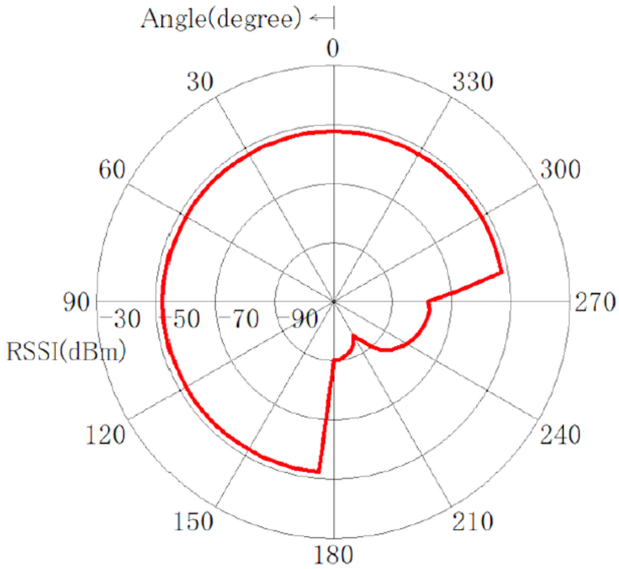


Figure 4.3: Received Signal Strength by Simulation using Antenna Pattern

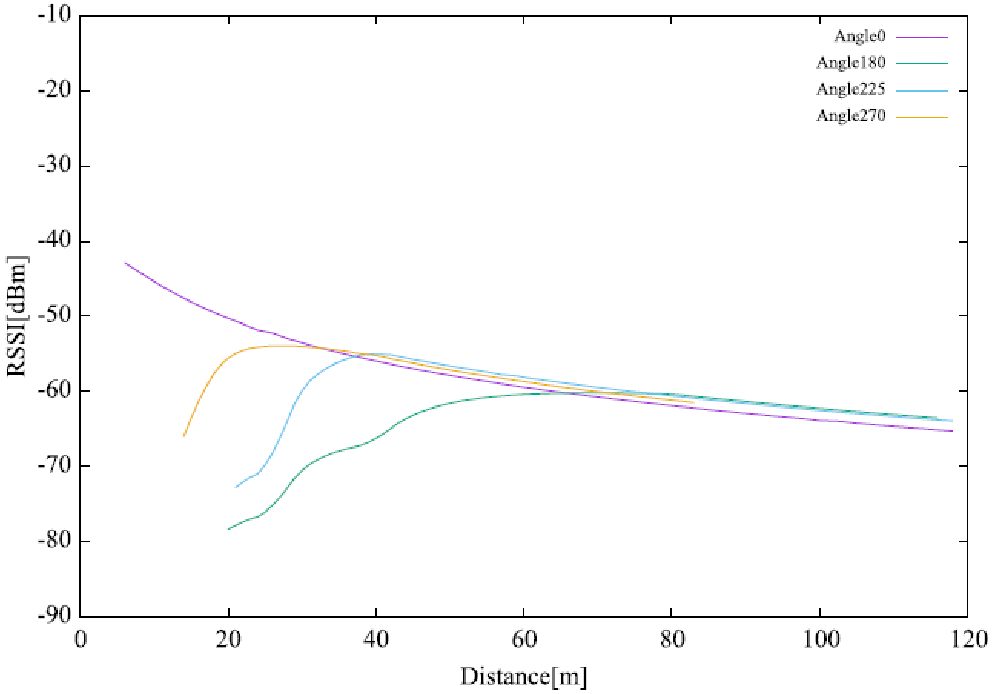


Figure 4.4: Received Signal Strength by Simulation

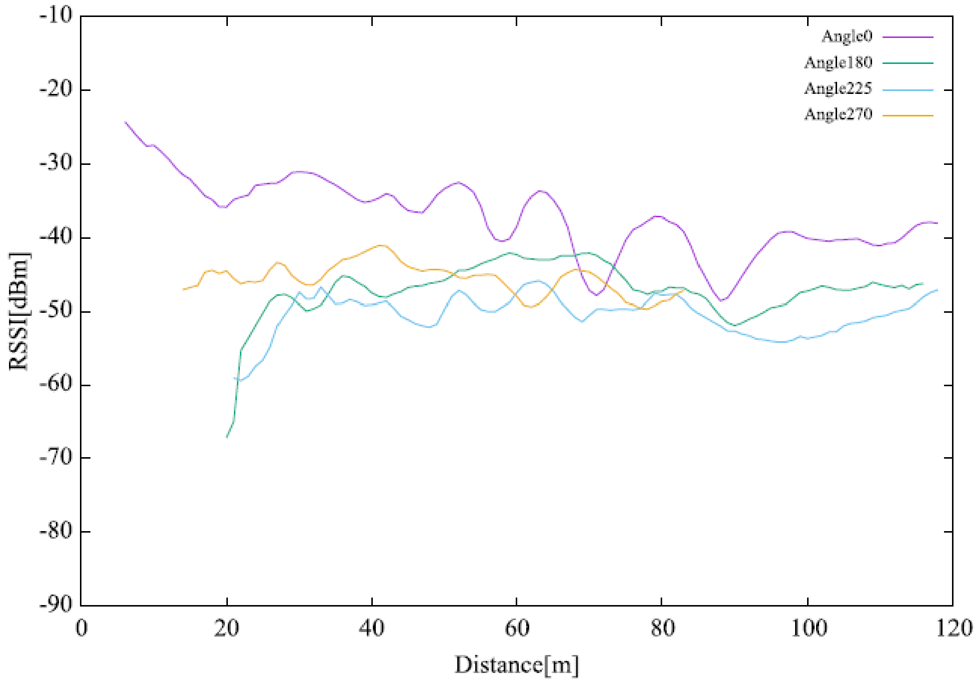


Figure 4.5: Received Signal Strength by Real Measurement

Table 4.2: Antenna Specification

Protocol	IEEE802.11g
Directional Type	Omni
Tx Power	50mW (17dBm)
Rooftop	ground+8.0m

As shown in Table 4.2, we use IEEE802.11g (2.4GHz) for availability for any other countries and omni-directional antenna with 17dBm Tx power located at 8.0m height (on the rooftop). Then in the polar coordinates centered at the center of the truck, we obtain each direction by varying from 0◦ to 180◦ and ϕ from 0◦ to 360◦ with step 5◦. For each of those directions, we simulated radio propagation using two different radio propagation models, ray tracing and the free-space propagation model. Then the virtual antenna gain G is obtained by $RSSI_H/RSSI_F$ where $RSSI_H$ and $RSSI_F$ are ray-tracing based RSS value and the value of the free-space propagation model, respectively.

The red plots in Figure 4.3 illustrate $RSSI_H$ values with left-front antenna. These values were measured on the circle with 15m radius centered at the center of the haul truck body. The angle increases from 0◦ to 360◦ counterclockwise where 0◦ is the forward direction. We note that plots at outer locations indicate stronger signals. As seen, RSSs between 280◦ and 360◦ (right-front) and those between 0◦ and 175◦ (left-front) are 49:55dBm. Meanwhile, those between 180◦ and 270◦ (right-back) are in the range [-88dBm, -70dBm], meaning more than 20dBm - 40dBm losses. This result clearly shows the shielding effect by the body.

4.3.2 Comparison with Real Measurement

We have also measured the real RSS values in cooperation with our partner company using the real haul truck. The antenna was set at the left-front and RSS was measured by Bitrieve AirPcap [75]. Figures 4.4 and 4.5 illustrate simulated and real RSS values, respectively, which are observed on the ground with 4 different angles varying distances.

It is noted that there are not so many spikes in the simulated values (Figure 4.4) while so many in real values (Figure. 4.5). This comes from that fact that the fading effect, which is random and hard to reproduce, is not taken into account in our simulation. Moreover, the simulated values show the clear decreasing trend with the longer distance than 80m, while the real values show almost flat trend. These differences may come from the limitation of the expressive and analytical capability of ray tracing models, which calculate the signal strength by using the limited number of rays. Although the general ray tracing techniques can trace multiple signal paths with reflections and diffractions, it is still hard to analyze the multi-path fading which has a great impact on fluctuation of RSSI values frequently observed in the real world. However, there is a certain correlation between measured values and simulated values since the Pearson coefficient of correlation in every direction is 0:65 ~ 0:79 (0◦ is 0.79, 180◦ and 270◦ are 0.65, 225◦ is 0.68).

We can see that $RSSI_H$ in Figure 4.4 can well-characterize the increasing trend of $RSSI_A$ (real measurement) of the measured values for 180◦, 225◦ and 270◦ in Figure. 4.5 within the range of 40m, though the values in three directions are 20dBm ~ 40dBm lower than those. Meanwhile, the difference around 120m is around 10dBm, meaning less effect of the body. Although the trends of 80 – 120 m are different, it is expected that both would decrease with the distance getting longer as the nature of wireless radiation. From the above results, we can say that the simulation captures the trend of attenuation, and that it can be used for the later simulation study in order to infer the blind spot in the mining sites.

4.4 Estimate the Ranges of Communication in Virtual Mining

In this section, using the antenna model designed in the previous section, we estimate the success or failure of inter-vehicle communication between two haul trucks for given information about (1) payloads (*p*), (2) antenna positions (*a*), (3) directions of the haul trucks (*d*, *d′*), (4) a terrain model (*g*) and (5) locations of the haul trucks (*l*, *l′*). In the experiments, we assume that the haul trucks have payloads and the value of *p* is fixed to 1. The antenna position *a* is left-front or middlefront (*a* ∊ *{Left Middle}*) and direction of the haul trucks is upward or downward (*d*, *d′* ∊ *{Up, Down}*). According to the general design guideline [72], we have developed a terrain that has multiple circle roads with four different height levels as shown Figures 4.6 and 4.7. Based on the terrain, we have developed two different terrain models whose curvature radiuses are 1=125 and 1=250 as *R*125 and *R*250, respectively. Since the haul trucks cannot move on the first level road and the second level road and these levels are developed through a process of mining the mineral by bench-cut method, haul truck *A* is located on only the bottom level road and another haul truck *B* is located on the bottom level road or the third level road. Haul truck *A* is fixed on the bottom level road and does not move from the location (*l* = 0). On the other hand, haul truck *B* is located different distances from haul truck *A* on two different levels. The positions of haul truck *B* are *l′* = {-120, -105, -90, ···, 105, 120}. We calculate RSS values in 136 cases (*a* ∊ *{Left, Middle}*, *d*, *d′* ∊ *{Up, Down}*, (*l*; *l′*) = (0, -120); (0, -105), ···, (0; 120)) for *g* = {*R*125, *R*250} in the experiments.

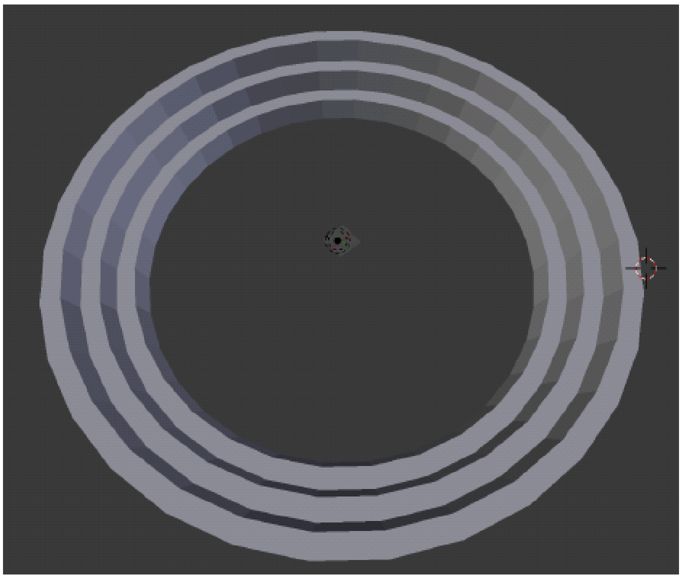


Figure 4.6: 3D Terrain Model (g = fR125, R250g)

Moreover, we have developed another terrain model as shown in Figure 4.8 according to a major copper mine Chuquicamata in Chile as shown in Figure 4.9. In the terrain, collision accidents are sometimes occurring at the intersections. We represent the terrain model as *T*. In *g* = *T*, a haul truck *A* is fixed on the low-level road (in the forefront road in Fig.8) at 120m away from the intersection(l = 0). Another haul truck *B* is located on the high-level road at just beside haul truck *A*. In the same way, haul truck *B* is located different distances from haul truck *A* on the level. The positions of haul truck *B* are l' = {-120, -150, -90, ··· , 105, 120}. The simulations are conducted to calculate RSS values between two haul trucks at different positions.

