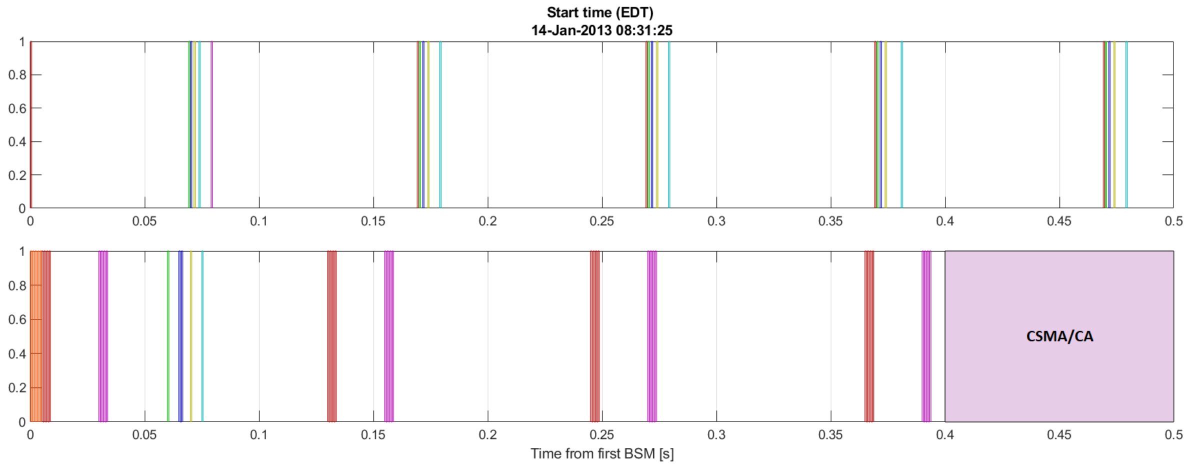
CHALMERS
UNIVERSITY OF TECHNOLOGY



Efficient radio resource management for cooperative safety applications based on centralized road-safety risk assessment

Master's thesis in Communication Engineering

CARL VON ROSEN JOHANSSON
ADAM WIKLUND

Department of Electrical Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2019

Efficient radio resource management for cooperative safety applications based on centralized road-safety risk assessment

CARL VON ROSEN JOHANSSON
ADAM WIKLUND

Department of Electrical Engineering
Division of Communication and Antenna Systems
Chalmers University of Technology
Gothenburg, Sweden 2019

Efficient radio resource management for cooperative safety applications based on centralized road-safety risk assessment
CARL VON ROSEN JOHANSSON
ADAM WIKLUND

Supervisors:
Erik Ström, Communication and Antenna Systems, Electrical Engineering
Marco Dozza, Crash Analysis and Prevention, Mechanics and Maritime Sciences
Examiner: Erik Ström, Electrical Engineering

Department of Electrical Engineering
Division of Communication and Antenna Systems
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: Baseline 802.11p naturalistic transmission and a suggested scheduler for the same scenario

Typeset in LaTeX
Printed by TeknologTryck
Gothenburg, Sweden 2019

Efficient radio resource management for cooperative safety application based on centralized road-safety risk assessment
CARL VON ROSEN JOHANSSON
ADAM WIKLUND
Department of Electrical Engineering
Chalmers University of Technology

Abstract

Road accidents are currently one of the most common causes of death in the world and the need for reliable vehicular safety systems is urgent. Especially in situations with higher rate of fatalities such as left turns across paths at intersections. This thesis focuses on the wireless communication aspect of future cooperative safety systems due to its potential to improve intersection safety. Current state of the art system based on Institute of Electrical and Electronics Engineers (IEEE) 802.11p are known to scale poorly as the number of vehicles within radio range increase. This thesis evaluates a new Medium Access Control (MAC) layer Time Division Multiple Access (TDMA) scheduler based on a centralized risk assessment from surrogate safety measurements, such as Post-Encroachment Time (PET), for Vehicle to Vehicle (V2V) communication. This centralized scheduler address an intersection scenario with a radio range coverage of 350 meters. Based on simulations with real-world data from Safety Pilot Model Deployment, the result of this thesis indicate that significant gain can be achieved when the number of vehicles inside the radio range coverage increase.

Keywords: V2V, 802.11p WAVE, ETSI ITS, Vehicular communication, Centralized risk assessment, TDMA, PET, MAC layer, Cooperative applications

Acknowledgements

We would like to thank our supervisors, Erik Ström and Marco Dozza, for their deep dedication to the thesis and for their great knowledge and feedback during the project. Without you, there would not be a project. We would also like to thank Anver Hisham Unnichiriyath Siddique for his thorough feedback and his knowledge. Furthermore the authors would like to show our gratitude to Carol Flannagan, Alex Cao, Helen Spradlin and James Sayer of UMTRI, University of Michigan, for helping us with the data access and their great knowledge in the dataset. Finally we would also like to thank our girlfriends, Freja Byström and Linda Wäppling, for their support and for proofreading the report several times.

Carl von Rosen Johansson, Adam Wiklund, Gothenburg, June 2019

Contents

List of Figures

List of Tables

List of Abbreviation

5GCAR 5G Communication Automotive Research and innovation
AC Access Category
ADAS Advanced Driver Assistance System
ADS Automated Driving System
AEB Automatic emergency Braking
AP Access Point
AV Autonomous Vehicles
BSM Basic Safety Message
BSS Basic Service Set
BSSID Basic Service Set Identifier
C-ITS Cooperative-ITS
CA Constant Acceleration
CAM Cooperative Awareness Message
CAN Controller Area Network
CDF Cumulative Density Function
CSMA Carrier Sense Multiple Access
CSMA/CA Carrier Sense Multiple Access with Collision Avoidance
CV Constant Velocity
DCC Decentralized Congestion Control
DCF Distributed Coordination Function
DENM Decentralized Environmental Notification Message
DOT Unites States Department of Transportation
DSRC Dedicated Short Range Communications
DCC Decentralized Congestion Control
EDCA Enhanced Distributed Channel Access
EDT Eastern Daylight time
EIRP Effective Isotropic Radiated Power
ETSI European Telecommunications Standard Institute
ETTC Enhanced Time to Collision
EU European Union
EuroNCAP European New Car Assessment Programme
FCW Frontal Collision Waring
FDMA Frequency Division Multiple Access
G5CC ITS-G5 Control Channel
G5SC ITS-G5 Service Channel
GNSS Global Navigation Satellite System
GPS Global Positioning System

HF High Frequency
IEEE Institute of Electrical and Electronics Engineers
ITS Intelligent Transport System
ITS-G5 Short Ranged Wireless Communication
LAN Local Area Network
LF Low Frequency
LOS Line Of Sight
LTOD Left turn opposite direction
LV Lead Vehicle
MAC Medium Access Control
MI Michigan
NHTSA National Highway Traffic Safety Administration
NLOS Non-Line Of Sight
OCB Out-of-Context BSS
OFDM Orthogonal Frequency-Division Multiplexing
PER Packet Error Rate
PET Post-Encroachment Time
POV Principal Other Vehicle
PSR Package Success Rate
QoS Quality of Service
RSE Roadside Equipment
RSU Roadside Unit
RTTT Road Transport and Traffic Telematics
SCP Straight Crossing Paths
SDG Sustainable Development Goals
SEMCOG Southeast Michigan Council of Governments
SPDM Safety Pilot Model Deployment
STA station
TDMA Time Division Multiple Access
TH Time Headway
TSR Total Success Rate
TTC Time to Collision
UMTRI University of Michigan Transportation Research Institute
UN United Nations
USA United States of America
V2I Vehicle to Infrastructure
V2V Vehicle to Vehicle
V2X Vehicle to Everything
WAVE Wireless Access in Vehicular Environments
WHO World Health Organization

1
Introduction

This thesis presents a Master thesis in Electrical engineering, EENX30 for two students at the masters program Communication Engineering at Chalmers University of Technology during the spring of 2019.

1.1 Background

In 2016, WHO reported that 1.35 million people were killed in road accidents and it was, therefore, the 8th most common cause of death in the world [1]. In recent years, Vehicle to Vehicle (V2V) communication has risen as a possible solution for preventing some of these crashes [2]. The National Highway Traffic Safety Administration (NHTSA) has identified that 22 of 37 pre-crash scenarios can be solved by different V2V solutions such as cooperative applications [2][3]. However, some reports indicate that the current standards, IEEE 802.11p WAVE and ITS-G5, have limitations when the number of installed V2V devices increase and further more there is a lack of solid requirements for wireless communication in cooperative applications [4][5]. The industry and academia have identified a need to define new standards that can handle channel congestion in these systems [6]. European Union (EU) has funded a Horizon 2020 program called 5G Communication Automotive Research and innovation (5GCAR) with the main objectives set to be [6]:

- ”Develop an overall 5G system architecture providing optimized end-to-end V2X network connectivity for highly reliable and low-latency V2X services, which supports security and privacy, manages quality-of-service and provides traffic flow management in a multi-RAT and multi-link V2X communication system”.
- ”Interworking of multi-RATs that allows embedding existing communication solutions and novel 5G V2X solutions”.
- ”Develop an efficient, secure and scalable sidelink interface for low-latency, high-reliability V2X communications”.
- ”Propose 5G radio-assisted positioning techniques for both vulnerable road users and vehicles to increase the availability of very accurate localization”.
- ”Identify business models and spectrum usage alternatives that support a wide

range of 5G V2X services”.

- ”Demonstrate and validate the developed concepts and evaluate the quantitative benefits of 5G V2X solutions using automated driving scenarios in test sites”.

Chalmers involvement, amongst others, in the 5GCAR program is defined within the Chalmers Area of Advance Transport where the two departments, Mechanics and Maritime Sciences and Electrical Engineering, are working together to bring synergies between traffic safety and communication in the project Automated Driving System (ADS) [7]. This thesis contributes to 5GCARs first item in the aforementioned list of objectives. Furthermore, the ADS project aims to collaborate with University of Michigan Transportation Research Institute (UMTRI) [7]. UMTRI have a large scale pilot project of vehicular communication which this thesis plan to use called Safety Pilot Model Deployment (SPDM). The SPDM project includes datasets of almost 3000 connected vehicles that generated naturalistic V2V data for more than a year [8].

1.2 Purpose

The purpose of this thesis is to investigate if it is possible to save radio resources while maintaining or increasing the level of vehicular traffic safety compared with the IEEE 802.11p standard in a naturalistic vehicular traffic scenario. The thesis also intends to contribute to the pursuit of wireless communication requirements for cooperative safety applications. It aims to do so by applying a smart scheduling that takes risk assessment into consideration. The thesis will explore several solutions were risk assessment may advise different communication requirements and scalabilities with respect to increasing level of distributed risk assessment.

1.3 Limits of the thesis

This thesis does not include any physical experiments with real world scenarios. It only simulates experiments with existing naturalistic data.

1.3.1 Traffic safety aspects

This thesis will use available data from the Safety Pilot Model Deployment (SPDM) dataset that has a large naturalistic data collection from both vehicles that transmits Basic Safety Message (BSM)s and Roadside Equipment (RSE)s, also called Roadside Unit (RSU), that are receiving BSMs in the area of Ann Arbour, Michigan (MI) [8].

The threat assessment and scenario selection will focus on evaluating scenarios where a V2V and Vehicle to Infrastructure (V2I) application could prevent a crash, using the NHTSA, Southeast Michigan Council of Governments (SEMCOG) and

European New Car Assessment Programme (EuroNCAP) as primary sources for analysis.

1.3.2 Communication aspects

This thesis will focus on achieving efficient radio resources with centralized scheduling methods in comparison with the IEEE 802.11p as a baseline. No decentralized scheduling will be evaluated.

This thesis will not evaluate radio resource management from scratch but rather assume a 5G-like system with an identical physical layer as the baseline and centralized base station at a road-side unit.

1.4 Ethical and Sustainable considerations

The thesis will consider several ethical and sustainable questions during the work of the thesis and is focusing on the two main topics:

The first topics is to manage privacy issues connected to positioning data that vehicular data generates. The dataset this thesis utilizes has made the vehicles anonymous. However, efforts made with this dataset could potentially spoil this anonymity. This report will consider these aspects when designing the simulations to avoid unintentionally breaking the anonymity of the vehicles.

The second topic that is regarded is the attempt to contribute to the United Nations (UN) Sustainable Development Goals (SDG) and, more specifically, to target 3.6: *by 2030 half global deaths from road traffic accidents*. Moreover, this projects contributors, both positive and negative, to the SDGs was identified during a workshop.

1.5 Related work

1.5.1 V2X communications

In 2013 Kenta Mori et al. investigated how IEEE 802.11p performed with respect to channel congestion in their report *Experimental Study on Channel Congestion using IEEE 802.11p Communication System* [9]. They found that the success rate of transmitted packages declined as the number of nodes and the packet size increased independently. They also found that the same result was reached when they decreased the contention window of the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) system.

Heecheol Song and Hwang Soo Lee wrote in their survey *A Survey on How to Solve a Decentralized Congestion Control Problem for Periodic Beacon Broadcast in*

Vehicular Safety Communications about the existing congestion control techniques for decentralized vehicular communication [10]. Song and Soo suggested that the industry and academia should aim to develop a V2V safety communication standard which can control beacon congestion adaptive with changes in vehicle density.

X.-F. Xie and Z.-J. Wang wrote about vehicular safety in a signaled intersection with aid from V2I communication in their article *SIV-DSS: Smart In-Vehicle Decision Support System for driving at signalized intersections with V2I communication* from 2018 [11]. They found that the help of V2I communications to a Smart In-Vehicle Decision Support System did not only reduce the number of needless stops at intersections but also increased safety as it reduced red light running [11].

In 2015 J. Rios-Torres, A. Malikopoulos and P. Piso wrote the article *Online optimal control of connected vehicles for efficient traffic flow at merging roads*, which investigated the use of centralized road side units to lower fuel cost in merging situations [12]. J. Rios et al. found that a centralized unit which could manage the flow of traffic minimized the need to stop and wait at merging situation [12]. This did not only lower the fuel cost but also minimized the travel time [12]. They came to this conclusion by allowing the centralized controller to decide when the approaching vehicle could enter the merging based on when the previous car left the merging area. This forced the approaching cars to either slow down or speed up to meet the required time window and, therefore, made a complete stop unnecessary [12].

1.5.2 Centralized TDMA scheduling

R. Zhan et al. describes in [13] a novel centralized TDMA-based scheduling protocol for vehicular networks where three main aspects are considered for channel access. First is the quality factor, second is the speed of the vehicle and the last is connected to the four different Access Category (AC) values of the 802.11p standard. Radio resource efficiency is mainly done by channel reuse, where the vehicles that are communicating within same time slot is more than 200 meters away from each other but within 500 meters from the road side equipment.

1.5.3 Safety Pilot Model Deployment related papers

The Safety Pilot Model Deployment (SPDM) dataset that will be used in this thesis have been used in several other studies connected to V2V communication.