4.4.1 Estimation Results

The results are illustrated in Figures 10, 11, 12 and 13. (I) (d; d') = (*Up;Up*) means the directions of both trucks are upward, and (II) (d; d') = (*Up;Down*) means the direction of haul track *A* is upward and that of another is downward. The number in each box indicates RSS values between the two haul trucks. In these experiments, we assume that the two haul trucks can communicate each other if RSS values are over -80dBm. The red and blue regions represent that the communication between the trucks succeeds and fail, respectively. The results in *a* = *Left* and *g* = *R*125 is shown in Fig. 10. From this result, we can see blue regions at 100m away from haul truck A in (I). In this situation, the communication between the trucks is blocked due to the haul trucks themselves and these payloads because the trucks and payload are located between their two antennas. We can see a similar trend in the cases in *a* = *Left* and *g* = *R*250 (Fig.11). Also, the result in *a* = *Middle* and *g* = *R*125 is shown in Fig.12. Compared with Figure 4.10, the RSS values are low and the number of blind spots increases. In particular, in the cases of (II), many regions in the behind of haul truck *A* are categorized into blind spots. From these results, we showed that RSS depend on antenna position (a), curvature radius ($g = R125; 250$) and directions of the haul trucks ($d; d'$). In addition, there are no blind spot when haul truck *B* is approaching to haul truck *A* while there are many blind spots when haul truck *B* is going away from haul truck *A*.

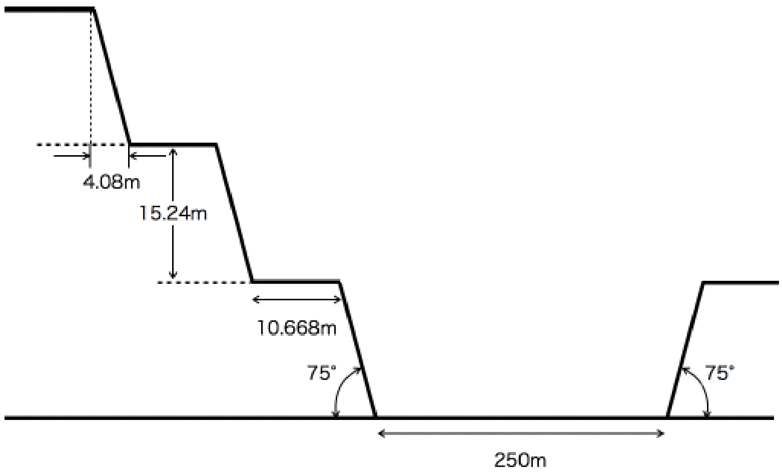


Figure 4.7: Blueprint of Mine Road

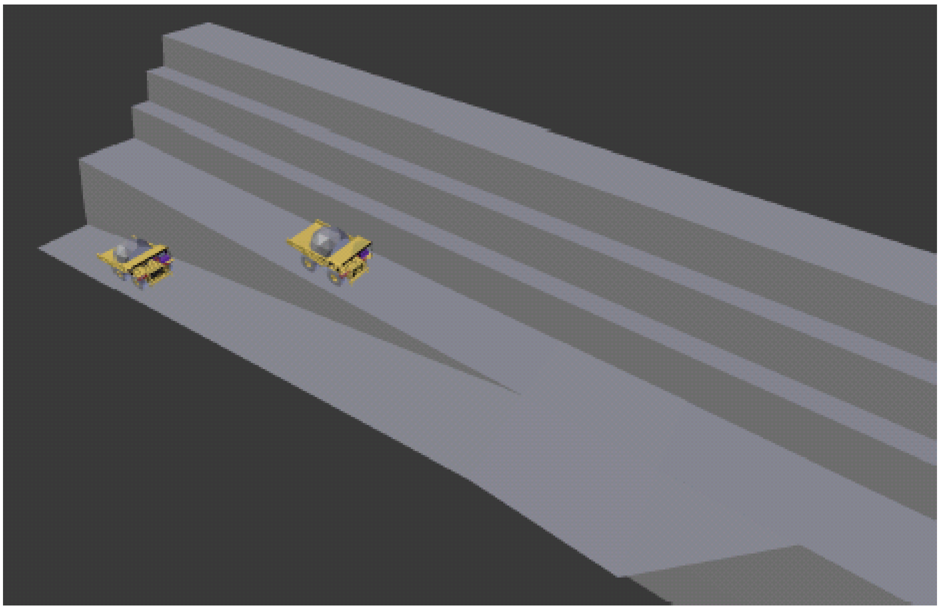
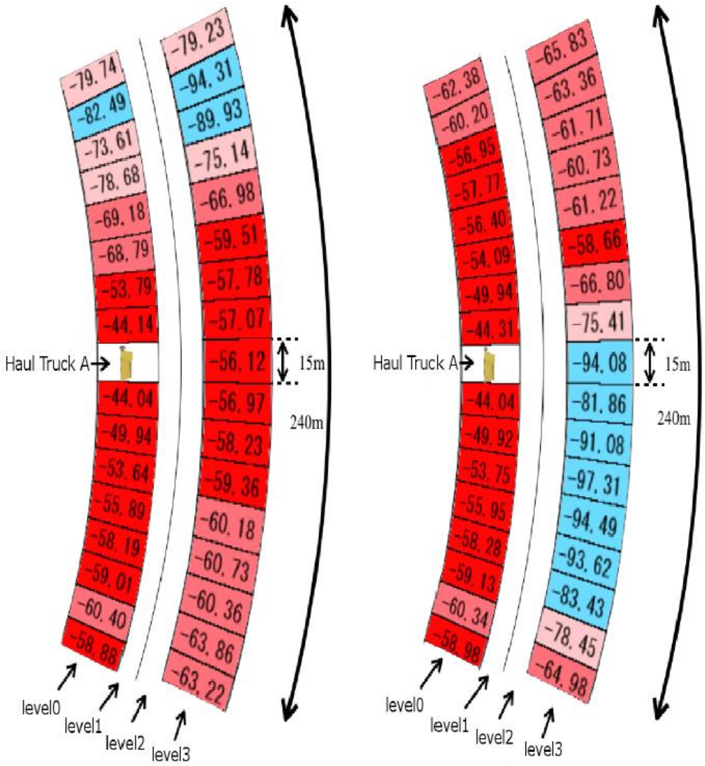


Figure 4.8: 3D Terrain Model (g = T)

Figure 4.9: Open Pit Mine Aerial Photograph

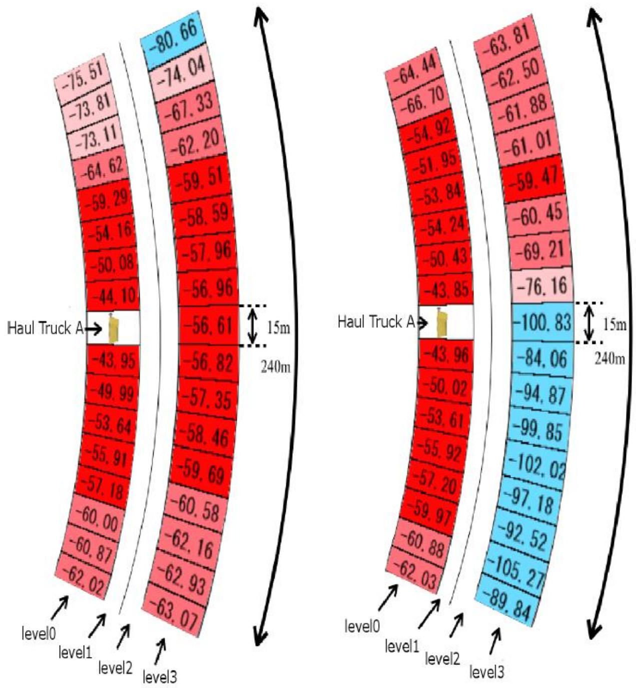
The result in $a = Left$ and $g = T$ is shown in Figure. 4.13. In this experiment, two trucks move in upward direction $(d;\ d')$ = $(Up;Up)$. Haul truck B can detect haul truck A within a range of 0m to 105m from haul truck A since there are no blind spots in the figure. However, there are several blind spots near the intersection and haul truck B near the intersection can't detect haul truck A. We can see that this could be a risk of collision accidents and both drivers should be careful in the situation even though the trucks have IVC feature.

From the results, although it is difficult to detect haul trucks which are going away, but haul tracks which are approaching could be detected. Thus, we can see that IVC based Wi-Fi technology is a useful method for detecting the presence of haul trucks nearby. We are now trying to develop a system to collect communication logs between haul trucks for visualization of communication history. Such history will help drivers to be aware of non-communicable positions in the terrain, but it usually takes time to collect those in all the location-peers. Our method can be used to supplement logs at the initial phases.



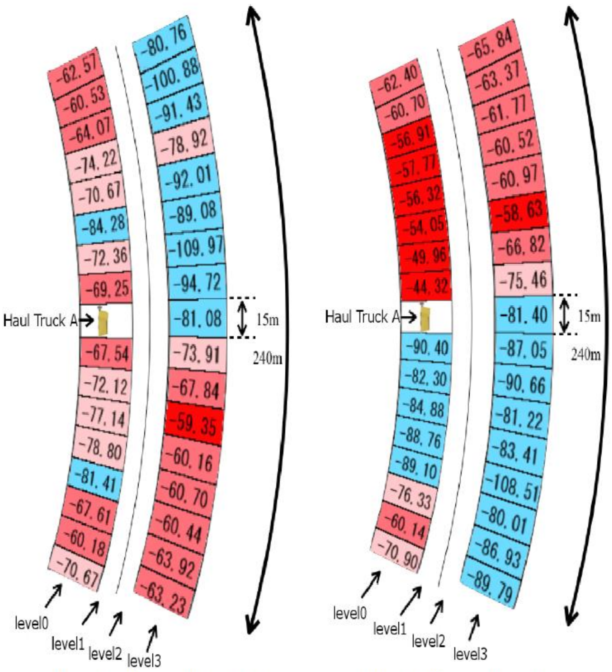
(I) $(d, d') = (Up, Up)$ (II) $(d, d') = (Up, Down)$

Figure 4.10: RSS Estimation Result (a = Left, g = R125)



(I) $(d, d') = (Up, Up)$ (II) $(d, d') = (Up, Down)$

Figure 4.11: RSS Estimation Result (*a* = *Left*, *g* = *R*250)



(I) $(d, d') = (Up, Up)$ (II) $(d, d') = (Up, Down)$

Figure 4.12: RSS Estimation Result (a = Middle, g = R125)

4.5 Conclusion

In this thesis, we have obtained the radio propagation model for haul trucks by real measurement and simulations. Based on the propagation model and realistic terrain model, we have also proposed a method to estimate the received signal strength for inter-vehicle communication for haul trucks. The results showed that a haul truck can communicate with haul trucks approaching while it is difficult to detect haul trucks going away by IVC. These results help to make wireless blind spot visible to the surface mine operators, and it alerts the potential presence of other vehicles in the blind spots. We are now going to apply this result to the safety system for the haul trucks in mines in cooperation with our partner company. Our future work includes enhancing the accuracy in simulation and evaluates the function in a variety of terrain models, rather than that we have used in this thesis.