In [14] X. Huang et al. partly evaluate the performance of the RSEs in SPDM, as an empirical study where they have selected four RSEs to evaluate. Further more, in [15], W. Wang et al. evaluates a Lane Departure Warning Systems based on the SPDM data. Finally, D. Zhao et al. evaluates different Vehicle safety systems based on the data in [16], [17].

2

Technical background

This chapter explains relevant background theory for this thesis.

2.1 Vehicular Communication

To be able to handle the future needs of an increasing number of Autonomous Vehicles (AV)s and Advanced Driver Assistance System (ADAS) a common set of rules in, amongst others, their way of communicating is needed. These rules should be efficient and just to increase traffic safety and reduce cost. In this section the two major and relevant communication standards are explained, as well as, the safety messages used by AVs and ADASs in this project.

2.1.1 IEEE 802.11p

2.1.1.1 Overview

The Institute of Electrical and Electronics Engineers (IEEE) has developed the IEEE 802.11p amendment to the Local Area Network (LAN) protocol IEEE 802.11, which is a standard used in wireless communications. IEEE 802.11p adds Wireless Access in Vehicular Environments (WAVE) to IEEE 802.11. The motivation to develop this standard begun in 1999 when 75 MHz of spectrum band was allocated at 5.9 GHz in the United States of America (USA) to be used solely for V2V and V2I communications [18]. This allocated spectrum is called the Dedicated Short Range Communications (DSRC) spectrum and has the primary goal of ensuring public safety and improving traffic flow for AV and ADAS vehicles [18]. DSRC is also the name of the wireless communication technology used for short ranged automotive communication and is based on IEEE 802.11p [19]. Moreover, the IEEE 802.11p standards purpose is to define MAC and physical layer requirements for functions and services sought out by the WAVE nodes and stations. These requirements ensure the ability to operate in rapidly changing environments while avoiding the time cost of having to join a Basic Service Set (BSS), which was required in the IEEE 802.11 and added delay to time critic processes [18]. Another purpose of the IEEE 802.11p standard is to specify the interface functions and signaling technique, which the IEEE 802.11 MAC controls, of WAVE [18].

2.1.1.2 Physical layer

The physical layer of IEEE 802.11p is identical to the physical layer of the IEEE 802.11 [19]. It enables the use of the frequencies centered around the 5.9 GHz band as mention above. The spectrum interval is defined between 5.850 GHz to 5.925 GHz with channel spacing of 5 MHz, 10 MHz and 20 MHz. Furthermore the IEEE 802.11p divides this spectrum interval into 9 channels, each with their dedicated purpose, shown in Figure 2.1.

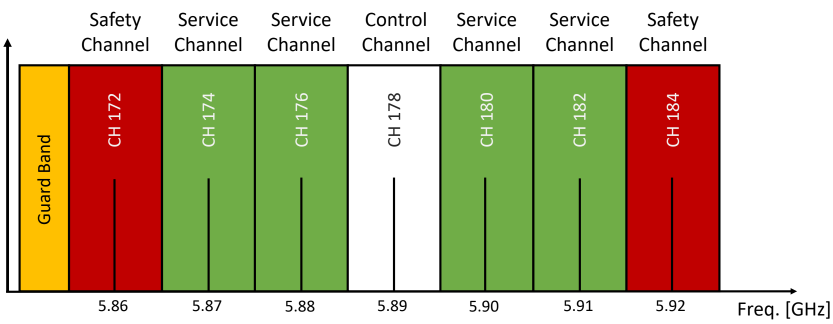


Figure 2.1: IEEE 802.11p frequency allocation

As can be seen in Figure 2.1 the spectrum intervals from 5.855 GHz to 5.865 GHz and from 5.915 GHz to 5.925 GHz are dedicated safety channels and are named "CH172" and "CH184" respectively [20]. The small spectrum interval of 5 MHz from 5.850 GHz to 5.855 GHz is dedicated to a guard band interval. Channels within the intervals 5.865 GHz to 5.875 GHz, 5.875 GHz to 5.885 GHz, 5.895 GHz to 5.905 GHz and 5.905 GHz to 5.915 GHz are service channels named "CH174", "CH176", "CH180" and "CH182" respectively [20]. IEEE 802.11p has also defined a control channel within the spectrum interval 5.885 GHz to 5.895 GHz, which is named "CH178" [20]. This control channel is defined to control the transmission broadcast and to control the established links [20]. The safety channels are appointed two task respectively. "CH172" is dedicated to handle serious security solutions while "CH184" is dedicated to act as protection towards congestion from other channels [20]. The service channels are destined to enable bidirectional communications between different units, which they can do as four individual channels or as two pairs of channels with 20 MHz channel space each [20]. The channels which are of the biggest interest in this thesis is the safety channels of 10 MHz as they are used for urgent safety messages such as BSMs or CAM/DENM [19].

2.1.1.3 Medium Access Control layer

The MAC layer in IEEE 802.11p is based on IEEE 802.11. Therefore, the MAC header in IEEE 802.11p has the following structure [21]:

- Frame control - 2 bytes
- Duration/ID - 2 bytes
- Address space 1 - 6 bytes
- Address space 2 - 6 bytes
- Address space 3 - 6 bytes
- Sequence Control - 2 bytes
- Address space 4 - 6 bytes
- Quality of Service (QoS) Control - 2 bytes

The frame control contains the protocol version, the type of the message, the sub type of the message, the indication which tells if the message is to or from the distribution system, fragmentation, power management and a protecting frame [21]. For the address elements of the MAC header DSRC uses operations without the need to join a Basic Service Set (BSS) [21]. This means that a Basic Service Set Identifier (BSSID) code is not used in the "Address 3" element for address matching or filtering when receiving a dataframe [21]. The QoS control element obeys the IEEE 802.11 standards specifications and is modified by variations of the activated bits [21].

As the IEEE standard is not obligated to join a BSS the standard is using an Out-of-Context BSS (OCB) instead [22]. Futhermore, the IEEE 802.11p standard's MAC algorithm relies on a Enhanced Distributed Channel Access (EDCA) called CSMA/CA [19][21]. The CSMA/CA requires the station (STA) to listen to the channel before transmitting [19]. This means that if the STA finds the channel occupied it has to step back for a random amount of time and then try again. This is done to avoid congestion on the channel but is the cause for costly retransmissions when the number of transmitting nodes within the topology increases.

2.1.2 Comparing ITS-G5 and DSRC

2.1.2.1 ETSI ITS-G5 overview

The European Telecommunications Standard Institute (ETSI) developed a standard of their own to meet the future needs of AVs and ADAS in Europe, which is called Short Ranged Wireless Communication (ITS-G5) and is based on the IEEE 802.11 standard [21]. The ETSI standard addresses multiple topics such as Cooperative-ITS (C-ITS). C-ITS aims to support autonomous driving with ITS-G5 for Road Transport and Traffic Telematics (RTTT) based on Vehicle to Everything (V2X) communication [23]. ITS-G5 is the name of the wireless communication technology used for short ranged automotive communication within ETSIs standard [19]. Just as DSRC ITS-G5 is also based on IEEE 802.11p. The system for direct V2X communication in ETSIs standard is based on the MAC and Physical layer of the IEEE 802.11p standard [23]. Like DSRC ITS-G5 does not need to join a BSS but relies on Decentralized Congestion Control (DCC) outside of a BSS instead [19]. C-ITS is not only a safety application, but can also increase traffic efficiency and with that; fuel and time reduction [23]. Intelligent Transport System (ITS) also addresses security, privacy, automotive radar and V2I communication [23].

2.1.2.2 Physical and MAC layer difference

As both the DSRC and the ITS-G5 are based on IEEE 802.11 the protocol in their physical layers and MAC layers are almost identical [19]. One difference is when they communicate outside of a BSS since DSRC technology relies on OCB and ITS-G5 relies on DCC [19]. Another difference is in their use of the allocated spectrum. While both are centered around 5.9 GHz they are not completely overlapping, as the ITS is spanning from 5.470 GHz to 5.925 GHz while IEEE 802.11p is spanning from 5.850 GHz to 5.925 GHz [19][21].

2.1.3 Safety message

The safety messages sent out by the AVs and ADAS needs to be of a certain structure to ensure stability in the traffic safety systems. Two of these message structures are more prominent and are called Basic Safety Message (BSM) and Cooperative Awareness Message (CAM)/Decentralized Environmental Notification Message (DENM). The IEEE and ETSI has set the default transfer rate of these messages to the same value of 6 Mbit/s [19]. The BSM is used in the DSRC standard while the CAM/DENM is used in the ITS-G5 standard [19].

2.1.3.1 BSM

The first part of the BSM is listed and contains information in the manner showed in Table 2.1.3.1 [24].

Type	Description	Size [byte]
DSRCmsgID	Data elements used in each message to define the Message type.	1
MsgCount	It can check the flow of consecutive messages having the same DSRCmsgID received from the same message sender .	1
TemporaryID	Represents a 4-byte temporary device identifier. When used in a mobile OBU device, this value is periodically changed to ensure anonymity	4
Dsecond	Represents two bytes of time information.	2
Latitude	Represents the geographic latitude of an object.	4
Longitude	Represents the geographic longitude of an object.	4
Elevation	Represents an altitude measured by the WGS84 coordinate system.	2
PositionAccuracy	Various quality parameters used to model the positioning accuracy for each given axis.	4
Speed	Represents the speed of the vehicle	2
Heading	The current direction value is expressed in units of 0.0125 degrees.	2
SteeringWheelAngle	Represents the current steering angle of the steering wheel	1
AccelerationSet4Way	It consists of three orthogonal directions of acceleration and yaw rate	7
BrakeSystemStatus	Represents a data element that records various control states related to braking of the vehicle.	2
VehicleSize	Represents the length and width of the vehicle.	3

The second part of a BSM contains optional information and is transmitted at events rather than at a steady frequency [25]. It generally contains information that is an amendment to the safety information in part one of the BSM, such as path history, path prediction and information about the vehicle status (brakes, light etc.) [25].

The generic BSM packet is structured in the way showcased in Figure 2.2 [19].

Type	PHY head	MAC head	LLC head	SNAP head	WSM head	BSM message	MAC trail	PHY trail
Size [byte]	5	26	3	5	11	~105	4	>1

Figure 2.2: Generic BSM structure with size of different headers.

The size of BSMs physical layer header (PHY head), MAC layer header (MAC head), Logical Link Control header (LLC head), Subnetwork Access Protocol header (SNAP head) and MAC trail are fixed at the sizes visualized in Figure 2.2 [19]. The WAVE short message header (WSM head) are commonly of a size of 11 bytes and the BSM message are on average the size of 105 bytes [19]. The physical layer trail (PHY trail) contains the tail bits and padding bits and is usually in the size of 6 to 293 bits [19]. The size of an average BSM is therefore about 160 bytes, to which security will add about 220 bytes and make the whole message approximately the size of 380 bytes [19]. In the SPDM dataset the average size of the BSM is 400 bytes, which, due to its approximation to the suggested average, is the value this project will be using in simulations and calculations hereinafter.

2.1.3.2 CAM and DENM

While the USA standard has BSM part 1 and BSM part 2 as time-triggered position and event driven message respectively, the European standard has CAM and DENM.

CAM is a time-triggered position message which is sent with a update rate of 1-10 Hz depending on the application [19]. The CAMs structured is showed in Table 2.1.3.2 [19].

Field	Description	Size [byte]
Header	Protocol version and ID of message and vehicle	6
Basic container	Position of vehicle based on Global Navigation Satellite System (GNSS), type of vehicle and timestamp from GNSS receiver	18
Basic vehicle container (High frequency)	Information about speed, heading, curvature, driving direction and the role of the vehicle. Every CAM contains this field	14
Basic vehicle container (Low frequency)	Information about the vehicle itself, path history up to 23 points of size 8 bytes each. Not included in all CAMs and maximum transmitted at every 500 ms	176
Special container	Included if the vehicle has special role and contains more precise information relevant to that role	1-4

The event driven message DENM has a different structure than CAM and this is displayed in Table 2.1.3.2 [19].

Field	Description	Size [byte]
Header	Protocol version and ID of message and vehicle	6
Management container	Information the detection of event, when the DENM was created, how often it should be transmitted,optional expiry time of event, unique ID and a field for termination of DENM transmissions	22
Situation container	Contains information of the type of the detected event	4
Location container	Contains position, heading and speed (if applicable) as well as path history of event with a resolution up to 10 points. Each point is approximately 8 bytes which yields its maximum size of 190 bytes	190
A la carte container	Conatins extra information about events when applicable	11

The generic packet structure of a CAM, which is applicable to DENM packets as well, is displayed in Figure 2.3.

Type	PHY head	MAC head	LLC head	SNAP head	BTP head	GN head	CAM data	MAC trail	PHY trail
Size [byte]	5	32	3	5	4	36	14(HF) 90(LF)	4	>1

Figure 2.3: Generic CAM structure with size of different headers.

The size of CAM physical layer header (PHY head), MAC layer header (MAC head), Logical Link Control header (LLC head), Subnetwork Access Protocol header (SNAP head), Basic Transport Protocol header (BTP head), GeoNetworking header (GN head) and MAC trail are fixed at the sizes visualized in Figure 2.3. The CAM data will have a different size depending of the nature of the CAM. If it only contains the High Frequency (HF) part it has a size of 14 bytes. If only the Low Frequency (LF) part is transmitted the CAM has a size of 90 bytes. If this where a DENM package instead the CAM head would be replaced with a DENM head and the size would 190 bytes at maximum. Lastly the PHY trail contains the tail bits and pad bits and is at least 6 bits long and at maximum 293 bits long [19]. With security the CAM will be about 326 bytes for HF CAM, about 402 bytes for LF CAM and the DENM would be at maximum about 500 bytes.

2.2 V2V communication evaluations and pilots

There have been several research projects on cooperative applications in Europe, *SAFESPOT SP 4 SCOVA - Cooperative systems applications vehicle based* tested V2V safety applications where one of the applications were a Frontal Collision Waring (FCW). The SAFESPOT project concluded that a FCW based on V2V communication where not improving traffic safety at 15 % penetration or below. However, at penetration levels above 15 % of all vehicles, improvements can be seen linearly up to 60 % increase in traffic safety. The trade off is worse traffic efficiency and higher amount of emissions [26]. Another project was DRIVE C2X which aimed to coordinate testing and evaluation of different cooperative application projects in Europe [27]. The function that the project found would have the biggest impact on vehicular safety was In-vehicle signage for speed limitations. With a high penetration of vehicles in Europe the function could potentially decrease fatalities with 15 % [27].

As mentioned earlier in this chapter, the 802.11p standard has been developed since 1999, however, the percentage of vehicles that have an installed device with the standard has been low [27]. To evaluate the system, several pilot programs have been deployed. The largest pilot program to date is the SPDM with more than 2800 vehicles [8]. The SPDM were conducted in the Ann Arbour area of South East Michigan during a year between October 2012 and October 2013. During the pilot were 29 Access Point (AP)s, called Roadside Equipment (RSE), placed in the north eastern parts of Ann Arbour. The RSE collected naturalistic data from all connected vehicles passing by. Meaning that a database with all messages received by a RSE is available to be used to evaluate the performance of the 802.11p system. This have partly been covered in [14] where the authors looked at different aspects of the channel in connection to intersections. There is also a dataset with all the transmitted BSM from the SPDM project. This dataset is based on every trip the vehicles made during the study.