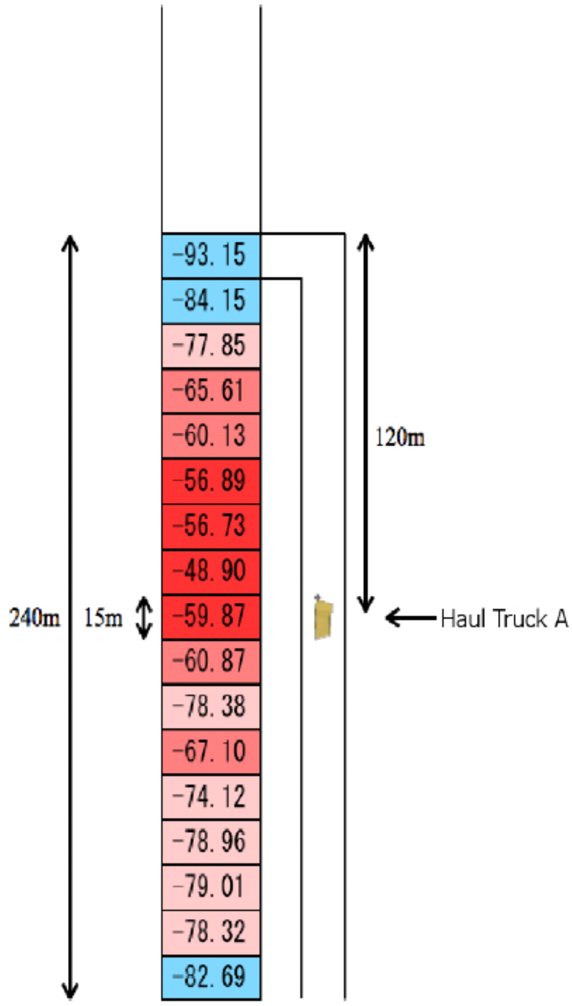


Figure 4.13: RSS Estimation Result ($g = T$)

Chapter 5

Analysis of Accident Risks from Driving Behaviors

5.1 Introduction

Driving is an important daily activity of people as it is their major means of transportation. They need to, willingly or not, drive vehicles in safety. The good news is that the rapid progress of situation awareness technologies would bring us fully-automated self-driving in future, which substantially reduces the amount of tragic accidents. However, at present, people are still exposed to the risk of being involved in the traffic accidents caused by human errors, particularly due to incautious, selfish driving such as overspeed and sudden lane change without turn signals. Such behavior is generally called *aggressive driving*. Aggressive driving has been studied for long years because it is known to have a strong correlation with traffic accidents. The investigation in [76] asserts that it is influential in causing the majority of accidents in the United States. Accordingly, auto insurance companies such as Progressive and Ingenie [92] cope with detecting aggressive driving and offer lower insurance rates to safer drivers to motivate their insurance subscribers to drive safely. Furthermore, knowing the bad influence of aggressive driving will contribute to social educational campaign for awareness of potential risks and others. It eventually leads to defusing traffic accidents, which is essential for smart cities with safe and intelligent transportation systems.

In order to detect aggressive driving, sensing technologies for drivers, vehicles or both are mandatory, and several types of devices such as inertial measurement unit (IMU), on-board diagnostic (OBD) device and smartphones have been used so far. Although each device has advantages and shortcomings, monitoring the driving behavior by smartphones seems the most promising approach as it is the most popular devices nowadays and the additional cost for deployment is much less than the dedicated devices due to their original rich functionalities of sensing and communications. In particular, their inertial sensors are able to continuously produce accurate motion information. On the other hand, difficulty is that they cannot directly measure the vehicle status such as speed and wheel steering as they are not directly connected to vehicles like OBD. Here the significant question of using smartphones is whether we can detect aggressive driving behavior by thorough analysis of smartphone-based measurement only.

To answer the above question, in this thesis, we have collected driving data for about 15 months from more than 800 drivers using smartphones. These drivers are under contract to car insurance in Japan and categorized into several groups of different ages and genders. The driving data contain each vehicle's GPS positions and accelerations at regular time intervals. Using those data, each driver is labelled by "safe driver" or "risky driver". For this classification, we focus on the history of drivers. In particular, those with 20 or longer years' driving experiences without accident records are labelled as safe drivers and those with more than two accident records as risky ones. As a result, 206 and 24 drivers are categorized into safe and risky ones, respectively. Using these labelled driving data, we have compared the appearance frequency of their aggressive driving behaviors such as sudden acceleration, sudden braking and sudden left/right turns. By statistical significance testing, we have found the threshold values of accelerations to identify the aggressive driving behaviors for unknown data. Based on those results, we have further investigated to obtain a classifier to identify safe and risky drivers. This classifier has been evaluated with the accident histories of drivers, and the accuracy is over 70% in most cases.

5.2 Assessment of Driving Behavior

Our objective is to find the features of driving behaviors that are observed by smartphones and have statistically correlated to driving accidents. Such correlation is essential to realize Pay How You Drive (PHYD) concept and is valuable for self-assessment of driving activities. The approach consists of the following three steps; (1) classification of drivers by their accident records, (2) observation of their driving behavior and (3) exploration of accident risk (AR) indexes which can statistically separate drivers based on their accident records.

5.2.1 Classification of drivers by accident record

In this thesis, we would like to classify drivers into two categories; *safe drivers* and *risky drivers*. The definition of each category is given in Table 1. Note that this definition is based on the report issued by Japan Safe Driving Center studying the correlation between the probability of accidents in a year and the number of accidents over last 5 years [104]. It reveals that the drivers with no accident record over in the last 5 years make accidents in the next year with the probabilities of 0.6 % on average. Meanwhile, the drivers with one, two, and three or more accident records make accidents in the next year with the probability of 1.7%, 3.9%, and 6.7%, respectively, without taking the type of accidents into account. We have defined safe drivers and risky drivers by the number of accidents over their driving history instead of the last 5 years, because it is hard to obtain the data of the number of accidents over the last 5 years. Only drivers with 20 years or longer driving experience have been chosen to find a clear border between safe drivers and risky drivers, because accident records of many inexperienced drivers may be "clean" due to their short-term experience. Also, we have examined drivers with the test duration, which means the accumulated time with driving data collection, longer than 20 minutes since too-short driving data would be unreliable. The sufficiency of 20 minutes comes from the investigation by [89] mentioning that driving data which are longer than 20 minutes can be regarded as stable. Moreover, we have confirmed how the distribution of acceleration converges by observing the standard deviation of acceleration along with the test duration as shown in Figure 5.1. The vertical axis shows the ratio of standard deviation with the test duration $\sigma(t)$ against the standard deviation of total test duration σ_{final} of the drivers whose test duration is longer than 100 minutes. The standard deviation at 20 minutes has less than 20 % difference for more than 80% drivers. Considering the trade-off between data precision and the number of samples, we have decided 20 minutes as the minimum test duration for both safe drivers and risky drivers.

Table 5.1: Classification of drivers

Category	Conditions
Safe drivers	● 20 years or longer driving experience ● no accident records ● Test duration is longer than 20 minutes
Risky drivers	● 20 years or longer driving experience ● Three or more accident records ● Test duration is longer than 20 minutes

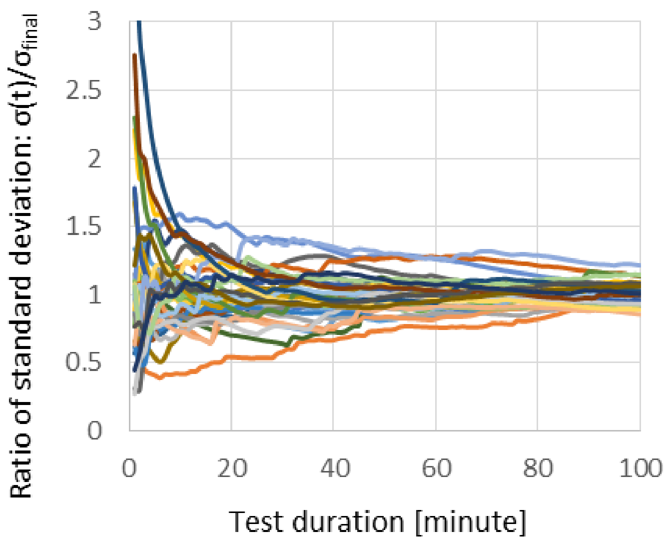


Figure 5.1: Ratio of standard deviation

5.2.2 Observing driving behaviors

Drivers' behaviors have been collected by their smartphones. Timestamps, 3-axes accelerations and GPS locations have been collected for the later analysis. We note that from the GPS locations, the speeds and headings are calculated and used for the analysis as well.

5.2.3 Exploration of AR-indexes

In this thesis, the indexes are explored for the following items listed in Table 5.2, which are typical events observed in aggressive driving as analyzed in [80] and [81].

Table 5.2: Items to be explored as AR-indexes

Item	Meaning
Sudden acceleration	Longitudinal acceleration which surpasses predefined threshold
Sudden braking	Longitudinal acceleration which underruns predefined threshold
Sharp left turn	lateral acceleration which surpasses predefined threshold
Sharp right turn	lateral acceleration which surpasses predefined threshold

5.3 Proposed Approach

5.3.1 System Architecture

The application running over smartphones has been developed, which works in each vehicle during driving and collects the driving data listed in Section 5.3.2. A screenshot of the application is shown in Figure 2. In this application, the video stream is displayed on the left side. When the smartphone detects higher acceleration than the predefined threshold, this video stream is recorded for future analysis. It also displays acceleration in the middle so that the driver can view acceleration in real-time. The right side shows the driving distance of the ongoing trip, the accumulated driving distance and the ranking of accumulated driving distance in order to encourage the drivers to launch this application in driving. The collected data is sent and stored in the server system, which is used to analyze driving behaviors through statistical processing.

When the driver launches the application initially, a few questionnaires appear on the screen. The questionnaires include the questions to ask their driving experiences and the history of accidents caused by the driver that are necessary for the definition of his/her accidental potential. The answer is sent to the server system together with the user ID and stored in the database. Once the data is stored, the application is activated and it starts to collect the driving data during driving.

The same cradles have been used for all the drivers for fixing smartphones on the dashboard as shown in Figure 5.3 in order to eliminate the different vibration characteristics of cradles. The data is sent every five minutes including the data contents listed in Section 5.3.2, and the sampling frequency of the data is 1 Hz for GPS and 20 Hz for the others.

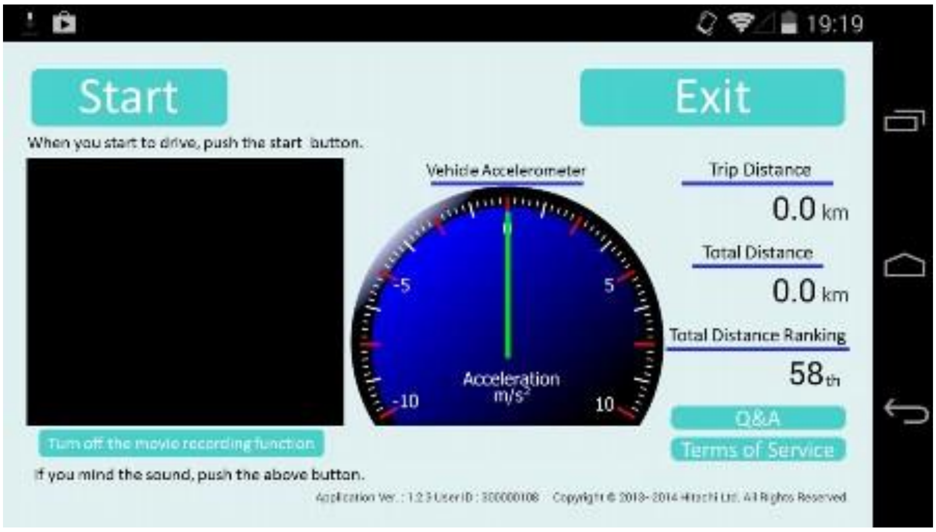


Figure 5.2: Screenshot of Smartphone Application

Figure 5.3: Mounting of Smartphone

5.3.2 Experimental Environment

In our experiment, 809 insurance subscribers joined this experiment totally, in cooperation with Hitachi Insurance Services, Ltd. All the insurance subscribers are general drivers driving their own cars, not commercial drivers. The experimental period is 15 months starting from December 2013 till February 2015. During the experimental period, the number of participants was gradually increased. We asked the participants to run the application to collect as much driving data as possible. The collected driving data cover almost the entire areas of Japan. The data are obtained on several types of roads such as highways, suburban roads and urban roads.

206 drivers of 809 insurance subscribers satisfy the conditions of safe drivers, and 24 drivers satisfy the conditions of risky drivers defined in Table 1. Tables 5.3, 5.4 show their distribution of ages, genders and test duration.

5.3.3 Data Analysis Procedure

The data processing flow is as follows.

1. Driving data collection
2. 3D data conversion
3. Noise reduction
4. Analysis

After collecting the driving data, the acceleration observed in the smartphone is converted to acceleration of vehicle because the angle of the smartphone is not the same as the angle of vehicle. The schematic figure is shown in Figure 5.4.

Hereafter, we let (x, y, z) denote the acceleration in the smartphone coordinate system, where x, y and z denote up-and-down direction, right-and-left direction, and perpendicular direction of the smartphone screen, respectively. Similarly, we let (X, Y, Z) denote the acceleration in the vehicle coordinate system, where X, Y and Z denote longitudinal direction, lateral direction and vertical direction of the vehicle, respectively. The conversion is performed in two steps as written in [80]. Firstly, the vertical axis is determined when the vehicle is stopping. Suppose the angle of perpendicular direction of smartphone differs by δ from the vertical direction of vehicle, it can be denoted as $R_{vertical}(\delta)$ where R is rotation matrix. Secondly, the longitudinal direction is detected when the vehicle starts moving. Suppose the angle of x' obtained from the previous conversion differs by γ from the longitudinal direction, it can be denoted as $R_{horizontal}(\gamma)$. As a result, the conversion can be expressed as eq. (1).

Table 5.3: Drivers' characteristics: ages and genders

	Age				Gender	
	30s	40s	50s	60s	Male	Female
Safe drivers	52	94	55	5	180	26
Risky drivers	3	16	5	0	21	3

Table 5.4: Test duration details

	20-50 min	50-100 min	100- min
Safe drivers	41	34	131
Risky drivers	5	3	16

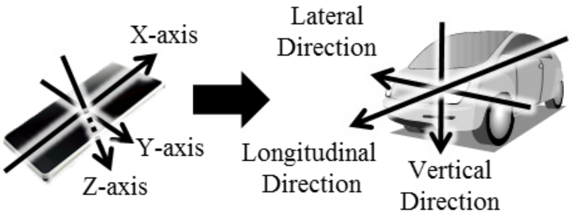


Figure 5.4: Conversion of acceleration

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = R_{horizontal}(\gamma) R_{vertical}(\delta) \begin{pmatrix} x \\ y \\ z \end{pmatrix} \qquad (1)$$

The next step is to filter noisy signals. In order to filter them, low-pass filter with a cutoff frequency of 2Hz was used. The last step is to test the indexes listed in Table 5.2, which is stated in Section 5.5.

5.4 Experimental Results

In this section, the experimental results for each index listed in Table 5.2 are presented.

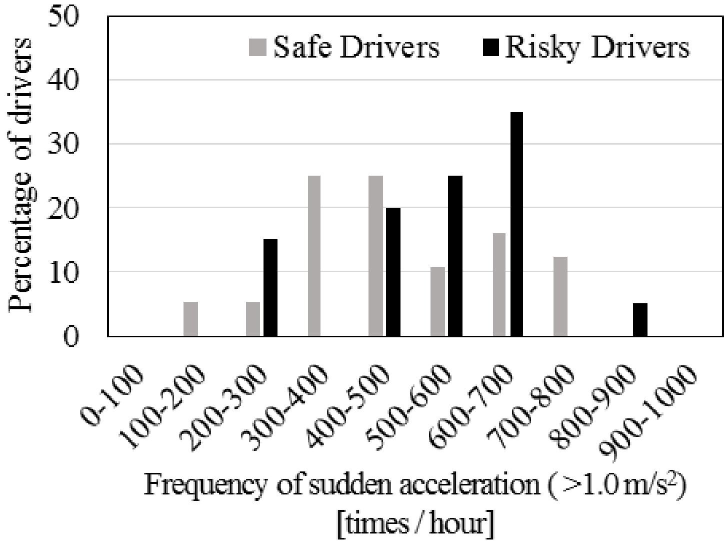


Figure 5.5: Histograms of sudden acceleration frequency with 1.0 m/s2 as threshold

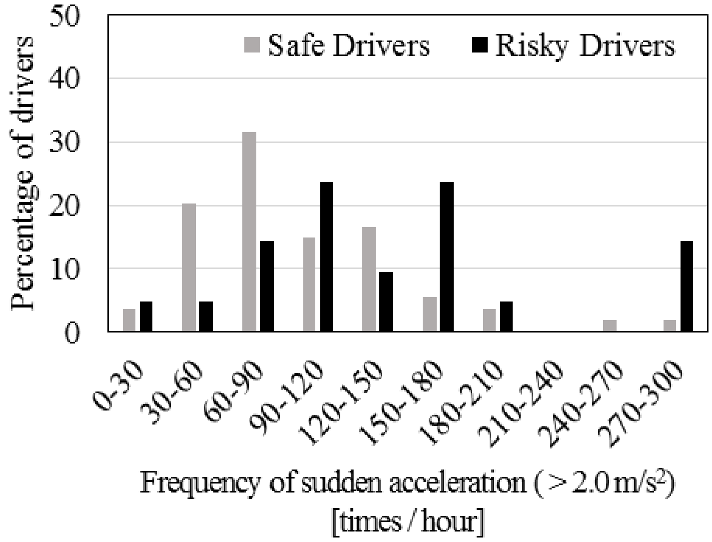


Figure 5.6:Histograms of sudden acceleration frequency with 2.0 m/s2 as threshold

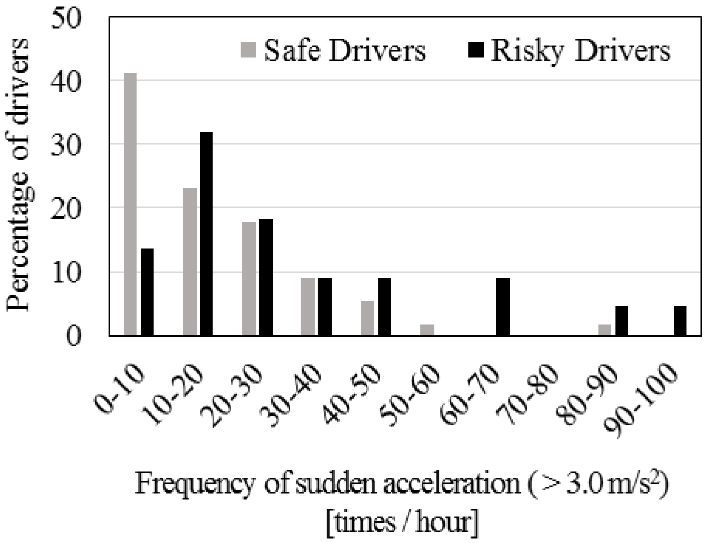


Figure 5.7: Histograms of sudden acceleration frequency with 3.0 m/s2 as threshold

Figures 5.5 – 5.7 illustrate the histograms of drivers with different frequencies of sudden acceleration using three different acceleration thresholds. Figure 5.5 shows the case that longitudinal acceleration quantity that exceeds 1.0 m/s^2 is regarded as a sudden acceleration. Similarly, in Figures 5.6 and 5.7, those cases using 2.0 m/s^2 and 3.0 m/s^2 are shown, respectively. The vertical and horizontal axes of these figures indicate the percentage of drivers in each category of safe drivers and risky drivers and the frequency of sudden acceleration, respectively.

From these figures, the distribution of risky drivers is shifted to higher frequency than that of safe drivers. Taking Figure 5.6 as an example, there are drivers who make sudden accelerations 270-300 times/hour. It means that the drive makes sudden accelerations with a rate about once in 12 seconds. Because the acceleration higher than 2.0 m/s^2 is not regarded as the effect of road surfaces, it is speculated as the result of aggressive driving in relatively heavy traffic repeating accelerations and decelerations. It is also noticed that such highly frequent sudden accelerations are seldom observed in the group of safe drivers. In order to examine the statistical significance of the difference between these two distributions, Brunner-Munzel test [90] has been used as a non-parametric test because the population structures are unknown.

The p-values of Brunner-Munzel test are calculated for this purpose. If the p-value is lower than 0.05, it means that the difference of distributions can be regarded as statistically significant. In Figure 8, sudden acceleration thresholds with step 0.1 m/s^2 versus these p-values are calculated and plotted. The result shows that p-values become lower than 0.05 within the threshold ranges of [1.2 m/s^2, 1.4 m/s^2] and [1.9m/s^2, 3.0 m/s^2]. The minimum p-value is 0.0137 at 2.4 m/s^2. Here, the hypothesis "*the distributions of safe drivers and risky drivers in terms of the sudden acceleration frequency are statistically different*" is NOT rejected when the threshold of the sudden acceleration is within the above-mentioned range.

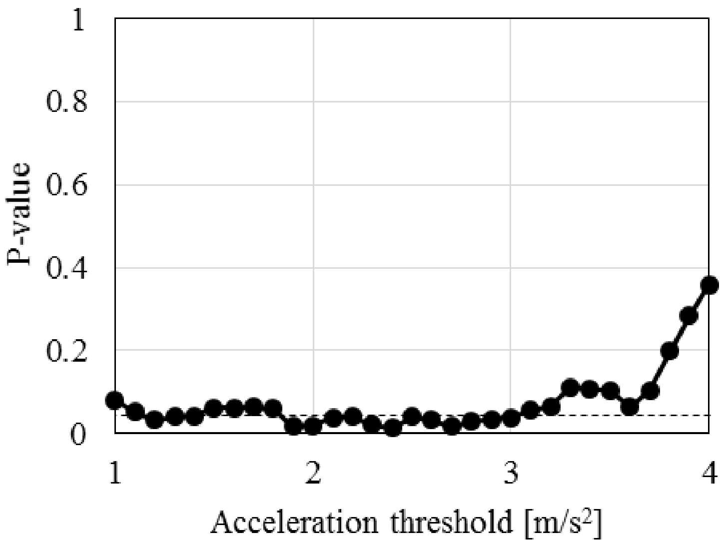


Figure 5.8: P-value with respect to sudden acceleration threshold

The same process is performed for deceleration, and Figure 5.9 illustrates the p-values for deceleration with step 0.1 m/s^2. As seen from Figure 5.9, the p-values are smaller than 0.5 when the threshold of the sudden deceleration is between 1.2 and 1.4. The minimum p-value is 0.033 at 1.4 m/s^2. Namely, the hypothesis "*the distributions of safe drivers and risky drivers in terms of sudden braking frequency are statistically different"* is NOT rejected when the definition of the sudden deceleration is between 1.2 and 1.4 m/s^2. It is also confirmed intuitively from Figure 5.10, which denotes the distributions of safe drivers and risky drivers with 1.2 m/s^2 threshold.