2.3 Vehicular safety and risk assessment

Vehicular safety is commonly described as when a vehicle can avoid a accident by either comfort or discomfort. Furthermore, if a accident can not be avoided it is still possible to mitigate the effects of an accident. In [28] Brännström et al. suggest mitigating actions for accidents through steering or braking intervention. The choice of steering or braking intervention is depending on speed and pre-crash scenario. Brännström et al. claims that for most naturalistic vehicular speeds, a collision can be avoided comfortably by either brake or steer at least 1.5 s [28]. The SAFESPOT SCOVA project defines dangerous situations as when Time to Collision (TTC) is between one and five seconds for a cooperative FCW application [26].

2.3.1 Vehicular motion model

Two different linear models of a vehicles motion is the constant velocity and the constant acceleration. The first model assumes constant velocity the other one constant acceleration [29]. The Constant Velocity (CV) can be described as an object with starting position x_0 and a velocity v_0 that travels during a given time $t = t_1 - t_0$ will get a new position, x_1 described in (2.1).

$$x_i = x_{i-1} + v_{i-1}t,\ v_i = v_{i-1},\ i = 1, 2, ..., 50 \tag{2.1}$$

In Constant Acceleration (CA) the velocity is no longer constant, $v_i = v_{i-1} + a_{i-1}t$, where a_{i-1} is the constant acceleration. This results in (2.2).

$$x_i = x_{i-1} + v_{i-1}t + \frac{a_{i-1}t^2}{2},\ a_i = a_{i-1},\ i = 1, 2, ..., 50 \tag{2.2}$$

These two equations are sufficient in a one dimensional context, however, as vehicles are moving in a two dimensional context, a model for position is required as well. One common model of a vehicle in motion is the bicycle model [30]. This thesis will use a simplified and modified version based on (30) in [30]. It can be described by the state vector found in (2.4) where x_{i-1}, y_{i-1} are the previous longitude and latitude respectively and d_i represents the distance travelled during the time interval t. The velocity, v_{i-1}, and acceleration, a_{i-1} are assumed to be constant, with a heading ϕ_{i-1} and yaw rate ω_{i-1}. The main difference between this thesis equation with [30] equation is that this thesis assume that no measurement noise exist and the calculations is based on global geographical positions rather than a local positions.

$$d_i = v_{i-1}t + \frac{a_{i-1}t^2}{2} \tag{2.3}$$

$$i = 1, 2, ..., 50$$

$$\begin{bmatrix} \hat{x}_i \\ \hat{y}_i \\ \hat{v}_i \\ \hat{a}_i \\ \hat{\phi}_i \\ \hat{\omega}_i \end{bmatrix} = \begin{bmatrix} x_{i-1} + d_i \cos(\phi_{i-1}) \\ y_{i-1} + d_i \sin(\phi_{i-1}) \\ v_{i-1} + a_{i-1}t \\ a_{i-1} \\ \phi_{i-1} + \omega_{i-1}t \\ \omega_{i-1} \end{bmatrix} \tag{2.4}$$

2.3.2 Safety surrogate metrics

The results from (2.4) is used in vehicular decision making equations such as TTC or Enhanced Time to Collision (ETTC) [31]. TTC is the rate between the relative position, p_r between ego vehicle position, $\mathrm{ego}_{x,y}$ and the Principal Other Vehicle (POV) position, $\mathrm{pov}_{x,y}$, and the v_r, relative velocity between the two vehicles according to (2.5). To improve precision in the measurement, the relative acceleration, a_r is considered in the ETTC described in (2.6).

$$\mathrm{TTC} = -\frac{p_r}{v_r} = -\frac{\mathrm{ego}_{x,y} - \mathrm{pov}_{x,y}}{\mathrm{ego}_v - \mathrm{pov}_v} \tag{2.5}$$

$$\text{ETTC} = -\frac{v_r - \sqrt{v_r^2 - 2a_r p_r}}{a_r} \tag{2.6}$$

TTC and ETTC are both common metrics for rear-end collisions, however, more types of collision can occur in an intersection. Therefore, a more general risk assessment is required for this thesis. One common metric for Left turn opposite direction (LTOD) and other turn related pre-crash scenarios is Post-Encroachment Time (PET). PET measures the time from the first vehicle exits the area of conflict (t_2) to the time the second vehicle enters the area of conflict (t_1) [32]. This term can be used as well for vehicles moving in the same direction, usually this metric is then called Time Headway (TH).

$$\text{PET} = t_2 - t_1 \tag{2.7}$$

Worth noting is that PET is in its original form and is, therefore, not taking acceleration into account. Equation (2.7) is explained visually, in Figure 2.4, with a fabricated situation from naturalistic BSM data from the SPDM dataset. However, the PET calculation in Figure 2.4 is taking acceleration into account according to (2.4).

(a) t_1, first vehicle (red) leaving the intersecting area

(b) t_2, second vehicle (green) entering the intersecting area

(c) 5 seconds path trajectory for two intersecting vehicles

Figure 2.4: Example of a PET calculation

2.4 Vehicular scenario description

National Highway Traffic Safety Administration (NHTSA) mentions the potential of V2V and lists 37 potential scenarios that could benefit from V2V or other V2X solutions in [2]. Figure III-4 in [2] describes a detailed scenario description of scenarios where V2V can make an impact. [2] uses the scenario descriptions from the 2003 Unites States Department of Transportation (DOT) report [3] and highlights 11 scenarios that represents 70 % of all light vehicle crashed in the United States.

Table 2.1 lists 22 out of the 37 pre-crash scenarios from the Scenario Typology described in [3] that could be addressed by V2V [2]. These 22 scenarios corresponds to more than 80 % of all light vehicle crashes in the United States [2]. Out of these 22 scenarios 10 were selected as priority scenarios as they correspond to approximately

60 % of all light vehicle crashes. The green rows in the table are of particular interest in this thesis due to their occurrences at the location of the RSEs in the dataset. The different clustering in Table 2.1 is based on similarity in the different typologies. For example, The rear-end pre-crash typology category have five different typologies based on the action of the lead vehicle such as stopping (LVS), decelerating (LVD) and accelerating (LVA).

Scenario [3]	Typology [3]	% of all crashes in USA [2]	Rank in Comprehensive cost [2]	V2V application [2]	5GCAR use case class [33]
Control loss/no vehicle action	3	23,5	1	N/A	N/A
SCP at non-signal | Turn at non-signal | Turn Right at signal	30|31|28	14,9|0,3|0,3	2|18|19	Intersection Assistance	UCC1 & UCC2
Rear-end/ LVS|LVD|LVM|LVA| Striking Maneuver	26|25|24|23|22	10,8|4,4|3,8|0,2|0,9	3|8|9|21|16	FCW/ AEB	UCC2
Opposite direction/no maneuver & maneuver	21|20	10,8|1,3	4|13	DNPW/ LCA	UCC1 & UCC2
Running red light & stop sign	4|5	6,6|1,1	5|15	Traffic Control Device	N/A
Left Turn signal & non-signal	27|29	5,6|5,4	6|7	Left turn assist	UCC1
Changing lanes/same direction	18	3,1	10	DNPW/ LCA	UCC1

Table 2.1: List of the most severe crash scenarios that V2V can adress and its connection to 5GCAR

3
Method

This chapter explains how and why this thesis suggested solutions were designed. The method of this thesis follows a certain flow, illustrated in Figure 3.1. Each step of the method is explained in individual sections.

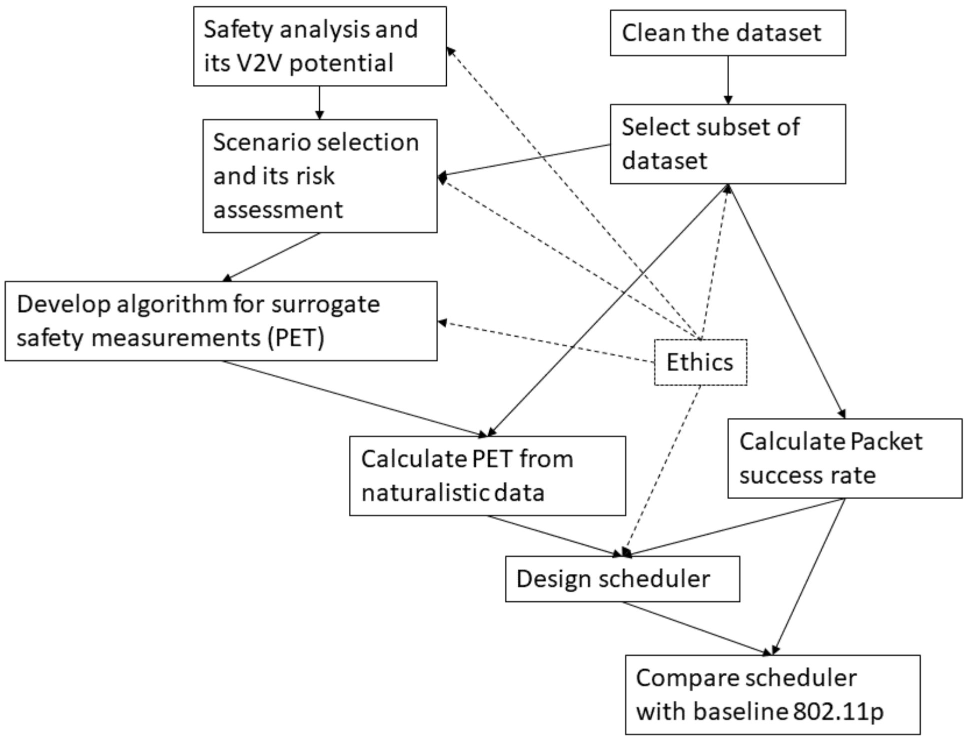


Figure 3.1: Flow chart of the steps followed in the method

3.1 Safety analysis and scenario selection

The first part of the safety analysis was to identify risks based on different intersections from the SPDM dataset without looking at the data itself. The first assumption was that national and regional crash databases had similar distribution of types of crashes as the intersections in the dataset. As seen in Table 2.1 and the Southeast Michigan Council of Governments (SEMCOG) crash map[1], this was a reasonable assumption. A deeper investigation in different pre-crash scenarios is described in the subsections below.

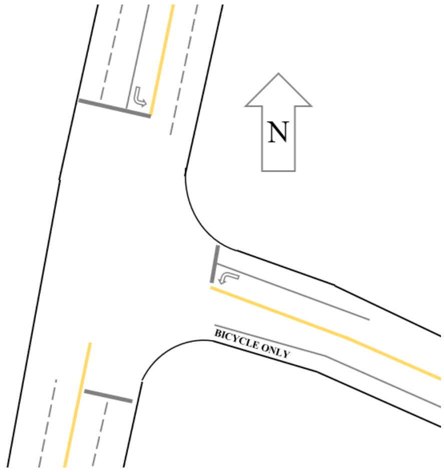
3.1.1 Safety analysis

The selection of scenarios continued after the initial overview of a number of different pre-crash scenarios in national and regional databases. The regional database from SEMCOG provided detailed maps of different intersections in the same area as the dataset in Ann Arbour. This helped to narrow down to potential intersections that were of interest. After looking at the SPDM data and the regional database, four intersections were finally chosen for further analysis in the subsection below.

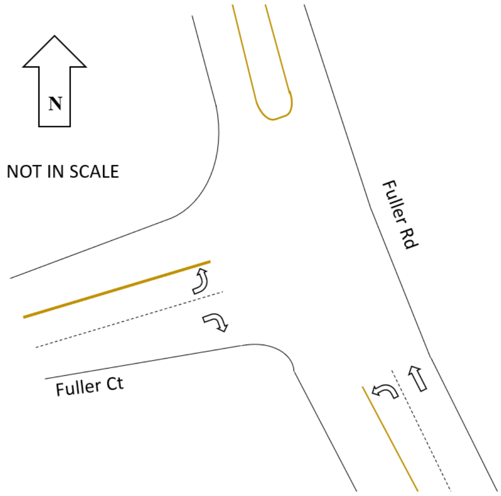
3.1.2 Possible scenario sites

To evaluate the potential of wireless communication, a couple of intersections in the SPDM have been evaluated from a risk assessment analysis perspective to see what type of crashes that can occur. The evaluated intersections can be seen in Figure 3.2. A brief overview of the SEMCOG crash database gave an overview of what type of crashes that have occurred at these intersections. The four intersections that have been evaluated were selected due to the fact that a LTOD is possible in these intersections.

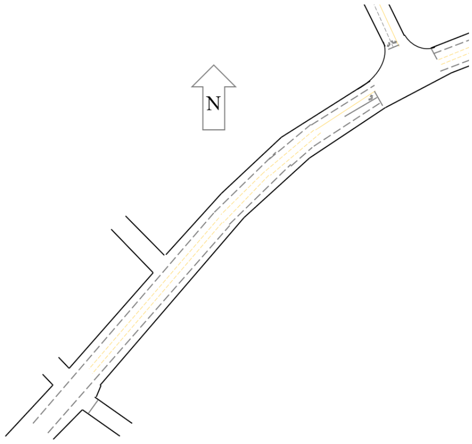
[1]https://maps.semcog.org/crashlocations/



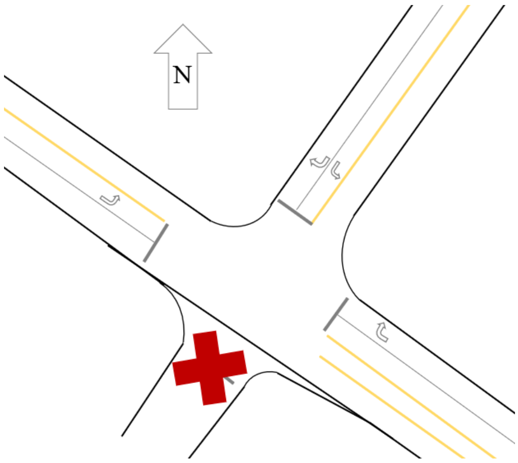
(a) Drawing of intersection between N. Main St. and Depot St.



(b) Drawing of the intersection between Fuller Rd. & Ct.



(c) Drawing of the the road segment of Plymouth Rd. near 2401 Plymouth Rd.