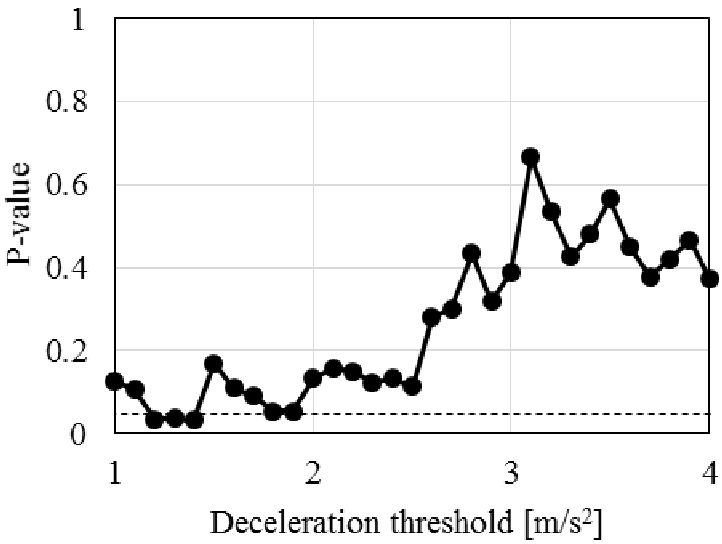


Figure 5.9: P-value with respect to deceleration threshold

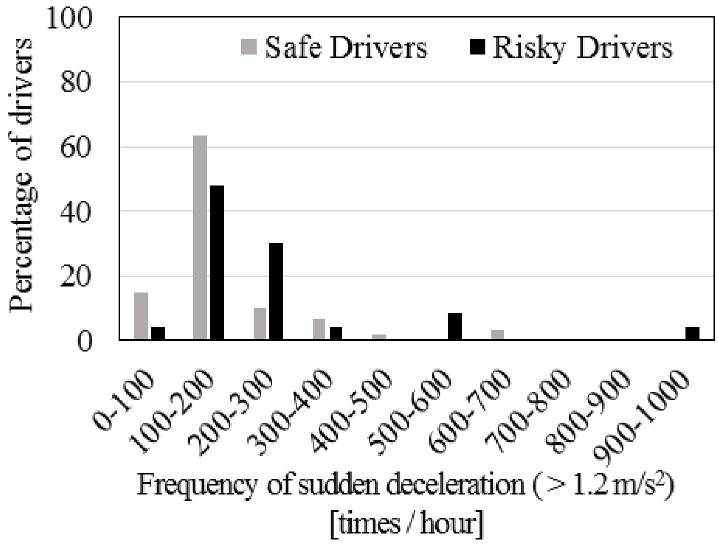


Figure 5.10: Histogram of sudden deceleration frequency with 1.2 m/s2 as threshold

Figure 5.11 illustrates the p-value of the right acceleration, which is typically recorded when the driver quickly turns right. As seen in the figure, it never falls below 0.05 (shown as a dotted line). Therefore, the hypothesis "*the distributions of safe drivers and risky drivers in terms of right acceleration frequency are statistically different"* is rejected. Figure 5.12 illustrates the p-value of the left acceleration, which is typically recorded when the driver quickly turns left. As seen from the figure, the p-value is smaller than 0.05 when the acceleration threshold is lower than or equal to 1.5 m/s^2. Namely, the hypothesis that "*the distribution of safe drivers and risky drivers in terms of left acceleration frequency are statistically different"* is NOT rejected when the acceleration threshold is 1.5 m/s^2 or smaller. Figures 5.13 – 5.15 illustrate the distributions of safe drivers and risky drivers in terms of the left acceleration with 1.0 m/s^2, 2.0 m/s^2 and 3.0 m/s^2, respectively. Note that vehicles are driven on the left in Japan.

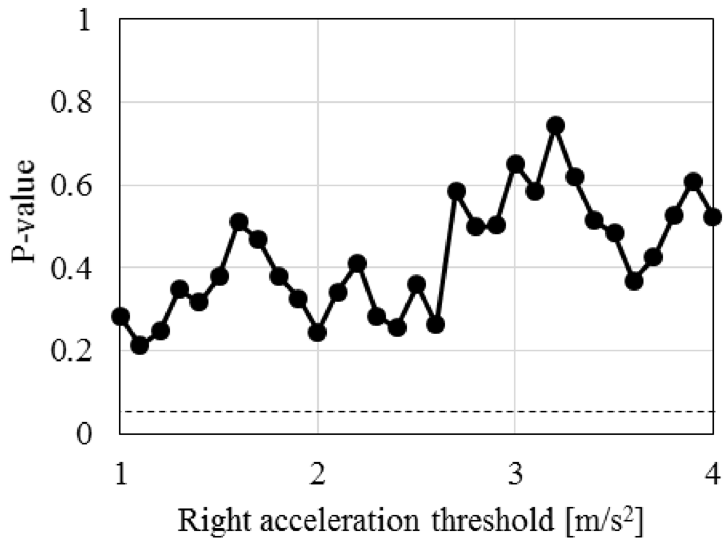


Figure 5.11: P-value with respect to right acceleration threshold

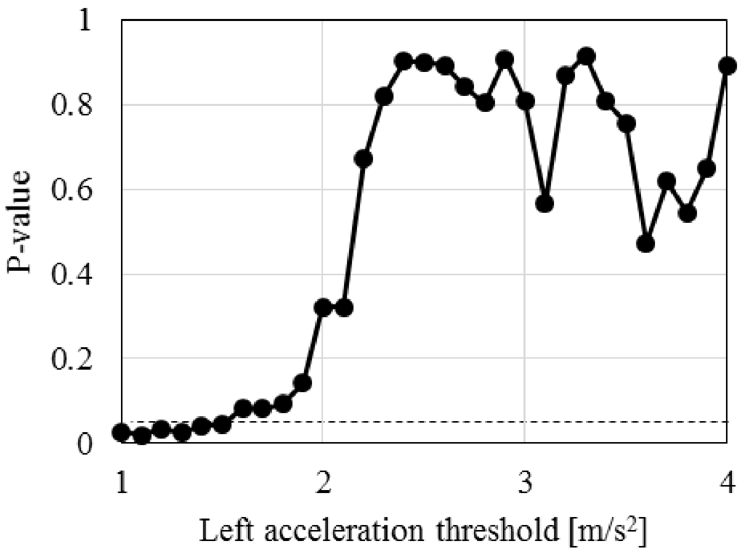


Figure 5.12: P-value with respect to left acceleration threshold

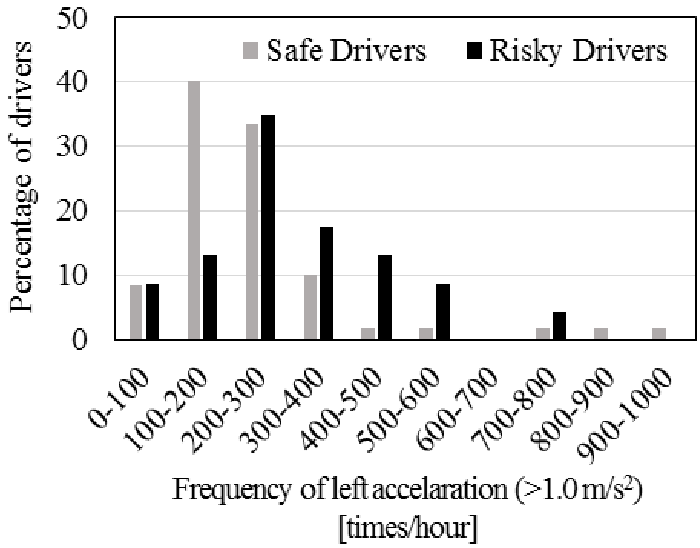


Figure 5.13: Histograms of left acceleration frequency with 1.0 m/s2 as threshold

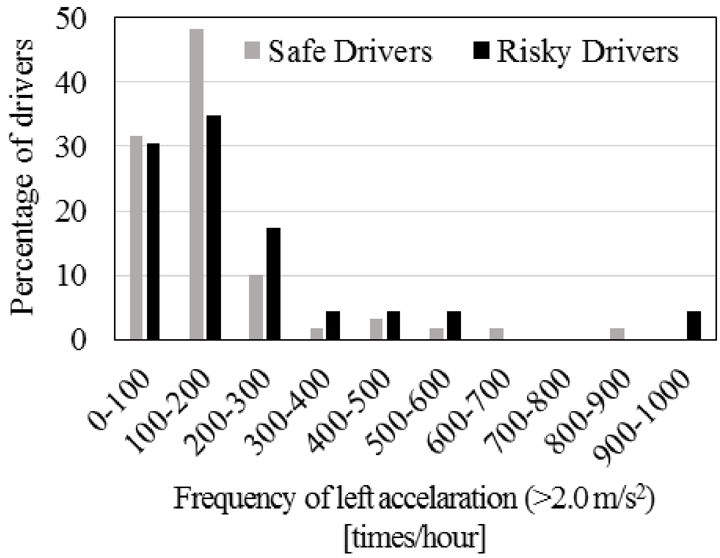


Figure 5.14: Histograms of left acceleration frequency with 2.0 m/s2 as threshold

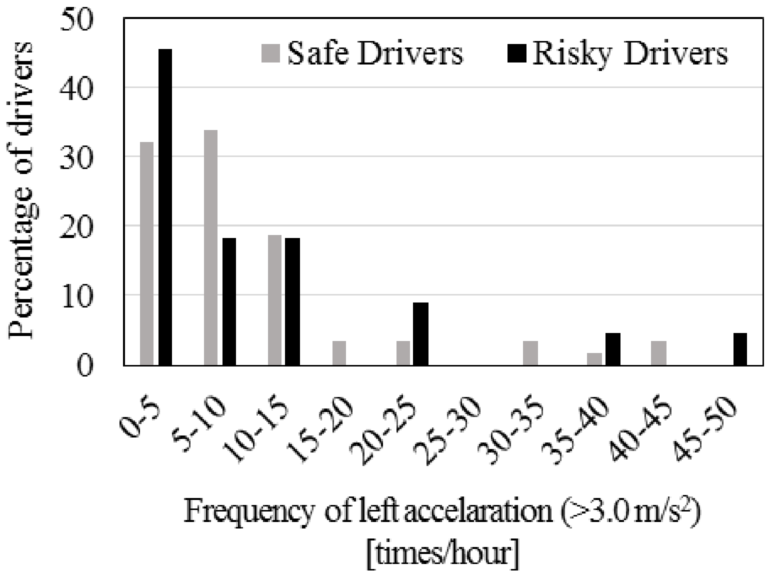


Figure 5.15: Histograms of left acceleration frequency with 3.0 m/s2 as threshold

5.5 Analysis of Accident Risks

5.5.1 Consideration of AR-indexes

In this section, we consider the reason why the p-value of acceleration behave as illustrated in the figures. In other words, we analyze why there is statistical difference in specific acceleration value ranges. As stated before, the distributions of acceleration frequency show statistically significant difference in the ranges between 1.2 m/s^2 and 1.4 m/s^2 and between 1.9 m/s^2 and 3.0 m/s^2. It is also notable that all the p-values in Figure 8 are lower than 0.15 with accelerations below 3.7 m/s^2. Considering the fact that the peak of risky drivers' distribution appears with higher acceleration, it is likely that risky drivers tend to make the sudden acceleration more frequently than safe drivers. It should also be addressed that this tendency does not depend on the specific acceleration range. We note that when the acceleration threshold is larger than 3.7 m/s^2, the statistically significant difference disappears as the number of observed samples decreases.

As for deceleration, the statistical difference between safe drivers and risky drivers can be found only in the range between 1.2 m/s^2 and 1.4 m/s^2. It is also noted that the p-value is close to 0.05 when the deceleration threshold is 1.8 m/s^2 or 1.9 m/s^2. This is due to limitations on the number of observed samples, and it is expected that the p-value would be flatter between 1.0 m/s^2 and 2.0 m/s^2 with more samples.

The trends of the p-values for right acceleration and left acceleration are quite different as shown in Figure 5.11 and Figure 5.12. The p-values never become lower than 0.05 for right acceleration, while they are lower than 0.05 below 1.5 m/s^2, with the lowest p-value at 1.1 m/s^2 for left acceleration. This may come from the asymmetry of road transportation. In Japan where the experiment has been performed, vehicles run on the left side. In this case, it is assumed that risky drivers may drive less gently than safe drivers in turning left. Meanwhile, there would not be significant difference in right turns because they often need to stop at intersections to cross the opposite lanes.

We would like to mention that the video data of longer than 10 hours are examined in order to understand the difference between safe and risky drivers. Although there seems no significant difference of driving environment such as road category and time zone, the following driving behavior is found more frequently from risky drivers.

- Sudden acceleration on starting
- Sudden deceleration due to short distance
- High speed driving on corners

5.5.2 Classifier of Accident Risks

In this section, it is confirmed that the obtained AR-indexes can classify safe and risky drivers. Support Vector Machine (SVM) [102] is used to obtain binary classifiers. In order to examine the impact and effectiveness of feature quantities on the classification performance, we have obtained three classifiers using partial feature vectors. In particular, we consider the following three features to form three-dimensional feature vectors; <(a) frequency of acceleration with 2.4 m/s^2 as threshold, (b) frequency of deceleration with the threshold 1.4 m/s^2 , (c) frequency of left acceleration with 1.1 m/s^2>. Then their partial vectors (i.e. one-dimensional vectors such as <(a)> and two-dimensional vectors such as <(a), (b)>) are also examined to build classifiers. We note that as the number of samples for safe and risky drivers are imbalanced, Synthetic Minority Oversampling TEchnique (SMOTE) [83] is applied. The obtained classifiers are evaluated with the original data. They are evaluated with two criteria Accuracy (denoted as A) and Recall (R), with the definition of risky drivers as positive and safe drivers as negative.

Classifiers with 1D feature vectors

Figure 16 shows the classifiers obtained by SVM for each of three one-dimensional vectors: <(a)>, <(b)> and <(c)>. In this figure, the dots and crosses indicate the safe drivers and the risky drivers, respectively. The vertical lines are the hyper-planes to classify them obtained by SVM. Because the hyper-planes of one-dimensional space are points, they are expressed as vertical lines for easy comprehensibility in the figure.

The accuracy and recall by these classifiers are <(a)>: A = 0.561, R = 0.708, <(b)>: A = 0.565, R = 0.625 and <(c)>: A = 0.600, R = 0.792.

Classifiers with 2D feature vectors

Figure 17 shows the classifiers with two-dimensional vectors <(a), (b)>, <(a), (c)> and <(b), (c)> as feature vectors. The solid lines are the hyper-plane obtained by SVM.

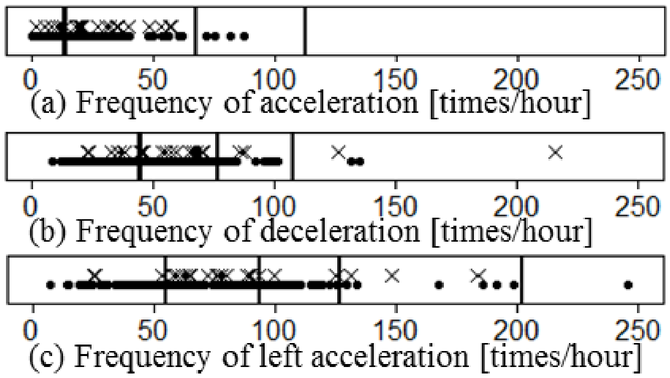


Figure 5.16: SVM-based Classifiers of Safe and Risky Drivers using 1D Feature Vectors

The Accuracy and Recall of each classifier obtained by SVM are <(a), (b)>: A=0.609, R=0.750, <(a), (c)>: A=0.691, R=0.750, and <(b), (c) >: A=0.639, R=0.750.

Classifiers with 3D feature vectors

Table 5.5 shows the number of safe drivers and risky drivers with respect to the prediction by the classifier using three dimensional feature vectors <(a), (b), (c)>. 20 of 24 risky drivers and 143 of 206 safe drivers are correctly identified. As a result, the Accuracy and Recall of this classifier are A = 0.709, R = 0.833.

In summary, both Accuracy and Recall are higher by feature vectors of higher dimensions. It is also remarkable that the classifiers with 2D feature vectors show some trend of choosing the left bottom part of the graph as safe and the upper right part of the graph as risky, while those with 1D vectors do not show any practical suggestion. Also, it is speculated that the complexity of classifiers with 2D feature vectors is derived from the insufficient number of samples of risky drivers and that the classifier would be simpler with more samples of risky drivers, reflecting the fact that the density of risky driver in upper right part is higher than safe drivers. Considering the difference between 1D and 2D classifiers, the classifier with 3D vectors is expected to show clearer tendency to select higher frequency part as risky although it is not shown due to limitation of visualization.

Table 5.5: Number of samples vs prediction

	Risky Drivers	Safe Drivers
Predicted as Risky	20	63
Predicted as Safe	4	143

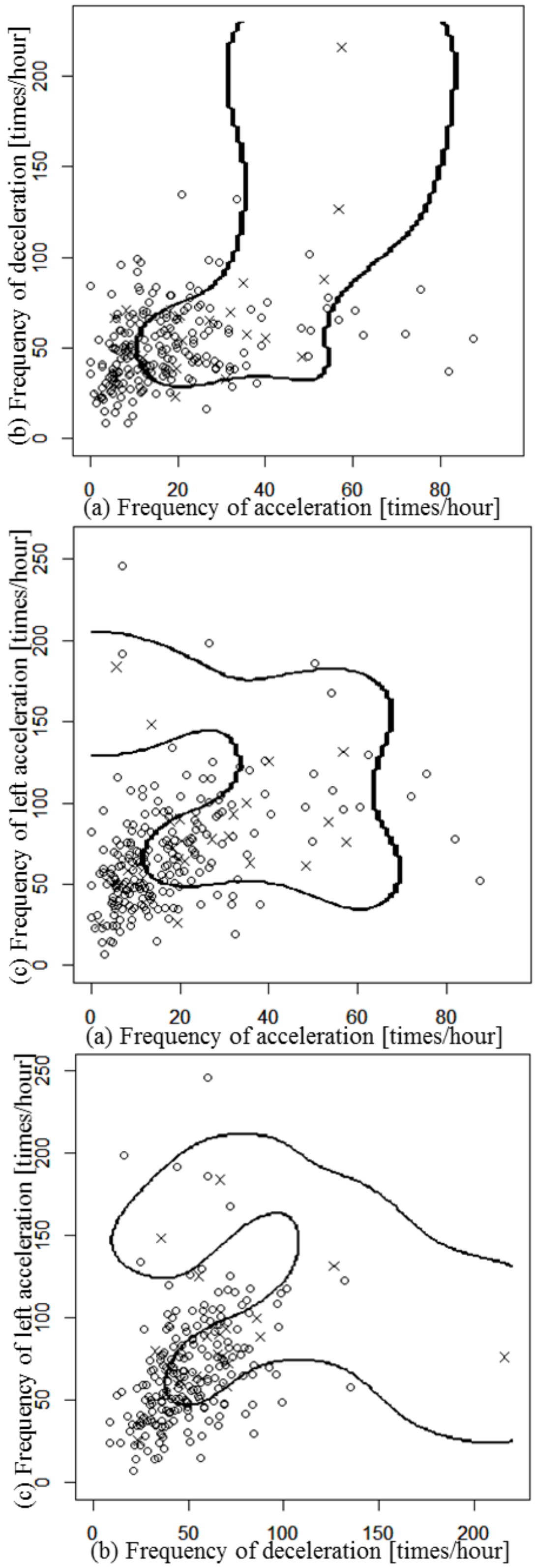


Figure 5.17: SVM-based Classifiers of Safe and Risky Drivers using 2D Feature Vectors

5.6 Concluding Remarks

We have performed the experiment to obtain the driving data and explore the accident risks indexes (AR-indexes), which statistically classify the safe drivers and risky drivers. By the statistical analysis, it has been found that the frequency of acceleration around 2.4 m/s^2, the frequency of deceleration around 1.4 m/s^2, and the left acceleration below 1.5 m/s^2 can be regarded as AR-indexes. We have also evaluated the classifier utilizing the AR-indexes. By using 3 AR-indexes, we could obtain the classifier with 70% or higher accuracy and 83% or higher recall for the samples obtained in our experiment.

The contribution of this thesis is to show the possibility of leveraging the smartphone data, which usually has limited accuracy and no direct information about maneuver of vehicles, to predict the driving behavior. Moreover, the feature sets are found which indicates the potential risk of drivers the best among a number of features. However, it is hard to claim that the classifier is applicable to any situations. For example, the impact of road category is not considered in this thesis. As we believe that the accuracy and recall can be improved by more data with such additional information, obtaining more data on different roads and utilizing them is part of our future work.

In addition, in order to apply driving behavior estimation results in this study to the determination of automotive insurance premiums, it is required to design insurance products complying with the guidelines defined by the Financial Services Agency. The accuracy of 83% shows enough potential to be utilized for cashback services with insurance special contract, but further improvement of the accuracy is needed in order to satisfy the conditions in the guideline “Risk management in case of wrong analysis results” and “Fairness for assured persons“.

On the other hand, as examples of the applications of this technology, driving skill improvement service called Manage How You Drive, can be considered. More specifically, such as “providing advices to drivers for driving skill improvement” and “giving an alert in case where risky drivers are close by using V2X technology described in Chapter 3”.

Chapter 6

Conclusion

This thesis focuses two key technologies to realize or support recognition function by wireless communications in order to enhance vehicle safety. One is inter-vehicle wireless communications, while another is driving behavior analysis. In particular, the inter-vehicle wireless communication protocol was proposed and the effect of decentralized congestion control was evaluated. Also, the radio propagation in the severe environment, surface mining site, was examined. Our study revealed that the inter-vehicle communications can cover sufficient range in order to avoid the collision even in the severe environment. The study regarding the behavior analysis was conducted. The experiments with more than 800 people were performed and the correlation between driving behavior and accidental risks were thoroughly investigated. The experiment has revealed that there are features which classify the population of safe drivers and risky drivers.

In Chapter 2, related researches were surveyed for ad hoc network technologies and it utilization to inter-vehicle communications. In addition, driving behavior analyses were surveyed.

In Chapter 3, we propose inter-vehicle communication protocol for general roads. The purpose of this protocol is to exchange information such as location, speed and direction among vehicles, so that they would judge if there are risk to collide with one another. In order to realize this purpose, the information must be frequently updated. In the case of general roads, vehicle safety would be increased by knowing the information of surrounding vehicles in sub-second. However, the number of surrounding vehicle on the roads varies from time to time, and thus, the number of packet to be transmitted would also vary from time to time. As the result, the technical issue for the inter-vehicle communication protocol is how to realize reliable communications in order to collect the information of surrounding vehicles in sufficiently short duration. We propose the technology to solve the issue by introducing congestion control mechanism which works in the decentralized environment.

In Chapter 4, we study the possibility to use inter-vehicle communications to enhance the safety in mining sites. In the case of mining sites, different from the general roads, the issue is the specific environment in the mining site. Namely, the number of vehicles would not be the issue in the mining sites, because the density of heavy equipment such as the haul truck, the shovel, the excavator are much smaller compared the general roads. So the congestion would not be the issue in the case of mining site. Meanwhile, the geometric environment such as steep slope would matter because the angle of the slope can be 70 degree in the extreme cases. So we primarily studied the actual radio propagation from the antenna attached to the heavy equipment. We also simulated the radio propagation with the extreme geometric conditions. As the results, we have successfully obtained the range where heavy equipment can communicate with each other.

In Chapter 5, we mention the technology to infer the traffic accident risk from the driving data. Here, the driving data means the data obtained by the smartphone to specify the driving. It includes GPS, three-dimensional acceleration, timestamp, etc. Until now, many analyses about aggressive driving have been reported. However, the direct correlation between aggressive driving and accidental risk has never been studied. In this thesis, we have analyzed the correlation between driving data and accidental history of the drivers. The purpose is to understand the correlation between aggressive driving and the accidental risks. As the result of this research, we have discovered that there are difference regarding the distribution of three driving features between safe drivers and risky drivers.

In summary, in this thesis, we focus on the vehicle safety enhanced by the inter-vehicle communications and driving analysis. The first research is about the inter-vehicle communication protocol which controls the packet congestion in a decentralized manner. The second research is about the applicability of inter-vehicle communications to the mining sites, which environment is quite harsh for the radio propagation. The third research is about the correlation between driving behavior and accidental risks. The objective of this thesis is to contribute to vehicle safety enhancement utilizing information and communication technologies, especially wireless communications.