(d) Drawing of the intersection between Fuller Rd. & Hurdon High School

Figure 3.2: Drawings of four different intersections that was considered for the project

3.1.2.1 N Main St/Depot St, RSE #153

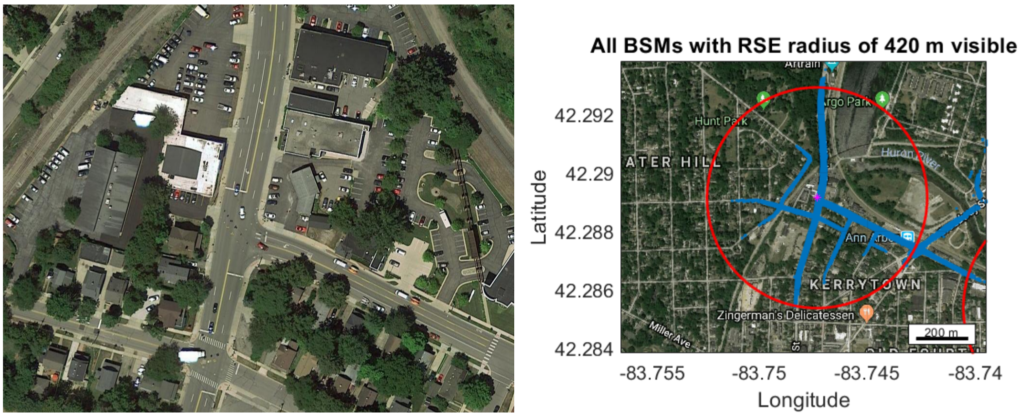


Figure 3.3: Satellite image of N Main St/Depot St, RSE #153

This intersection was selected because it was one of the few intersections with a RSE that have a limited geographical area where no other RSE can have received the same BSMs since there is no overlap between the RSEs. This is illustrated in Figure 3.3. This intersection have multiple lanes incoming from all three directions while the lanes from north and east only have one left turn lane. In total there are 12 lanes incoming and outgoing from the intersection. All scenarios described in Table 2.1 can be considered except the non-signaled ones. The SEMCOG Crash map indicate that Rear-end/LVS and LTS is the most common historical crash at this intersection.

3.1.2.2 Fuller Rd/Fuller Ct RSE #173

This intersection, that is visible in Figure 3.4, was selected due to the low traffic complexity but still with at least one left-turn possibility. In this intersection there are a main road (Fuller Rd) and a secondary road (Fuller Ct) that meets in a signaled intersection. From west and south, there are two separate lanes into the intersection, one for only left turn and and the other one for right turn/straight path, see Figure 3.2b. This means all typology numbers in Table 2.1 for signaled intersections are relevant except SCP.

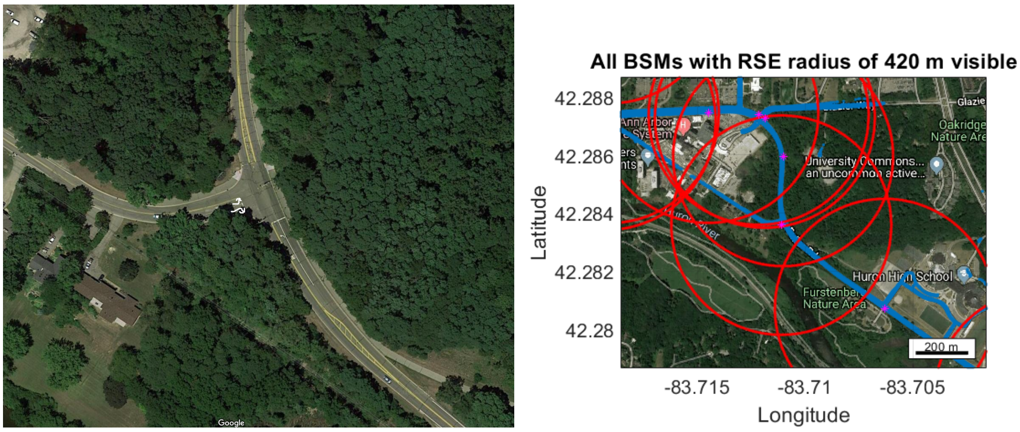


Figure 3.4: Satellite image of Fuller Rd/Fuller Ct RSE #173

3.1.2.3 2401 Plymouth Rd, RSE #159

This intersection, shown in Figure 3.5, was selected since it can be considered less complex than the other two and since it has only one RSE that is within range from its position. Therefore, making it possible to exclude BSM from other RSE due to geographical factors. The primary intersection for the RSE would then be excluded.

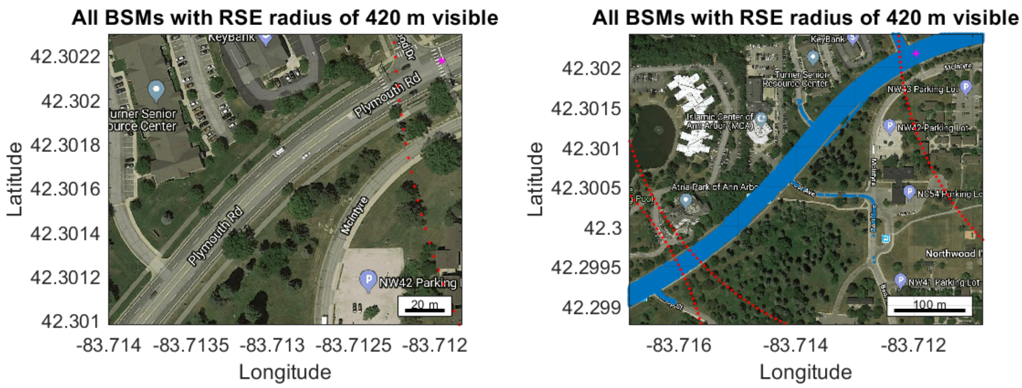


Figure 3.5: Satellite image of 2401 Plymouth Rd, RSE #159

This intersection consists of two main areas of pre-crash scenarios, found in Table 2.1, such as rear-end (all different kinds are possible, typology # 22-26) and lane change (typology # 18). However, from the parking there are two scenarios as well, Right & Left turn at non-signal junction (typology # 29 & 31).

3.1.2.4 Fuller Rd/Hurdon High school, RSE #175

This intersection, seen in Figure 3.6, has been selected due to the type of traffic typically seen at this site. The intersection is a four way signaled intersection where the main road is the north west/south east road, Fuller Rd, while the north east road leads to a high school making it possible to get high traffic volumes two times per day when students start and ends school. The fourth road leads to a small parking lot. When looking at the recorded high traffic volumes in the *BSM_P1.csv* dataset from April 2013, the parking lot to the south west was not accessed by the vehicles in the dataset at all. Because of this it is disregarded and only the three other paths are considered, which yields eight different pre-crash scenarios.

The typology of the pre-crash scenarios in this intersection, excluding the parking lot, is: All five read-end scenarios (typology #22-25), Turn right and turn left (typology #27-28) at signaled intersections.

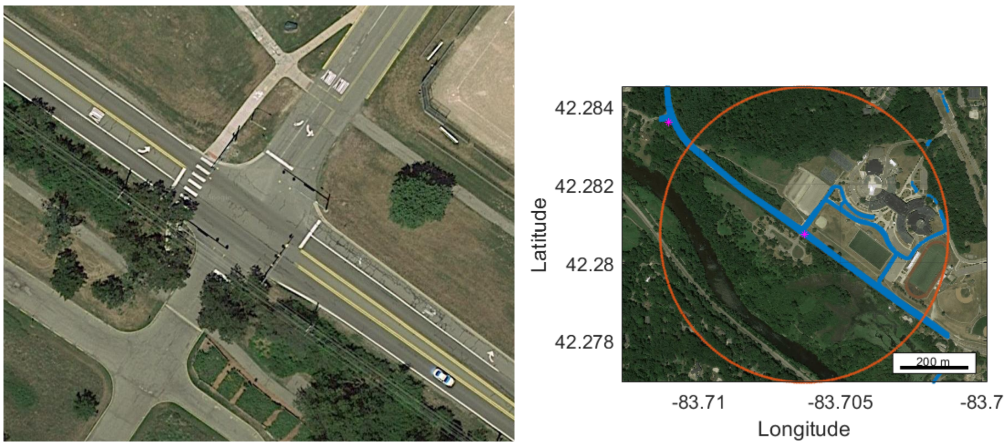


Figure 3.6: Satellite image of Fuller Rd/Hurdon High school, RSE #175

3.1.3 Final scenario selection

The chosen intersection for this thesis were selected by looking at the collected data in the publicly available dataset called *RSE_BSM.csv* and investigate each intersection more thoroughly to identify a left-turn. Simplicity in the risk assessment and number of connected vehicles at the same time were also evaluated. The chosen intersection was the intersection at Fuller Rd. & Hurdon High-school with RSE #175. It was chosen with the adjustment that the thesis regards the path to south west as being close or unused to simplify the risk assessment, see Figure 3.7.

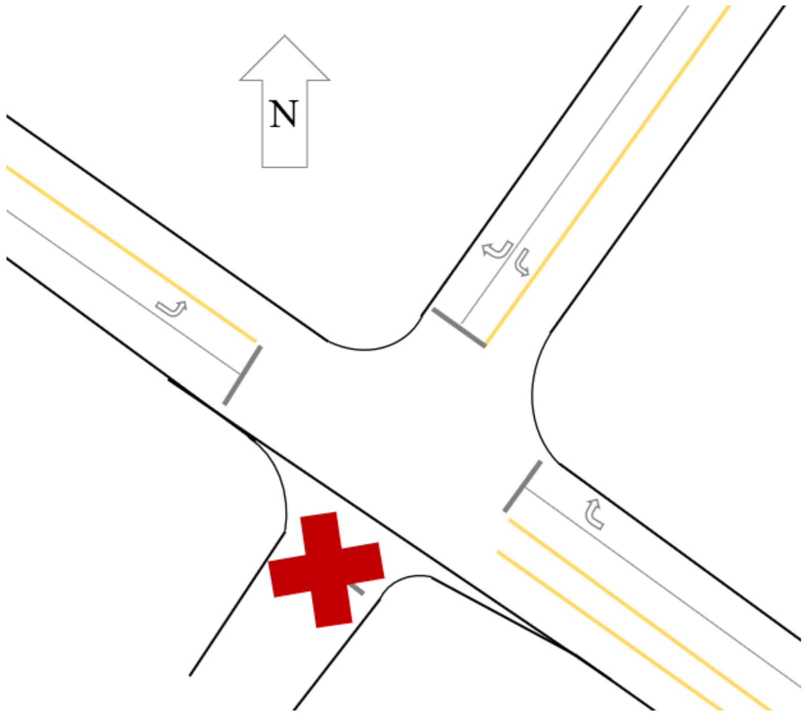


Figure 3.7: Assumed intersection drawing of RSE #175

3.2 Safety Pilot Model Deployment dataset

The SPDM dataset is divided into subsets of datasets were different types of information are stored. The two most important datasets for this thesis are the two that contains BSMs. The first one, henceforth called the transmitting dataset, contains all BSMs for every trip, except a random number of BSMs up to 8 %, at the beginning and end of each trip. These are removed due to privacy concerns. In the second one, henceforth called the receiving dataset, is where all BSM that have been received by a specific receiver are stored. Within this dataset is a subset containing each RSE and their collected data but also of a few vehicles which acted as receivers as well. These two datasets have a publicly available subset of data that the thesis initially retrieved to get familiarized with the data. These subsets were more anonymous than initially expected as it was not possible to identify which RSE corresponded to which dataset of received BSMs when the key *RxDevice* was used. The public subset was also missing timestamps, which made it impossible to replay the actual situations in the simulations. Due to these limitations a direct data request to University of Michigan was necessary to retrieve the sought out information.

3.2.1 Data request to University of Michigan

The data request to University of Michigan asked for both the dataset with complete trip data, called the transmitting dataset, and the data of what the RSEs have listened to during same time period. This is called the receiving dataset. Both the transmitting dataset and the receiving dataset were limited to a geographical area of a square centered at the RSE called ”175” (were each side of the square has a length of 1 200 meters). Both datasets have all metrics in SI units except the timestamp, which had the key *Gentime*. To be able to synchronize events in both dataset a common form of the timestamp was needed. According to [8], to get the time in a format as elapsed seconds since 2004-01-01 00:00:00, the *Gentime* needs to divide by 1 000 000 and then subtract by an offset of 35 seconds.

3.2.2 Selections of subparts of dataset

To make a relevant selection of data the thesis assumed that a RSE is in a system of RSEs, which can be seen as cells in a combined cellular system. For the purpose of this thesis, the thesis assume that the cell is a perfect circle of 350 meters in diameter in accordance to Figure 3.8.

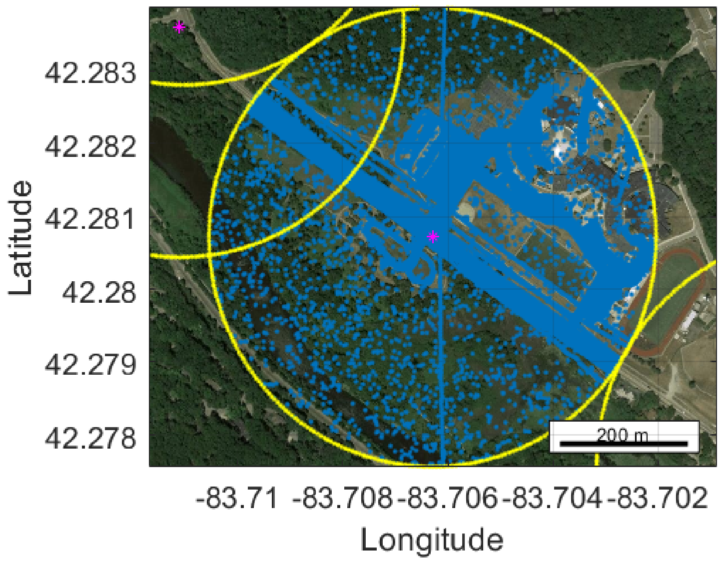


Figure 3.8: RSE 175 and its surrounding RSEs with their 350 meter radius cell division. The blue dots are all BSM from the transmitting dataset within the circle.

In Figure 3.8 it is clear that there was a percentage of the data that had inaccurate Global Positioning System (GPS) coordinates. To counter this issue, a *KML*-file with coordinates of only the road and parking segments within 350 meters from the RSE was created in Google Earth Pro. This was done to remove the outliers and the result of it can be found in Figure 3.9.

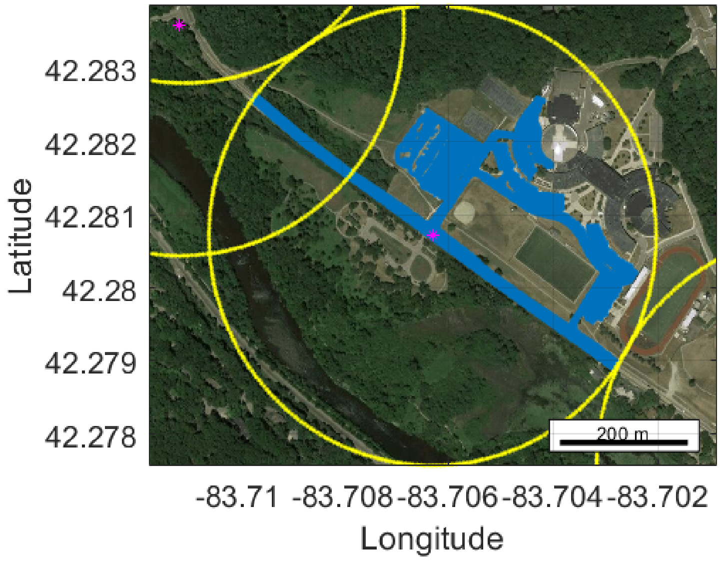


Figure 3.9: RSE 175 and its surrounding RSEs with their 350 meter radius cell division. The blue dots are all BSMs from the transmitting dataset without the removed outliers.