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References

[1] H. Winner, *Handbook Intelligent Vehicles.* Springer-Verlag, 2012.

[2] W. D. Jones, “Keeping cars from crashing,” *IEEE Spectrum*, vol. 38, no. 9, pp. 40–45, 2001.

[3] Intelligent Transport Systems—Full Speed Range Adaptive Cruise Control Systems—Performance Requirements and Test Procedures, International Standard Organization 22179 TC204/WG14, 2009.

[4] Advanced Safety Vehicle, “Going for safe and secure traffic by harmonization between human and vehicles,” 2015, (in Japanese). Available: http://www.mlit.go.jp/jidosha/anzen/01asv/resourse/data/asv5pamphlet.pdf

[5] S. Ishida and J. Gayko, “Development, evaluation and introduction of a lane keeping assistance system,” in Proc. of IEEE Intelligent Vehicle Symposium, pp. 299-304, 2009.

[6] USDOT, “The U.S. Department of Transportation (USDOT) Plans for the Future of Intelligent Transportation Systems (ITS),” Available: http://www.its.dot.gov/press/2014/its_future.htm

[7] T. Kitagawa, T. Koshizawa, and H. Aoyama, “Introduction of Mimamori-kun online service,” in Isuzu Technical Report, vol. 115, pp. 77–84, 2006.

[8] C. Stiller, A. Simon, and H. Weisser, “A driving robot for autonomous vehicles on extreme courses,” in *Proc. of International Federation Automatic Control Conference Telematics Applications Automation Robotics*, pp. 361–367, 2001.

[9] C. Lindemann and O. Waldhorst, “A distributed search service for peer-to-peer file sharing in mobile applications,” in *Proc. of the 2nd IEEE Conference on Peer-to-Peer Computing*, pp. 71–83, 2002.

[10] C. Lindemann and O. Waldhorst, "Consistency mechanisms for a distributed lookup service supporting mobile applications," in *Proc. of the 3rd ACM Workshop on Data Engineering for Wireless and Mobile Access*, pp. 61–68, 2003.

[11] A. Klemm, C. Lindemann, and O. Waldhorst, "A special-purpose peer-to-peer file sharing system for mobile ad hoc networks," in *Proc. of IEEE 58th Vehicular Technology Conference*, pp. 2758–2763, 2003

[12] C. E. Perkins, *Ad Hoc Networking.* Addison-Wesley, 2001.

[13] C. -K. Toh, *Ad hoc mobile wireless networks: protocols and systems*. Prentice-Hall, 2002.

[14] C. E. Perkins and E. M. Royer, "Ad hoc on-demand distance vector routing," in *Proc. of the 2nd IEEE Workshop on Mobile Computing Systems and Applications*, pp. 99–100, 1999.

[15] D. B. Johnson, "Routing in ad hoc networks of mobile hosts" in *Proc. of the Workshop on Mobile Computing Systems and Applications*, pp. 158–163, 1994.

[16] T. Clausen, P. Jacquet, A. Laouiti, P. Muhlethaler, A. Qayyum, and L. Viennot, "Optimized link state routing protocol for ad hoc network," in *Proc. of IEEE International Multi Topic Conference*, 2001.

[17] B. Bellur and R. G. Ogier, "A reliable, efficient topology broadcast protocol for dynamic networks," in *Proc. of the Eighteenth Annual Joint Conference of the IEEE Computer and Communications Societies*, pp. 178–186, 1999.

[18] B. Williams and T. Camp, "Comparison of broadcasting techniques for mobile ad hoc networks," in *Proc. of the 3rd ACM International Symposium on Mobile Ad Hoc Networking & Computing*, pp. 194–205, 2002.

[19] C. Ho, K. Obraczka, G. Tsudik, and K. Viswanath, "Flooding for reliable multicast in multi-hop ad hoc networks," in *Proc. of the International Workshop on Discrete Algorithms and Methods for Mobile Computing and Communication*, pp. 64–71, 1999.

[20] J. Jetcheva, Y. Hu, D. Maltz, and D. Johnson, "A simple protocol for multicast and broadcast in mobile ad hoc networks," Internet Draft, draft-ietf-manet-simple-mbcast-01.txt, 2001.

[21] S. Ni, Y. Tseng, Y. Chen, and J. Sheu, "The broadcast storm problem in a mobile ad hoc

network," in *Proc. of the ACM/IEEE International Conference on Mobile Computing and Networking*, pp. 151–162, 1999.

[22] H. Lim and C. Kim, "Multicast tree construction and flooding in wireless ad hoc networks," in *Proc. of the ACM International Workshop on Modeling, Analysis and Simulation of Wireless and Mobile Systems*, pp. 61–68, 2000.

[23] W. Peng and X. Lu, "Efficient broadcast in mobile ad hoc networks using connected dominating sets," *Journal of Software*, vol. 12, no. 4, pp. 529–536, 2001.

[24] W. Peng and X. Lu, "On the reduction of broadcast redundancy in mobile ad hoc networks," in *Proc. of the 1st ACM International Symposium on Mobile Ad Hoc Networking & Computing*, pp. 129–130, 2000.

[25] W. Peng and X. Lu, "AHBP: An efficient broadcast protocol for mobile ad hoc networks," *Journal of Science and Technology*, pp. 114–125, 2002.

[26] A. Qayyum, L. Viennot, and A. Laouiti, "Multipoint relaying: an efficient technique for flooding in mobile wireless networks," Technical Report 3898, INRIA - Rapport de recherche, 2000.

[27] J. Sucec and I. Marsic, "An efficient distributed network-wide broadcast algorithm for mobile ad hoc networks" CAIP Technical Report 248 - Rutgers University, 2000.

[28] G. Korkmaz, E. Ekici, F. Ozguner, and U. Ozguner, "Urban multi-hop broadcast protocol for inter-vehicle communications systems," in *Proc. of 1st ACM International Workshop on Vehicular Ad Hoc Networks*, pp. 76–85, 2004.

[29] M. Sun, W. Feng, T.-H. Lai, K. Yamada, H. Okada, and K. Fujimura, "GPS-based message broadcasting for inter-vehicle communications," in *Proc. of the 2000 International Conference on Parallel Processing*, pp. 279–286, 2000.

[30] L. Briesemioster and C. Hommel, "Role-based multicast in highly mobile but sparsely connected ad hoc networks," in *Proc. of the 1st ACM International Symposium on Mobile Ad Hoc Networking & Computing*, pp. 45–50, 2000.

[31] F. Visintainer, L. D'Orazio, M. Darin, and L. Altomare, "Cooperative systems in motorway environment: the example of trento test site in Italy," in *Advanced Microsystems for Automotive Applications 2013*, Springer, pp. 147–158, 2013.

[32] F. Sanchez, J. L. Diez, R. Blanco, V. Sixto, M. Segovia, J. A. Fernandez, R. Rodriguez, and M. Rial, "SISCOGA–Results of Spanish FOT on cooperative systems," 19th ITS World Congress, 2012.

[33] IEEE Std 802.11p - IEEE Standard for Information technology—Telecommunications and information exchange between systems Local and metropolitan area networks—Specific requirements; Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications; Amendment 6: Wireless Access in Vehicular Environments, 2010.

[34] IEEE 1609.3 - IEEE Standard for Wireless Access in Vehicular Environments (WAVE) - Networking Services, 2010.

[35] IEEE 1609.4 - IEEE Standard for Wireless Access in Vehicular Environments (WAVE)--Multi-channel Operation, 2010.

[36] Draft ETSI EN 302 637-2 V1.3.0; Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part2: Specification of Cooperative Awareness Basic Service, 2013.

[37] Draft ETSI EN 302 637-3 V1.2.0; Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part3: Specifications of Decentralized Environmental Notification Basic Service, 2013.

[38] ARIB STD-T109 Version 1.2: 700MHz Band Intelligent Transport Systems, 2013.

[39] A. Weimerskirch, "V2X security & privacy: the current state and ITS future," 18th ITS World Congress, 2011.

[40] M. Wolf and T. Gendrullis, *Design implementation, and evaluation of a vehicular hardware security module*. Springer Berlin Heidelberg, pp. 302–318, 2012.

[41] A. Weinfeld, "Methods to reduce DSRC channel congestion and improve V2V communication reliability," 17th ITS World Congress, 2010.

[42] ETSI TS 102 687 V1.1.1 Intelligent Transport Systems (ITS); Decentralized Congestion

Control for Intelligent Transport Systems operating in the 5GHz range; Access layer part, 2011.

[43] M. Torrent-Moreno, J. Mittag, P. Santi, and H. Hartenstein, “Vehicle-to-vehicle communication: fair transmit power control for safety-critical information,” in *Proc. of IEEE Transactions on Vehicular Technology*, vol. 58, no. 7, pp. 3684–3703, 2009.

[44] T. Tielert, D. Jiang, Q. Chen, L. Delgrossi, and H. Hartenstein, “Design methodology and evaluation of rate adaptation based congestion control for vehicle safety communications,” *IEEE Vehicular Networking Conference*, pp. 116–123, 2011.

[45] T. Osafune, L. Lin, and M. Lenardi, “Multi-hop vehicular broadcast (MHVB),” in *Proc. of 6th International Conference on ITS Telecommunications*, pp. 757–760, 2006.

[46] M. Mariyasagayam, T. Osafune, and M. Lenardi, “Enhanced multi-hop vehicular broadcast (MHVB) for active safety applications,” in *Proc. of 7th International Conference on ITS Telecommunications*, pp. 1–6, 2007.

[47] Y. P. Fallah, C. L. Huang, and R. Sengupta, “Analysis of information dissemination in vehicular ad-hoc networks with application to cooperative vehicle safety systems,” in *Proc. of IEEE Transactions on Vehicular Technology*, vol. 60, no. 1, pp. 233–247, 2011.

[48] R. Baldessaro, D. Scanferla, L. Le, W. Zhang, and A. Festag, “Joining forces for vanets: a combined transmit power and rate control algorithm,” in *Proc. of International Workshop on Intelligent Transportation*, 2010.

[49] F. Tobagi and L. Kleinrock, “Packet switching in radio channels: part II--the hidden terminal problem in carrier sense multiple-access and the busy-tone solution,” *IEEE Transactions Communications*, vol. 23, no. 12, pp. 1417–1433, 1975.

[50] D. Vassis and G. Kormentzas, “Throughput analysis for IEEE 802.11 ad hoc networks under the hidden terminal problem,” in *Proc. of Consumer Communications and Networking Conference*, pp. 1273–1276, 2006.

[51] MSHA, “Safety standards for surface haulage; proposed rule,” http://arlweb.msha.gov/REGS/FEDREG/PROPOSED/1998PROP/ 98-20351.htm.

[52] R. F. Randolph, and C. M. Boldt, "Safety analysis of surface haulage accidents," Virginia Polytechnic Inst. and State Univ., Blacksburg, Department of Mining and Minerals Engineering, Tech. Rep., 1996.

[53] G. Parker, "Haul truck and light vehicle collision," NSW Government Department of Industry Resources & Energy, Tech. Rep., 2015.

[54] M. Inspectorate, "Vehicle collisions - how long before it's really bad?" Queensland Government Department of Natural Resources and Mines, Tech. Rep., 2009.

[55] G. Agamennoni, J. Nieto, and E. Nebot, "Mining GPS data for extracting significant places," in *Proc. of IEEE International Conference on Robotics and Automation*, pp. 855–862, 2009.

[56] T. M. Ruff, "Test results of collision warning systems for surface mining dump trucks," National Institute for Occupational Safety and Health, Tech. Rep., 2000.

[57] W. H. Schiffbauer, "Active proximity warning system for surface and underground mining applications," *Mining engineering*, vol. 54, no. 12, pp. 40–48, 2002.

[58] E. Sun, A. Nieto, and Z. Li, "Real-time Google Earth 3D assisted driving system in surface mining operations," in *Proc. of IEEE 10th International Conference on Computer-Aided Industrial Design & Conceptual Design*, pp. 2095–2099, 2009.

[59] E. Sun and X. Zhang, "3D assisted driving system for haul trucks in surface mining," in *Proc. of 2011 International Conference on Transportation, Mechanical, and Electrical Engineering*, pp. 363–366, 2011.

[60] E. Sun, X. Zhang, and Z. Li, "Internet of things based 3D assisted driving system for trucks in mines," in *Proc. of International Conference on Innovation Management and Industrial Engineering*, vol. 1, pp. 510–513, 2011.

[61] E. Nebot, J. Guivant, and S. Worrall, "Haul truck alignment monitoring and operator warning system," *Journal of Field Robotics*, vol. 23, no. 2, pp. 141–161, 2006.

[62] P. Jacquet, P. M¨uhlethaler, T. Clausen, A. Laouiti, A. Qayyum, and L. Viennot, "Optimized link state routing protocol for ad hoc networks," in *Proc. of IEEE International Multi Topic Conference on Technology for the 21st Century*, pp. 62–68, 2001.

[63] S. Worral and E. M. Nebot, "A comprehensive approach to improving vehicle safety in mining." The Australasian Institute of Mining and Metallurgy, 2007.

[64] H. Wu, L. Liu, and X. Yuan, "Remote monitoring system of mine vehicle based on wireless sensor network," in *Proc. of International Conference on Intelligent Computation Technology and Automation*, vol. 2, pp. 1015–1019, 2010.

[65] W. Ni, I. B. Collings, R. P. Liu, and Z. Chen, "Relay-assisted wireless communication systems in mining vehicle safety applications," *IEEE Transactions on Industrial Informatics*, vol. 10, no. 1, pp. 615–627, 2014.

[66] D. Laurence, "Safety rules and regulations on mine sites–the problem and a solution," *Journal of safety research*, vol. 36, no. 1, pp. 39–50, 2005.

[67] S. Enji, A. Nieto, and L. Zhongxue, "GPS and Google Earth based 3D assisted driving system for trucks in surface mines," *Mining Science and Technology*, vol. 20, no. 1, pp. 138–142, 2010.

[68] C. Wang, X. Cheng, and D. I. Laurenson, "Vehicle-to-vehicle channel modeling and measurements: recent advances and future challenges," *IEEE Communications Magazine*, vol. 47, no. 11, pp. 96–103, 2009.

[69] M. Boban, J. Barros, and O. Tonguz, "Geometry-based vehicle-to-vehicle channel modeling for large-scale simulation," *IEEE Transactions on Vehicular Technology*, vol. 63, no. 9, pp. 4146–4164, 2014.

[70] J. Maurer, T. Fugen, M. Porebska, T. Zwick, and W. Wiesbeck, "A ray-optical channel model for mobile to mobile communications," in *Proc. of 4th Mathematical and Computer Modelling Conference*, vol. 2100, pp. 6–8, 2008.

[71] A. S. Akki and F. Haber, "A statistical model of mobile-to-mobile land communication

channel," *IEEE Transactions on Vehicular Technology*, vol. 35, no. 1, pp. 2–7, 1986.

[72] I. Sen and D. W. Matolak, "Vehicle–vehicle channel models for the 5-ghz band," *IEEE Transactions on Intelligent Transportation Systems*, vol. 9, no. 2, pp. 235–245, 2008.

[73] W. A. Hustrulid, M. Kuchta, and R. K. Martin, *Open Pit Mine Planning and Design, Two Volume Set & CD-ROM Pack*. CRC Press, 2013.

[74] V. Degli-Esposti, "Ray tracing propagation modelling: Future prospects," in *Proc. of 8th European Conference on Antennas and Propagation*, pp. 2232–2232, 2014.

[75] Space-Time Engineering, "Space-time engineering website," https://www.spacetime-eng.com/jp/.

[76] Bitrieve, "Bitrieve inc. products information," http://www.bitrieve.co.jp/products/lan analyzer/131.

[77] American Automobile Association, "Aggressive driving: Research update," 2009.

[78] C. Saiprasert and W. Pattara-Atikom, "Smartphone enabled dangerous driving report system," in *Proc. of IEEE 46th Hawaii International Conference on System Sciences*, pp. 1231–1237, 2013.

[79] C. -W. You, N. D. Lane, F. Chen, R. Wang, Z. Chen, T. J. Bao, M. Montes-de-Oca, Y. Cheng, M. Lin, L. Torresani, and A. T. Campbell, "CarSafe app: alerting drowsy and distracted drivers using dual cameras on smartphones," in *Proc. of ACM 11th International Conference on Mobile Systems, Applications, and Services*, pp. 13–26, 2013

[80] B. -G. Lee and W. -Y. Chung, "A smartphone-based driver safety monitoring system using data fusion," *Sensors*, vol. 12, no. 12, pp. 17536–17552, 2012.

[81] J. Paefgen, F. Kehr, Y. Zhai, and F. Michahelles, "Driving behavior analysis with smartphones: insights from a controlled field study," in *Proc. of ACM 11th International Conference on Mobile and Ubiquitous Multimedia*, no. 36, pp. 1–8, 2012.

[82] P. Chaovalit, C. Saiprasert, and T. Pholprasit, "A method for driving event detection using SAX on smartphone sensors," in *Proc. of IEEE 13th International Conference on ITS Telecommunications*, pp. 450–455, 2013.

[83] H. Eren, S. Makinist, E. Akin, and A. Yilmaz, "Estimating driving behavior by a smartphone," in *Proc. of 2012 IEEE International Intelligent Vehicles Symposium*, pp. 234–239, 2012.

[84] R. Araújo, A. Igreja, R. de Castro, and R. E. Araujo, "Driving coach: a smartphone application to evaluate driving efficient patterns," in *Proc. of 2012 IEEE International Intelligent Vehicles Symposium*, pp. 1005–1010, 2012.

[85] G. Guido, A. Vitale, V. Astarita, F. Saccomanno, V. P. Giofré, and V. Gallelli, "Estimation of safety performance measures from smartphone sensors," *Procedia-Social and Behavioral Sciences*, vol. 54, pp. 1095–1103, 2012.

[86] J. E. Meseguer, C. T. Calafate, J. C. Cano, and P. Manzoni, "Drivingstyles: a smartphone application to assess driver behavior," in *Proc. of 2013 IEEE International Symposium on Computers and Communications*, pp. 535–540.

[87] D. A. Johnson and M. M. Trivedi, "Driving style recognition using a smartphone as a sensor platform," in *Proc. of IEEE 14th International Conference on Intelligent Transportation Systems*, pp. 1609–1615, 2011.

[88] G. Castignani, R. Frank, and T. Engel, "Driver behavior profiling using smartphones," in *Proc. of IEEE 16th International Conference on Intelligent Transportation Systems*, pp. 552–557, 2013.

[89] J. -H. Hong, B. Margines, and A. K. Dey, "A smartphone-based sensing platform to model aggressive driving behaviors," in *Proc. of 32nd ACM SIGCHI International Conference on Human Factors in Computing Systems*, pp. 4047–4056, 2014.

[90] C. Miyajima, Y. Nishiwaki, K. Ozawa, T. Wakita, K. Itou, K. Takeda, and F. Itakura, "Driver modeling based on driving behavior and its evaluation in driver identification," in *Proc. of the IEEE*, vol. 95, no. 2, pp. 427–437, 2007.

[91] U. Munzel and E. Brunner, “Nonparametric methods in multivariate factorial designs,” *Journal of Statistical Planning and Inference*, vol. 88, no. 1, pp. 117–132, 2000.

[92] G. Castignani, T. Derrmann, R. Frank, and T. Engel, “Driver behavior profiling using smartphones: a low-cost platform for driver monitoring,” *IEEE Intelligent Transportation Systems Magazine*, vol. 7, no. 1, pp. 91–102, 2015.

[93] Ingenie Services Limited, “Black box car insurance for young drivers,” https://www.ingenie.com/

[94] Aviva PLC, “Aviva drive app,” http://www.aviva.co.uk/drive/

[95] State Farm Mutual Automobile Insurance Company, “State farm insurance,” https://www.statefarm.com/insurance/auto

[96] P. Mohan, V. N. Padmanabhan, and R. Ramjee, “Nericell: rich monitoring of road and traffic conditions using mobile smartphones,” in *Proc. of 6th ACM International Conference on Embedded Network Sensor Systems*, pp. 323–336, 2008.

[97] J. Almazan, L. M. Bergasa, J. J. Yebes, R. Barea, and R. Arroyo, “Full auto-calibration of a smartphone on board a vehicle using IMU and GPS embedded sensors,” in *Proc. of IEEE International Intelligent Vehicles Symposium*, pp. 1374–1380, 2013.

[98] M. Fazeen, B. Gozick, R. Dantu, M. Bhukhiya, and M. C. González, “Safe driving using mobile phones,” *IEEE Transactions on Intelligent Transportation Systems*, vol. 13, no. 3, pp. 1462–1468, 2012.

[99] E. Berdoulat, D. Vavassori, and M. T. M. Sastre, “Driving anger, emotional and instrumental aggressiveness, and impulsiveness in the prediction of aggressive and transgressive driving,” *Accident Analysis & Prevention*, vol. 50, pp. 758–767, 2013.

[100] J. F. Coughlin, B. Reimer, and B. Mehler, “Monitoring, managing, and motivating driver safety and well-being,” *IEEE Pervasive Computing*, vol. 3, pp. 14–21, 2011.

[101] L. Malta, C. Miyajima, and K. Takeda, “A study of driver behavior under potential threats in vehicle traffic,” *IEEE Transactions on Intelligent Transportation Systems*, vol.

10, no. 2, pp. 201–210, 2009.

[102] Y. Zhang, W. C. Lin, and Y. K. S. Chin, “A pattern-recognition approach for driving skill characterization,” *IEEE Transactions on Intelligent Transportation Systems*, vol. 11, no. 4, pp. 905–916, 2010.

[103] C. Cortes and V. Vapnik, “Support-vector networks,” *Machine learning*, vol. 20, no. 3, pp. 273–297, 1995.

[104] N. V. Chawla, K. W. Bowyer, L. O. Hall, and W. P. Kegelmeyer, “SMOTE: synthetic minority over-sampling technique,” *Journal of Artificial Intelligence Research*, pp. 321–357, 2002.

[105] Japan Safe Driving Center, “A survey on dependency of traffic accidents, violation of traffic regulations and rates of subsequent accidents, No. II,” 2012, (in Japanese).

[106] ETSI TS 102 636-4-2 V1.1.1 Intelligent Transport Systems (ITS); Vehicular Communications; GeoNetworking; Part4: Geographical addressing and forwarding for point-to-point and point-to-multipoint communications; Sub-part 2: Media-dependent functionalities for ITS-G5, 2013.

[107] K. Bilstrup, E. Uhlemann, E. G. Strom, U. Bilstrup, “On the ability of the 802.11 p MAC method and STDMA to support real-time vehicle-to-vehicle communication,” *EURASIP Journal on Wireless Commun. and Networking*, vol. 2009, 2009.

[108] Bilstrup, Katrin Sjoberg, Elisabeth Uhlemann, and Erik G. Strom. “Scalability Issues of the MAC Methods STDMA and CSMA of IEEE 802.11 p When Used in VANETs,” *IEEE International Conference on Communications Workshops*, 2010.

[109] Sjöberg, Katrin, Elisabeth Uhlemann, and Erik G. Ström. "Delay and interference comparison of CSMA and self-organizing TDMA when used in VANETs,” *7th International Wireless Communications and Mobile Computing Conference*, 2011.

[110] Lenoble, Mathieu. “Throughput Improvement Technique for D-TDMA-Based Vehicular Ad-Hoc Networks.” *IEICE transactions on communications*,” vol. E94-B, No.10, pp. 2776-2784, 2011.

[111] ITU Recommendation ITU-R M1371, “Technical characteristics for universal shipborne automatic identification system using time division multiple access in the VHF maritime mobile band,” 2001.

[112] ARIB STD-T109 Version1.0; 700 MHz Band Intelligent Transport Systems, 2012.