The majority of traffic occurrences in the dataset were scarce. This is also confirmed in Figure 27 in [14] were more than 75 % of the time, in rush hour, there were either 0 or 1 vehicles within the RSEs cell area.

3.3 Calculation of surrogate safety measurements

To identify the risk two vehicles are facing in a traffic situation several risk assessments needs to be calculated. The surrogate safety measurement is selected based of the scenario selection. As mentioned in the previous section, an intersection with four paths has been selected but the thesis assumes, for simplicity, that the path from south west is not used. This means that the thesis will not have SCP pre-crash scenarios. However, many of the other intersection related scenarios are applicable. Since this thesis is dealing with intersections, the normal Time to Collision (TTC) and Enhanced Time to Collision (ETTC) can not be applicable for turning vehicles. Therefore, PET is used as a metric. Worth noting is that a PET is equal to TH when the Principal Other Vehicle (POV) has the same heading and is in front of the ego vehicle.

The first step to calculate the surrogate safety measurements was to identify if vehicles were in the scenario at same time instance. To identify this the thesis used an interval of 0.1 s as the time instances as all vehicles have an updating frequency of 10 Hz for the BSMs. For each time instance with a minimum of two BSM a risk analysis was made, of which method is described in the subsection below. The risk assessment is done with a time window of 5 seconds. This is partly due to the fact that a warning system and a intervention system could act in a pre-crash time frame of 1.5 to 5 seconds. It is also done partly since the next message is expected 0.1 seconds later when a new prediction is made by the vehicles. Due to both privacy concerns and for simplicity of the RSE, nothing about the vehicles is stored in the RSE. Every time instance is, therefore, memoryless and this is also why no filtering such as Kalman filtering is made.

The PET calculations were made by looping over all vehicles at the same time instances and evaluate each pair of vehicles. To avoid excessive calculations a couple of basic calculations and assumptions were made:

1. Since all BSM are anonymous, and does not contain information about the vehicles, the thesis set the size of all vehicles to be the same. The chosen size was the one of Volvo Cars XC90 of width and length of 2008 mm and 4950 mm respectively.

2. Some of the calculations are based on geographical coordinates and are, therefore, SI conversions based on Table 8 in [34]. These calculations converts geographical degrees to meters, $1° = 60 \cdot 1852$ m.

3. Some issues with duplicates in the dataset exists and therefore a check is made to investigate if the vehicles are overlapping. If there is overlapping a duplicate/crash and PET = 0 is assumed.

4. The thesis did a quick TH calculation and set PET $= \infty$ if TH > 10 s. This is to speed up processing time.

5. The thesis checked if the POV is behind by looking at the direction (az) to the POV, az $> 100°$, then PET $= \infty$.

6. If the POV is within $< 15°$, measuring both from center to center and front of ego to back of the POV, in front of the POV the TH is calculated instead of a full PET calculation. A ETTC calculation can be done in this sequence according to (2.6).

If none of the assumptions above are fulfilled, an enhanced PET calculation is done. This is done by predicting the paths of the two vehicles for 5 seconds, with an update step of 0.1 s, by using (2.4). For every time step, a bounding box of the vehicle is calculated and then merged to one long path as seen in Figure 2.4c. When the paths are defined, MATLAB internal function *intersect* is used to identify the overlapping area and at what times it occurs. These times are used to calculate PET according to (2.7).

The two self-developed functions *pet_gps_calc* and *car_points* can be found in Appendix A.

3.4 Prioritization for the need of communication

After all time instances with a minimum of two vehicles are processed according to the PET calculations described in the section above, they are placed in a risk matrix where each time instance represent one object that contain the following:

1. All vehicles BSMs of that time instance.
2. The distance for those vehicles to the intersection.
3. Each vehicles PET calculation to all the other vehicles of that time instance.

The generated risk matrix is thereafter processed based on the need for communication. This is done by looking at the lowest PET value each vehicle has in its risk matrix and assign priority 1-4 based on this value. The priority is based on need of reliability (numerous transmissions of same BSM) and time requirement for updated information (frequency of transmissions of new BSMs) to calculate new kinematics. This priority will be described in the next section.

In a read-end case, only the following vehicle gets a PET. Since the following vehicle needs information from the lead vehicle, the lead vehicle will be assigned with this PET as well. This will happen if the lead vehicle has no other PET that is lower than the following vehicles PET, since the lead vehicle would broadcast at a higher communication priority anyway if this were the case.

3.5 Delay requirements for wireless communication in cooperative applications

In order to know the delay requirements for wireless communication, i.e. how long a message can be delayed with preserved safety, the maximum time delay for a message needs to be found. This is the delay for a message to be received from a normal to a critical point in terms of safety. The first assumption the thesis make is that the cell is surrounded by other cells which have an overlap large enough to avoid complex edge cases. The second assumption the thesis make is that safety will be preserved if at least the same amount of messages is received as in the baseline's datasets. To calculate this the thesis initially measured the amount of messages the RSE has received in comparison with how many messages that was transmitted. This generated a baseline PSR that can be compared with simulated values described later in this chapter.

The thesis can assume that a vehicle with a low PET have a high need for communication, both in terms of reliability and update frequency for kinematic calculations. Therefore a low threshold is set to PET ≤ 2 s, which will get highest priority (see Table 3.1 for a detailed list of priority levels). This is to get a 0.5 second margin in which an automatic emergency system can act to avoid an crash in 99.999 % of all different vehicle speeds found in the SPDM dataset within 350 meters from the selected RSE. This can be seen in Figure 3.10. This assumes both braking and steering actions can be done by the vehicles automatic emergency system. The response time of minimum 1.5 s is obtained from [28]. The highest priority level will need to have a very high certainty of a successful transmission and therefore the 5GCAR definition of a very high reliability of 99.999 % will be used in this thesis [6].

PET	Priority	No. of transmissions	Frequency
≤ 2 s	1	4	120 ms
$2 <$ & ≤ 5 s	2	3	200 ms
$5 <$ & ≤ 10 s	3	2	500 ms
< 10 s	4	1	500 ms

Table 3.1: PET Priority levels and their corresponding amount of transmissions of a single BSM and the frequency of how often an updated BSM will be transmitted.

The second highest priority will be given to vehicles that are in a danger zone but not in imminent danger since they have PETs between 2 and 5 seconds. The third priority level consist of vehicles that have PET values between 5 and 10 seconds but are, therefore, not within a warning range. The fourth type is all other vehicles that do not have a PET and therefore lack need for communication. These will get a high delay (around 2-3 seconds) before achieving high certainty of PSR at 99.9 %.

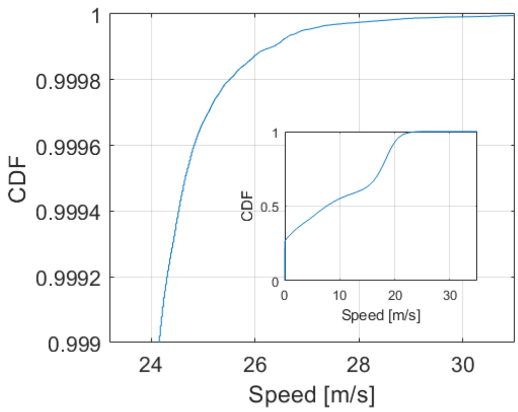
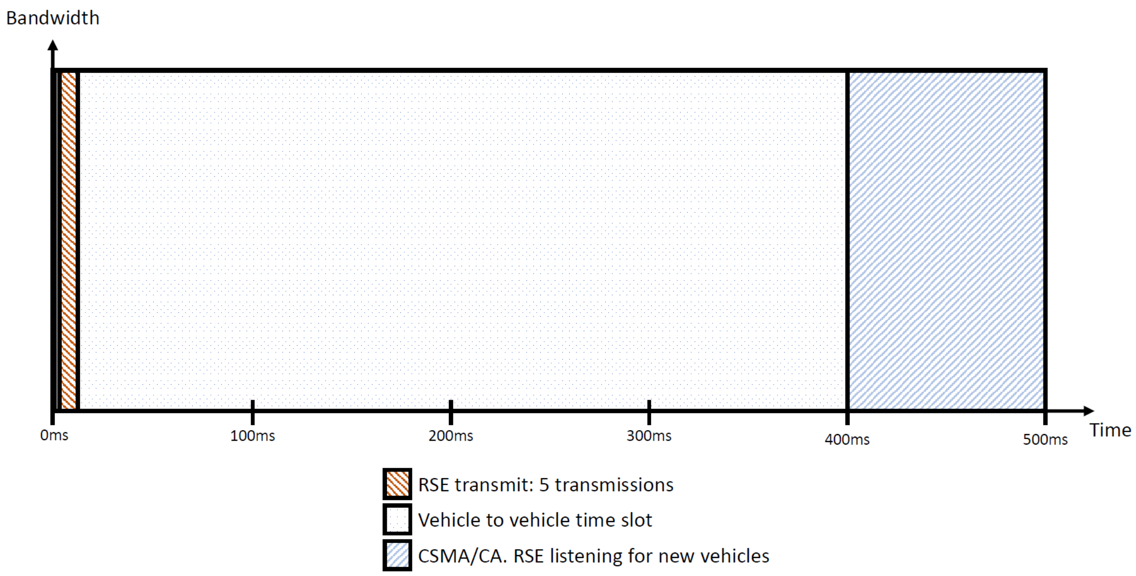


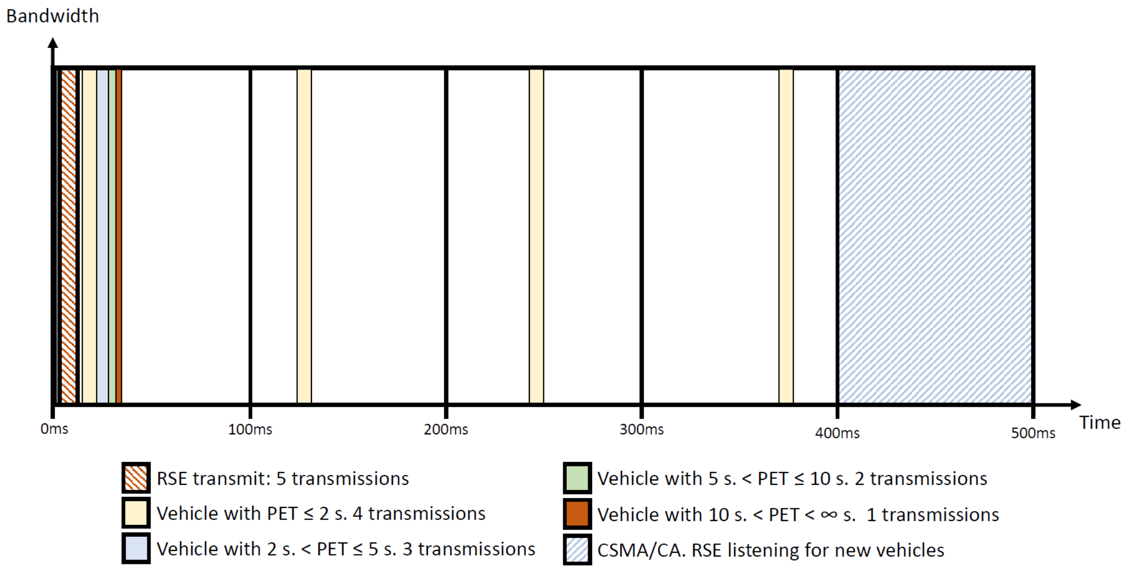
Figure 3.10: CDF of vehicle speeds in the transmitting dataset

3.6 Channel scheduling in time domain

The structure of the TDMA channel can be divided into three different instances. The first one is the RSE Transmit, in which the RSE transmits the scheduling schematics and time synchronization to the vehicles within its range. Since the TDMA channel scheduling is initiated with this instance's procedure the first message the RSE will not transmit anything else than the time synchronization. The next instance is the vehicle to vehicle time slot, which internal scheduling of vehicles is based on the urgency to communicate. The BSMs collected by the RSE is used to calculate the PET between intersecting vehicles where the vehicle with lowest PET is allowed to communicate first and with the most repetitions in the scheduling. The scheduling prioritization is done according to the method described in Section 3.5. During this instance the RSE is continuously listening to the transmission between the scheduled vehicles to stay updated with their latest BSM. The third instances is the CSMA period, where the RSE listens to any newly arrived vehicles which wishes to join the TDMA scheduled channel. The BSMs from the new cars and the BSMs transmitted during the vehicle to vehicle time slot instance are then used to calculate a new vehicle to vehicle time slot scheme, which is transmitted to all the vehicles in the next RSE transmit. The scheduling of the channel as well as the suggested structure of the vehicle to vehicle time slot is illustrated in Figure 3.11a and 3.11b respectively.



(a) TDMA channel scheduling



(b) Suggested vehicle to vehicle scheduling with repetition of the pairs with highest urgency to communicate

Figure 3.11: Suggested TDMA Scheduling window

Within the vehicle to vehicle scheduling time slot, portrayed in Figure 3.11b, the repetitive scheduling repeats the most prioritized vehicles four times at every consecutive 0.12 seconds. This means that it will transmit four different BSM, four times each, in total 16 messages. Since the vehicles generate a new BSM every 100 ms the four transmissions of a BSM needs to occur within 100 ms from when the BSM was generated. The succeeding level of prioritization will have three repetitions of the same BSM but only two transmissions of different BSMs spaced out by 200 ms, as demonstrated in Figure 3.11. The next level, with PETs between 5 and 10 seconds, will have 2 transmission of a BSM but not more than one BSM. The final level, which is without urgent need for communication, will get one slot for one BSM during the entire scheduling block.

3.7 Estimating wireless channel characteristics

To construct a ”real-life” wireless communications scenario in a simulated environment, relevant data was retrieved from the SPDM dataset and inspiration and pointers were retrieved from Katrin Sjöbergs thesis *Medium access control for vehicular ad hoc networks* [19].

3.7.1 Time delay of a BSM

When estimating a naturalistic TDMA system the time of which each BSM delay the channel width is a important parameter. The time it takes for a BSM to travel between the transmitters and the receivers MAC layers was estimated with help from Katrin Sjöbergs PhD thesis [19].

3.7.1.1 RSE to vehicle time delay

The required time for a RSE to receive, decipher and transmit to a node unit and the time it takes for that node unit to interpret the RSE-message is called MAC-to-MAC delay. This MAC-to-MAC delay is, in turn, divided into three shorter intervals which notations and roles are the following:

1. τ_{ca} - The channel access delay, which is the time it takes for the RSE to interpret the collected input.
2. τ_t - The transmission delay, which is the sum of the transmission time for the RSE message to reach the node unit and the propagation delay.
3. τ_{dec} - The decoding delay, which is the time it takes for the node unit to decode the received message and deliver it to a higher layer.

The channel access delay (τ_{ca}) and the decoding delay (τ_{dec}) is set to a fixed estimated value of negligible size. This is motivated by the nature of a TDMA-channel and by the fact that the system only experiences a low amount of transmitters within radio range. However, the access and decoding delay time is presumed to increase if the number of transmitting vehicles within radio range would increase. The transmission delay (τ_t) is calculated by using the results from the transmission time (3.1) and the propagation delay (3.2) in (3.3):

$$T_t = \frac{\text{Size of RSE packet}}{\text{Data rate}} \tag{3.1}$$

$$p_t = \frac{\text{Distance between transmitter and receiver}}{\text{Speed of light}} \tag{3.2}$$

$$\tau_t = T_t + p_t \tag{3.3}$$

These all add up to the MAC-to-MAC delay (τ_{MM}) in accordance with (3.4)

$$\tau_{MM} = \tau_{ca} + \tau_t + \tau_{dec} \tag{3.4}$$

The RSEs and each vehicles τ_{MM} are simulated in MATLAB based on BSM position data from the SPDM dataset and estimations from Sjöbergs PhD thesis [19].
As the IEEE 802.11p is using guard interval of 1.6 μs as a way to prevent interference between the BSMs this should be added to the end of every BSMs τ_{MM} as well [19]

3.7.1.2 Vehicle to vehicle transmission delay

The time delay between vehicles which needs to be allocated on the channel is only the transmission delay with added guard interval. While the transmission delay is calculated using (3.3) the guard interval is estimated from Sjöbergs PhD thesis [19]. The sum of the transmission delay and the guard time makes up the total time needed to be allocated on the channel for a single BSM transmission.

3.7.2 IEEE 802.11p channel usage

The vehicles in the SPDM project, which used the IEEE 802.11p protocol, transmitted their BSMs at a frequency of 10 Hz [8]. This makes it possible to calculate the total number of transmitted BSMs during a time interval, T_{CSMA}, through (3.5).

$$N_{BSMs,T_{CSMA}} = N \times f \times T_{CSMA} \tag{3.5}$$

The number of vehicles (N) is multiplied with the transmissions frequency (f) and the desired time interval (T_{CSMA}) in (3.5), which yields the total number of transmitted BSMs during the time interval ($N_{BSMs,T_{CSMA}}$). This total number of BSMs is used as the baseline for comparing the performance and channel usage of the custom designed TDMA system.

3.7.3 Estimating probability of PSR with SPDM dataset

To estimate the PSR from the naturalistic data, the thesis simply divided the amount of received BSM with the amount of transmitted BSM during their overlapping time period. However, as seen in Figure 3.12, this indicated faulty results since the RSE were not receiving large parts of the time. Therefore, data within the times of day 16 to 26 and day 39 to 45 were selected to get a more realistic result.

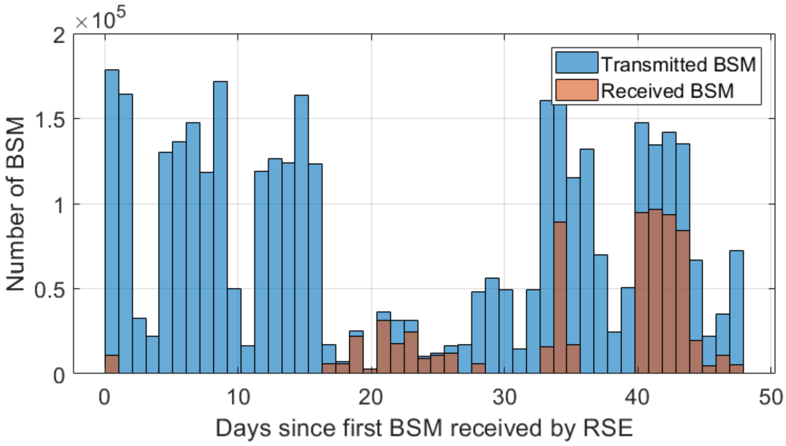


Figure 3.12: Histogram of all transmitted and received BSMs within the time limits of the receiving dataset.

3.8 Calculating probability of successful transmissions

To be able to compare each simulations result their probability of a successfully transmission are calculated. The chosen metric for illustrating this is Package Success Rate (PSR). The PSR is the probability of a package arriving at the receiver. As the vehicles generate a new BSM every 100 ms the PSR of a single burst of a unique BSM and multiple, different, transmissions of these bursts BSMs needs to be separated. For a single burst of a unique BSM the PSR after n transmissions, i.e. the size of the burst, within 100 ms is notated as PSR_n and is calculated using (3.6).

$$\text{PSR}_n = 1 - (1 - \text{PSR})^n \tag{3.6}$$

The number of BSMs within the burst and the number bursts is notated as $\text{PSR}_{N,n}$. To find the PSR of $\text{PSR}_{N,n}$ (3.7) is used

$$\text{PSR}_{N,n} = 1 - (1 - \text{PSR}_n)^N \tag{3.7}$$

The probability that a vehicle has successfully transmitted one or more BSMs within the 400 ms vehicle to vehicle communication time slot is notated $PSR_{N,n}$ in (3.7).

The probability of successful communications between vehicles within 500 ms is achieved by combining (3.6) and (3.7), which results in (3.8)

$$\mathrm{PSR}_{N,n} = 1 - ((1 - \mathrm{PSR})^n)^N \tag{3.8}$$

3.9 Ethical and Sustainable considerations

As a part of this thesis a workshop to identify which Sustainable Development Goals (SDG) this thesis contributes to were held. The tool SDG Impact Assessment Tool were used to identify which goals and targets the thesis affects. It is clearly stated in the World Health Organization (WHO) annual report for road accidents that death by road accident is one of the major causes for death in the world, which this thesis aims to be a part of solving (SDG 3.6) [1]. To further investigate how this thesis affects different sustainability issues such as environment and ethics, a workshop were conducted where discussions about the global goals were conducted. One ethical aspect off this project is the personal integrity when monitoring and centralizing vehicles road movements. There is a clear risk of using this type of technology to surveillance individual. One of the design decision made in the thesis were, therefore, to make the centralized risk assessment memoryless, meaning the RSE will not store old BSMs to make better path predictions. The trade-off of this was a slightly worse path prediction which affected the risk assessment. However, this is manageable since the next BSM should arrive within the time needed to identify a new risk. It is worth considering the fact that by reducing communication between vehicles, in an already adequately working system such as the 802.11p, the thesis might actually make safety worse.

Furthermore, during the workshop four other targets were the thesis could contribute to were identified. Under SDG 9 both target 9.1 and 9.5, seen in Figure 3.13, can be contributed to since this thesis is a part of Chalmers work within 5GCAR. 5GCAR is a EU funded research project that aims to achieve sustainable infrastructure for vehicles (SDG 9.1) and enhance/upgrade current communication protocols (SDG 9.5) [33]. By using public data and co-working with University of Michigan to improve the use and understanding of cooperative applications for vehicles the thesis contribute to SDG 17.6, seen in Figure 3.13. Finally, SDG 11.2 is contributed to since the thesis aims to develop vehicle communication which can be applied in commercial vehicles used in public transportation and not only light vehicles. By making vehicle communication safer and more reliable, more people would be keen to use public transportation such as buses. All five targets mentioned can be seen in Figure 3.13.

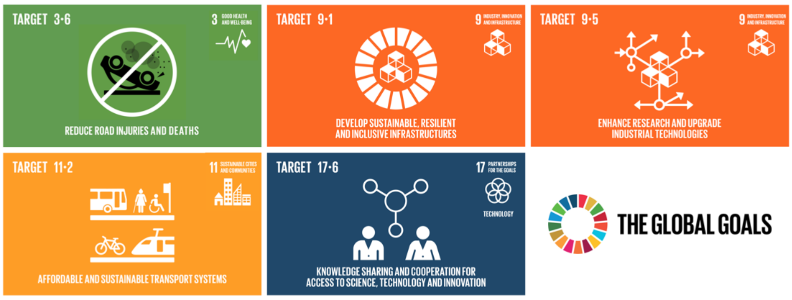


Figure 3.13: Targets that this thesis contributes to direct or indirect. These images are accessed as *CC BY-SA 3.0* from Project Everyone.

3.10 Software tools

Picking out the relevant data was done with the help of *MATLAB* and *Microsoft Excel*, which where chosen on the authors expertise.

3.11 Thesis writing

The thesis was constructed in *OVERLEAF*

4

Results

In this chapter the results gained from both traffic safety and communication scheduling will be presented, starting with the data analysis and cleaning, continuing with the risk assessment and safety requirements for communication to finally present the results of the communication scheduling.

4.1 Comparison of transmitting and receiving datasets

When the data from the dataset, including all transmitted BSMs, was cleaned from the outlier points outside the roads, the remaining parts, seen in Figure 3.9, were 79.8031 % of the total dataset of 14 468 098 BSMs within the 350 meter cell.

Furthermore, to identify overlap in time between the receiving dataset and the transmitting dataset were the same BSM could be found, all data after 2013-01-22 was removed. This resulted in 2 914 468 BSMs remaining during an overlapping period of 47.0520 days. These BSMs were used for the PET calculation. However, for the calculations of channel estimation, all days with no or low amount of receiving data in comparison with transmitting data were removed to get a fair comparison. The remaining days of data were day 16 to 26 and day 39 to day 45 seen in Figure 3.12. The final overlap was based on the parameter called *TxDevice* where it was identified that the receiving dataset only had 330 vehicles. Removing all other vehicles, the total number of remaining BSMs were 649 643 for the channel estimation calculation.

4.2 Surrogate Safety Measurement

In the transmitting dataset, within the same time period as in the receiving dataset, there was a total of 404 224 time instances with minimum of two vehicles during the same time period. This generated 2 328 849 risk assessments of which 1.7992 % had an PET that had a value between zero and infinity. 98.9046 % of the PET values of interest were above 0 seconds and 1.0954 % below, the reason for values below 0 was probably due to noisy measurements in the position. All the negative PET values was measured in the parking lot. The histogram of the PET values can be found in Figure 4.1. The maximum amount of vehicles within same time instance was 7 vehicles.

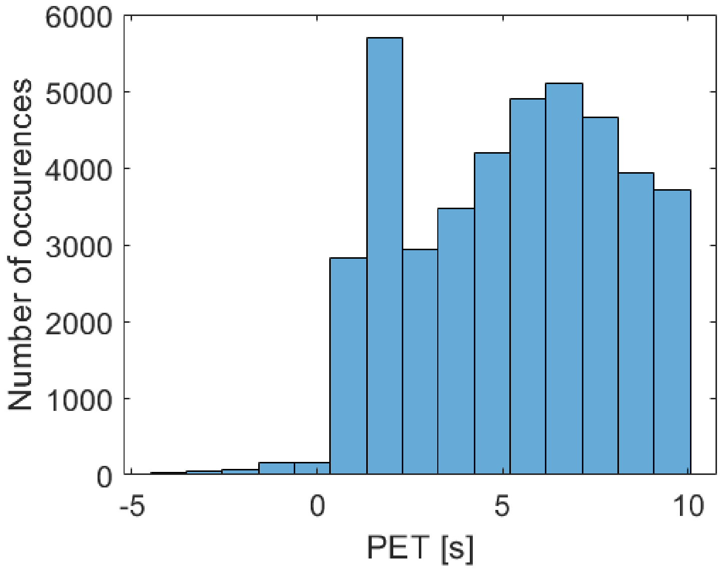


Figure 4.1: Histogram of the PET values from the transmitting dataset with respect to occurrences.

4.3 Channel delay of transmitted BSM

To estimate the channel usage of the aforementioned systems the time of which each packet occupies the channel is estimated as well. The result of calculations with the naturalistic data from the SPDM dataset by (3.3) and (3.4) is displayed in Table 4.1. As the channel access delay (τ_{ca}) is set to a negligible value the transmission delay and the MAC to MAC delay are the same.

Distance between transmitter and receiver [m]	MAC to MAC delay [ms]
5	0.57495
50	0.57512
100	0.57528
150	0.57545
200	0.57561
250	0.57578
300	0.57595
350	0.57611

Table 4.1: Relationship between distance from RSE and transmission delay.

The results presented in Table 4.1 indicate that the distance between the transmitter and receiver does not change the MAC to MAC delay considerably.

4.4 Baseline - 802.11p empirical

The result of the baselines channel usage is retrieved from collected naturalistic transmission data of transmitted BSMs from the SPDM dataset. The transmission data from the SPDM dataset is retrieved between 2012-12-06 10:46:55 Eastern Daylight time (EDT) and 2013-01-22 11:00:16 EDT, of which a small demonstrative sample with 6 vehicles is showed in Figure 4.2.

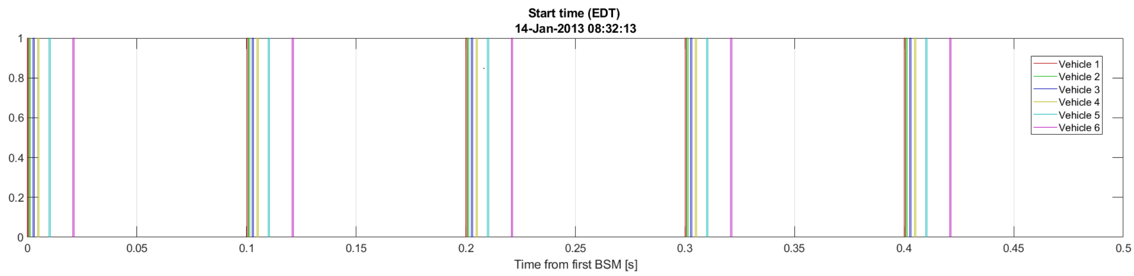


Figure 4.2: Sample of CSMA/Baseline channel of naturalistic transmissions from the dataset. The width of the pillars in the figure represents the MAC-to-MAC delay during the transmission

In Figure 4.2, the total number of transmitted BSMs, successful or not, is plotted with respect to the time interval from which they were transmitted. The BSMs are transmitted according to the literature, with a frequency of 10 Hz. As can be seen, none of the transmissions in Figure 4.2 encountered congestion.

4.5 Channel PSR based on SPDM dataset

Only 81.49 % of all BSMs in the transmitting dataset were in the receiving dataset during the selected time period. This means that the RSE received on average 81.49 % of all the BSM during the selected time period. However, worth noting is that out of all BSMs in the receiving dataset, 99.51 % of them could be found in the transmitting dataset. This means that there is a small percentage of outliers in the receiving dataset, which are neglected due to their low quantity. Nevertheless, the percentage of received BSM with respect to distance to the RSE is visualized with a 10 meter binned histogram in Figure 4.4. This is to illustrate how the PSR changes over distance from the RSE. This is also displayed as a table in Table 4.2. As seen in Table 4.2 and in Figure 4.3, PSR decreases the further away from the RSE the vehicle is.

Max distance in bin to RSE	Number of transmitted BSM	PSR
10	12216	90.52 %
20	18391	86.07 %
30	32690	83.74 %
40	26701	90.85 %
50	17783	86.77 %
60	16048	86.83 %
70	14982	84.97 %
80	15902	86.17 %
90	15180	85.90 %
100	14767	85.00 %
110	14233	84.80 %
120	23112	87.89 %
130	25365	89.66 %
140	18264	85.92 %
150	17311	83.50 %
160	21623	84.67 %
170	18226	79.39 %
180	18365	84.40 %
190	15110	79.07 %
200	16876	80.32 %
210	17124	80.21 %
220	19058	75.08 %
230	39348	76.48 %
240	29716	83.79 %
250	19101	80.47 %
260	21012	80.14 %
270	22867	75.46 %
280	18367	82.40 %
290	13948	78.99 %
300	13871	76.35 %
310	13203	72.21 %
320	14170	70.00 %
330	11831	65.81 %
340	11515	61.15 %
350	11367	61.04 %

Table 4.2: Relationship between distance from RSE and PSR, visulized in Figure 4.3.

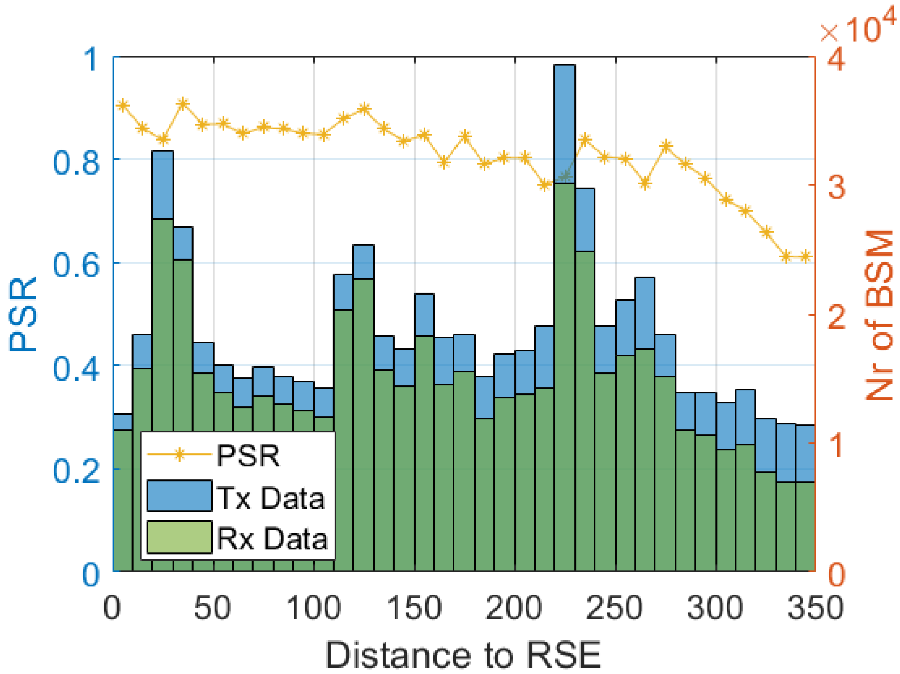


Figure 4.3: Histogram with 10 meter bins of both transmitting and receiving data with an overlay of PSR from Table 4.2.

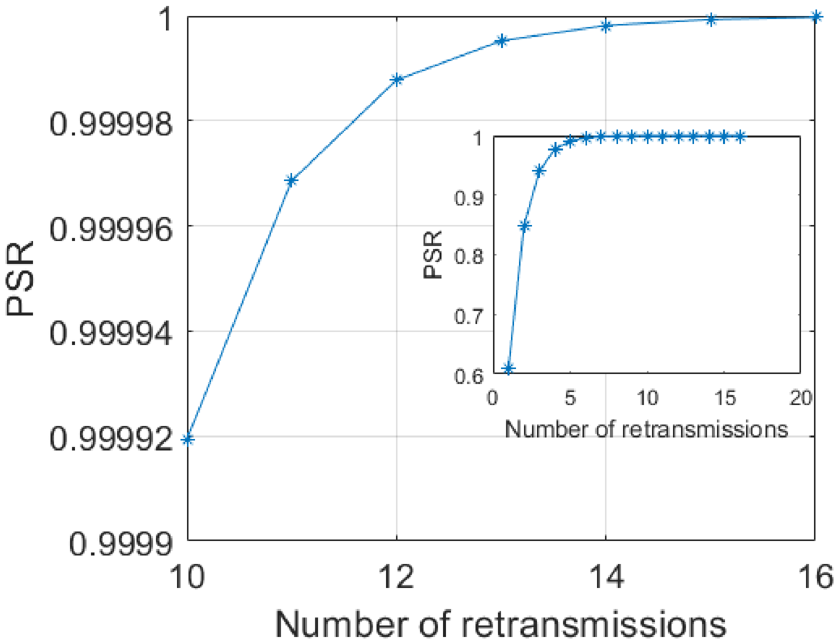


Figure 4.4: Lowest bin PSR of Table 4.2 as a function of how many retransmissions according to (3.6) & (3.7).

4.6 Centralized TDMA scheduling - simulated

The estimated channels PSR, based on collected data from the SPDM dataset, is used to simulate the TDMA scheduling. To get a good approximation of how many transmissions are necessary to ensure a high reliability for the TDMA scheduler the number of transmissions is calculated using (3.6) and (3.7). The chosen PSR for simulations is the lowest PSR from the estimation in Figure 4.4 as this will yield a ”worst case scenario” reassurance to the simulations and cover the entirety of the RSE cell. The results are displayed in Table 4.3.

Number of transmissions	Minimum PSR
1	61.0363 %
2	84.8183 %
3	94.0847 %
4	97.6952 %
5	99.1020 %
6	99.6501 %
7	99.8637 %
8	99.9469 %
9	99.9793 %
10	99.9919 %
11	99.9969 %
12	99.9988 %
13	99.9995 %
14	99.9998 %
15	99.9999 %
16	99.99997 %

Table 4.3: Minimum PSR for a given number of transmissions, including both transmissions of a specific BSM and new BSMs.

Since the minimum PSR of transmitted BSMs is 61.04 % a BSM needs to be transmitted at least 12 times for the system to provide a PSR of about 99.999 %, which is considered as very high reliability. Compared to the baseline, which achieves 99.1 % during 500 ms, 12 transmissions within the suggested TDMA scheduling time provides a significant higher PSR. In the light of this, in the TDMA scheduling, the vehicles with a PET of 2 seconds or less is allowed 4 transmissions at 4 different time instances spaced apart by 120 ms. The increase from 12 transmissions to 16 transmission is to improve the probability that the BSM reaches the vehicles involved in time even more, as the system aims to ensure traffic safety. The increase in PSR, and thereby traffic safety, is both in terms of a specific BSM and in terms of new BSMs for continuous kinematics risk calculations. The second highest priority, vehicles with a PET between 2 and 5 seconds, get 3 transmissions of 2 different BSMs. This is to ensure higher PSR in the TDMA scheduling than in the baseline while still not using excessive radio resources. The vehicles with a PET between 5 and 10 seconds is allowed 2 transmission. This means that they might suffer from packet losses in the short term but will manage to successfully transmit an adequate number of BSMs to be able to act before the situation escalates. The remaining vehicles, which have a PET of 10 seconds or higher will only get 1 transmission within the scheduling. This is since their need to communicate is small enough to allow for several seconds delay before achieving a high PSR. The four prioritization levels for V2V communication are motivated by the delay requirements of wireless communication in cooperative applications describes in Section 3.5. The simulated result of the TDMA scheduling, based on the aforementioned structure, compared to the baseline is visualized in Figure 4.5.

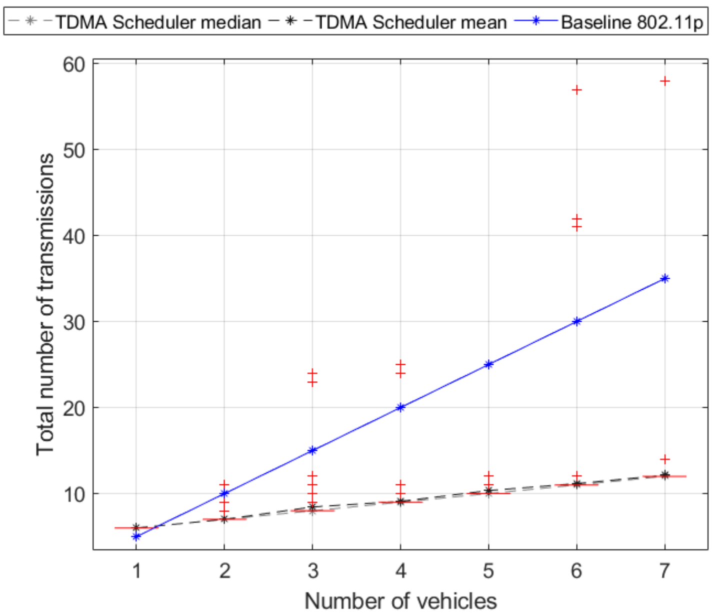


Figure 4.5: Comparison of baseline and suggested TDMA scheduler based on the naturalistic transmitted data with respect to the total number of transmissions and the number of vehicles.

An outlier case were the TDMA scheduling performed worse, in regards to channel utilization, is showed in Figure 4.6.

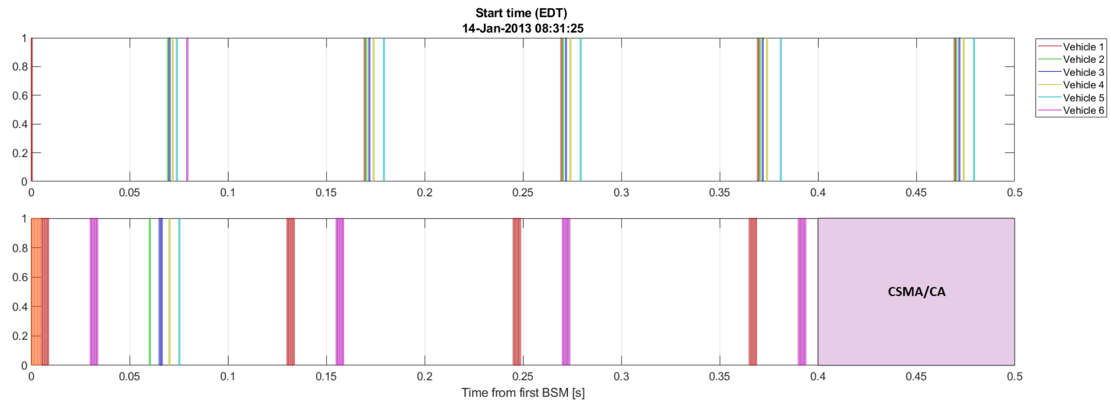


Figure 4.6: Baseline naturalistic scenario with six vehicles and its comparison with suggested TDMA scheduling. The orange messages at the beginning in the TDMA is the RSE time sync and scheduling message. The pink time slot at the end is reserved for new vehicles to join the scheduling

The scalability of this proposed system can be estimated by using (4.1).

$$\text{Number of vehicles} = \frac{\text{Time slot duration}}{\text{Transmission time}} \tag{4.1}$$

The results in Table 4.1 show that the average transmission time for a BSM is about 0.575 ms. According to (4.1), as the duration of the suggested TDMA scheduled time is 395 ms without the RSE and CSMA/CA time slots, the largest number of vehicles which can fit without congestion in the suggested system is about 686 vehicles. Worth noting is that this number is only achievable when all the vehicles have a PET of 10 seconds or more, which means that they only get 1 transmission each. If all the vehicles within the RSE cell have a PET value which is smaller than or equal to 2 seconds, and thereby gets 16 transmissions each, a maximum of about 42 vehicles fit. The baseline has a theoretical maximum capacity of 218, but worth noting is that this is with a lower degree of certainty during scenarios with more than 1 vehicle when compared to the suggested system [35].

5
Discussion

In this chapter the result of the thesis is reflected upon and discussed.

5.1 Vehicular safety

5.1.1 Scenario selection

The selected scenarios are based on a specific intersection in the SPDM dataset. The intersection contains the RSE number ”175” and one of the incoming lanes to the intersection is disregarded. Furthermore, a more complex scenario than the one chosen could have been selected to gain more examples of left turns in the scenario. This would have been used to identify even better metrics to help avoid accidents related to LTOD. However, a simpler intersection was chosen to simplify the risk assessment and shorten the already excessive processing time. Furthermore, a larger amount of scenarios, with the same type of risk assessment, could have been selected. But with the low amount of vehicles at the same time instance in the data set, more scenarios with same type of risk assessment would be difficult to find.

5.1.2 Single threat assessment algorithm

The most important part to keep in mind with the risk assessment in this thesis is that it is evaluating all scenarios with the same function, an enhanced PET. A normal PET risk function has no derived parameters such as acceleration and yaw rate. The fact that the thesis use these for path prediction enhances reliability in comparison with a baseline PET. In reality however, a much more complex risk assessment, including required deceleration for rear-end would have been needed to address multiple scenarios.

For example, in our risk assessment, there are negative values of PET, as seen in Figure 4.1. In reality, as no accident occurred at the selected intersection with the SPDM vehicles, no negative PET values should be present. The ones that did occur are probably due to errors in GPS measurements. However, the errors could also be derived from the fact that the thesis uses a memoryless path projection which possibly predicted the positions that generated the negative PETs. The scenarios where negative PET occurred were mostly at the parking lot at the high school when the heading difference between the two vehicles was larger than 15 degrees and the following vehicle did not have a large enough yaw rate yet. The fact that the function used in the risk assessment delivered PET values above zero in more than 95 % of all cases indicates that PET could be used as a general first indicator of risk in the given scenario. However, since less than 3 % of all vehicles are equipped with V2V communication technology, it is hard to predict what would happened if all vehicles would use it. The SAFESPOT SCOVA project indicated that low traffic safety gain can be made with less than 15 % penetration of the technology.

5.1.3 Measurement errors

The path projection model has not considered measurement errors, which might have affected the results. Furthermore it is a memory less path prediction, which means that the risk assessment is based on predictions rather than true paths. This memory less path prediction was used to simulate as real as possible situations for the RSE, which does not store old BSM for better prediction and do not know the outcome of the vehicles.

It is also worth discussing the size of the vehicles. The majority of the vehicles were defined as light vehicles. However, an average size were not defined and for privacy reasons there were no information about the dimensions of the vehicle in the BSMs. In the future, the vehicle size should be included for a better risk assessment. The reason for selecting Volvo Cars XC90 model as the base is that it resides in the larger end of the consumer car size spectrum. A larger car size puts the PET estimations further into the safe size as the initial PET decreases with a large vehicle size.

5.1.4 Critical communication delay

The resulting scheduler is based on the needs of vehicular communicate in different safety applications used in AVs and ADAS. The results indicate that the scheduler can handle most situations in the chosen intersection with the given, naturalistic, dataset. This is mainly because the number of vehicles in the dataset is fairly low. However, when taking the entire cell into account and looking at a scenario where the number of vehicles with V2V equipment is much higher the scheduler will not scale as well as the baseline. This is due to the fact that a lot of the critical PET situations happens at the parking lot and are, therefore, at risk to delay the communications in the primary intersection.

Furthermore, the assumptions made to define the maximum delay between two successfully received messages have used the assumption that the baseline gives good enough service today. This might not be the case in edge case scenarios. Furthermore, it was not possible to look at the amount of messages a vehicle receive but only how many BSM the RSE has received. This means that the thesis can not say with certainty how big the success ratio of BSMs was for vehicles but only for RSEs.

5.2 Channel estimation

The performance of the real world channel in the SPDM project was estimated and generalized with respect to distance from the collected data. As the parameter used to estimate the channel was only the rate of success for transmitted packets between the vehicles and the RSE no information about channel fading, channel gain or channel congestion were regarded. Since the maximum number of vehicles within the RSEs area in the SPDM dataset is 7 the channel congestion is assumed to be insignificant.

5.3 TDMA scheduling

The scheduling scheme, which is presented in Figure 4.5, showcase the result based on estimations of the real world channels performance. As the estimations are based on a limited time sequence of real world data a proper model for the general case is not achieved. But, with the mentioned limitations, the performance of the suggested TDMA scheduling, in contrast to a CSMA/IEEE 802.11p random access method, is clearly improving the effective use of channel resources in the limited case. As the suggested TDMA scheduling is able to, via its ability to prioritize, limit the amount of excessive communication on the channel while allowing the necessary communication to ensure more successful transmissions.

5.3.1 Prioritizing in TDMA scheduling

In Figure 4.6 a naturalistic sample of s when the TDMA scheduling is using more radio resources than the baseline is shown. However, the scheduling is improving safety compared to the baseline as the vehicles with high urgency got transmissions and, therefor, a higher PSR in the TDMA scheduling.

The prioritizing in the TDMA scheduling is using the calculated PET of every vehicle within the RSEs range to determine which vehicles are in the most urgent need of communication. Although effective from a communications perspective, the prioritizing based on PET results does not give any indication whether the possible accident is severe or not. This is because a PET does not indicate if it is a rear-end or a LTOD, which means that a scheduler could schedule a not as severe pre-crash scenario above a much severer one. With this in mind the prioritization could give priority to a non lethal accident over a lethal one, which could lead to that a lethal accident occurs while a non lethal one is avoided.

The prioritizing is not taking the distance to the RSE or the potential channel gain into consideration either. From a pure communications perspective this is ineffective as it is giving more resources to a communication link with lower probability of success. But as this system is taking the vehicular safety aspect first hand the reason for not taking the distance to the RSE or channel gain into account is well motivated.

5.3.2 Scalability

One of the parts of the suggested scheduler is to address the scalability issue in the baseline MAC layer. The majority of the scenarios from the naturalistic data shows that the suggested system will transmit a significant lower number of packets than 802.11p. This can be seen in Figure 4.5 where the vertical distance between baseline and the mean of the suggested scheduling is increasing with the increase of vehicles. To expand the discussion further than what is only possible in the dataset, when all vehicles have a critical PET at the same time, the suggested system can only handle 42 vehicles. As the baseline can, theoretically, handle up to 218 vehicles the suggested system has a worse scalability when the total number of transmitted BSMs are compared. However, with the increase of PSR in the suggested system, it is hard to compare the two systems as the baseline might scale better but at a cost of PSR while the suggested system scales worse but maintain a high PSR for the a few, urgent, pre-crash situations. This situation is, however, out of this thesis scope as it does not exist in the SPDM dataset. Another unlikely situation which is still worth discussing is when all the vehicles within the RSE cell have PETs larger than 10 seconds. In this case the suggested system can handle up to 686 vehicles as all of them only get 1 transmission each. In this situation the baseline outperforms the suggested system significantly when it comes to the PSR. But since the RSEs PET calculations has found no urgent danger for these vehicles the higher PSR of the baseline is redundant. On that note it is also important to reflect over an edge case scenario when the suggested systems channel is at capacity and a new vehicle enters the RSEs cell. In this case the new vehicle will not get a chance to broadcast until another vehicle leaves the cell, which could lead to severe outcomes.

5.3.3 Channel interference

This thesis ignores the fact that a real world TDMA scheduled channel that works as a compliment to a CSMA/CA structure could suffer from interference from vehicles which enters the cell during the vehicle-to-vehicle phase. This might be an aspect which would lower the PSR of the suggested TDMA scheduling but due to the low vehicle density in the naturalistic dataset and that the RSEs cell is not assumed to be an edge-cell this has been overlooked.

5.4 Future Work

5.4.1 Vehicular safety

Most safety evaluations in this thesis are based on a given physical location with its limitation and boundaries. To generalize the analysis is therefore of high interest. An initial step could be to evaluate the surrogate safety measurements over more scenarios or expand them into more complex models. It would also be interesting to look at different types of improvements such as customizing vehicular bounding boxes if it is possible without compromising anonymity. The path prediction is also worth considering, if one could include better path predictions with Kalman filtering without compromising privacy. In that case, adding measurement errors of the GPS location should be considered.

5.4.2 Vehicular safety restrictions on communication

One of the most critical components when designing a MAC-layer scheduler based on centralized vehicular risk assessment is to define the maximum delay the system could have without compromising safety. To calculate this metric in a more general scenario it is necessary to conclude if radio resources actually will be saved when BSMs are scheduled.

Furthermore, it is necessary to look at the maximum delay in a situation when a cell is at an edge of the system and vehicles is coming from a rural area approaching intersections, when vehicles is supposed to change from a 802.11p to a TDMA scheduled protocol.

5.4.3 Scheduling design

Future studies should look into how radio resources can be saved in low volume scenarios when only one or no vehicles are present within the cell structure. One question to look into is if the system could be adaptable, meaning that at some hours, baseline 802.11p will be used and at some hours the TDMA scheduling in use. Furthermore, future studies need to consider the possibility to reschedule vehicles with a higher priority if a vehicles BSMs was not heard by the RSE.

Another scheduling aspect to evaluate is another adaptable scheduling which further adapts the scheduling to the number of vehicles with low PET values. Preferably, if the number of vehicles with a PET below 2 seconds is higher than the capacity of the system it would prioritize the fatal accidents over the non-fatal.

5.4.4 Time diversity

As the thesis is based on the IEEE 802.11p's physical layer, while modulating the MAC layer, improvements such as time diversity are not permitted. However, as the suggested TDMA scheduling is transmitting the same BSM several times, time diversity would potentially improve the PSR of the system.

5.4.5 FDMA

As this thesis solely investigate the TDMA scheduling as a possible improvement to the current vehicle communication standard it is limited in frequency. Further investigations with respect to FDMA could potentially improve the spectral efficiency of the system even more.

5.4.6 Complexity

Future work within this thesis area of research should consider the complexity of a centralized TDMA system. This could potentially decrease the utilization of the channel as the RSE access time increases.

5.5 Ethics

This thesis evaluates a way to save radio resources, and thereby cost, in potentially lethal traffic scenarios. While the state of the art systems is considered to provide good enough PSR, as long as the number of connected vehicles within communication range is adequately low, the pursuit of lower cost at the risking traffic safety is morally debatable. Since this thesis improves the PSR, and thereby the vehicular safety, while also streamlining the radio resources this ethical dilemma is managed.

6
Conclusion

This chapter finalizes the result of the discussion and concludes the entirety of the thesis.

6.1 Vehicular safety with wireless communication

The results indicate that a generalized risk assessment based on PET could be used to identify potential accidents in the observed situations in the selected scenario. This was achieved by

- Identifying a connected intersection with potential of LTOD pre-crash scenario in the naturalistic dataset.
- Create a generalized risk assessment from naturalistic BSM data retrieved from the SPDM dataset.
- Base the risk assessment on an enhanced, predictive, PET that takes acceleration, heading and yaw rate into account.

Furthermore, the results indicate that a RSE can detect and successfully schedule two vehicles in urgent need to communicate if the time between consecutive, successful, transmissions between the vehicles do not exceed the time required to act by a modern automatic emergency braking and steering system. This assumes that both emergency steering and emergency breaking can be used. The thesis also identified four levels of priority and their need for communication. Their need to communicate were defined in terms of maximum time delay until a successful transmission occurs, which is required to ensure functionality of cooperative safety applications such as cooperative FCW.

The results of this thesis presents significant improvements to the state of the art systems in a naturalistic scenario through changes in the MAC layer. The results argue that a centralized V2I system, which schedules V2V communication based on traffic safety aspects, improves the average use of radio resources as the number of vehicles within the RSE cell increases past 1. The results also suggest that the PSR is maintained with an increasing number of vehicles within the RSE cell compared to the state of the art systems. Furthermore, the thesis found that the suggested TDMA scheduling system scales better than the state of the art system when there is no vehicle with an urgent need to communicate. However, the suggested system scales worse in cases were there are several vehicles with a high urgency to communicate. As the thesis research is limited to the naturalistic traffic scenario data from the SPDM dataset the results can not be assumed to be universal for all traffic scenarios.

6.2 Naturalistic BSM dataset

This thesis have thoroughly investigated small parts of two datasets from the SPDM project. The findings of these investigations were the following

- The transmitting dataset contains a lot of high quality data during the entire test period, however the accuracy of the GPS is not as high as in the receiving dataset.
- The transmitting data has several cases of outliers in terms of position that needs manual processing if it is to be used.
- The receiving dataset has fewer active days with data. This thesis was only able to retrieve 20 days of high quality data from the receiving dataset which could be compared with the transmitting dataset, see Figure 3.12.

Bibliography

[1] World Health Organization, "Global status report on road safety 2018," tech. rep., World Health Organization, 2018.

[2] J. Harding, G. Powell, R. Yoon, J. Fikentscher, C. Doyle, D. Sade, M. Lukuc, J. Simons, and J. Wang, "Vehicle-to-vehicle communications: Readiness of V2V technology for application," tech. rep., United States. National Highway Traffic Safety Administration, 2014.

[3] W. G. Najm, B. Sen, J. D. Smith, B. Campbell, *et al.*, "Analysis of light vehicle crashes and pre-crash scenarios based on the 2000 general estimates system," tech. rep., United States. National Highway Traffic Safety Administration, 2003.

[4] S. Eichler, "Performance evaluation of the IEEE 802.11 p WAVE communication standard," in *Vehicular Technology Conference, 2007. VTC-2007 Fall. 2007 IEEE 66th*, pp. 2199–2203, IEEE, 2007.

[5] K. Bilstrup, E. Uhlemann, E. G. Strom, and U. Bilstrup, "Evaluation of the IEEE 802.11p MAC Method for Vehicle-to-Vehicle Communication," in *2008 IEEE 68th Vehicular Technology Conference*, pp. 1–5, Sep. 2008.

[6] A. Fernandez and M. Fallgren, "5GCAR scenarios, use cases, requirements and KPIs," *Fifth Generation Communication Automotive Research and innovation, Tech. Rep. D*, vol. 2, 2017.

[7] "Safety in automated driving (ADS): modelling interaction between road-users and automated vehicles." https://www.chalmers.se/sv/projekt/Sidor/Safety-in-automated-driving-QADSQQ-modelling-interaction-between.aspx, 2019. [Online; accessed 27-May-2019].

[8] D. Bezzina and J. Sayer, "Safety pilot model deployment: Test conductor team report," *Report No. DOT HS 812 171*, Jun. 2015.

[9] K. Mori, O. Shagdar, S. Matsuura, M. Tsukada, T. Ernst, and K. Fujikawa, "Experimental study on channel congestion using IEEE 802.11p communication system," in *IPSJ Technical Workshop on Mobile Computing and Ubiquitous Communications*, 2013.

[10] H. Song and H. S. Lee, "A survey on how to solve a decentralized congestion control problem for periodic beacon broadcast in vehicular safety communica-

tions," in *2013 15th International Conference on Advanced Communications Technology (ICACT)*, pp. 649–654, IEEE, 2013.

[11] X.-F. Xie and Z.-J. Wang, "SIV-DSS: Smart In-Vehicle Decision Support System for driving at signalized intersections with V2I communication," *Transportation Research Part C: Emerging Technologies*, vol. 90, pp. 181–197, 2018.

[12] J. Rios-Torres, A. Malikopoulos, and P. Pisu, "Online optimal control of connected vehicles for efficient traffic flow at merging roads," in *Intelligent Transportation Systems (ITSC), 2015 IEEE 18th International Conference on*, pp. 2432–2437, IEEE, 2015.

[13] R. Zhang, X. Cheng, L. Yang, X. Shen, and B. Jiao, "A novel centralized tdma-based scheduling protocol for vehicular networks," *IEEE Transactions on Intelligent Transportation Systems*, vol. 16, no. 1, pp. 411–416, 2015.

[14] X. Huang, D. Zhao, and H. Peng, "Empirical study of dsrc performance based on safety pilot model deployment data," *IEEE Transactions on Intelligent Transportation Systems*, vol. 18, pp. 2619–2628, Oct 2017.

[15] W. Wang, D. Zhao, W. Han, and J. Xi, "A learning-based approach for lane departure warning systems with a personalized driver model," *IEEE Transactions on Vehicular Technology*, vol. 67, no. 10, pp. 9145–9157, 2018.

[16] D. Zhao, H. Lam, H. Peng, S. Bao, D. J. LeBlanc, K. Nobukawa, and C. S. Pan, "Accelerated evaluation of automated vehicles safety in lane-change scenarios based on importance sampling techniques.," *IEEE Trans. Intelligent Transportation Systems*, vol. 18, no. 3, pp. 595–607, 2017.

[17] D. Zhao, X. Huang, H. Peng, H. Lam, and D. J. LeBlanc, "Accelerated evaluation of automated vehicles in car-following maneuvers," *IEEE Transactions on Intelligent Transportation Systems*, vol. 19, no. 3, pp. 733–744, 2018.

[18] D. Jiang and L. Delgrossi, "IEEE 802.11 p: Towards an international standard for wireless access in vehicular environments," in *Vehicular Technology Conference, 2008. VTC Spring 2008. IEEE*, pp. 2036–2040, IEEE, 2008.

[19] K. Sjöberg, *Medium access control for vehicular ad hoc networks.* Chalmers University of Technology, 2013.

[20] A. M. Abdelgader and W. Lenan, "The physical layer of the IEEE 802.11 p WAVE communication standard: the specifications and challenges," in *Proceedings of the world congress on engineering and computer science*, vol. 2, pp. 22–24, 2014.

[21] ETSI, TCITS, "Intelligent Transport Systems (ITS); European profile standard on the physical and medium access layer of 5 GHz ITS," *Draft ETSI ES*, vol. 202, no. 663, p. V0, 2009.

[22] A. M. Wyglinski, R. Getz, T. Collins, and D. Pu, *Software-defined radio for engineers.* Artech House, 2018.

[23] M. Arndt, "Automotive intelligent transport," 2019. https://www.etsi.org/technologies/automotive-intelligent-transport.

[24] J.-W. Kim, J.-W. Kim, and D.-K. Jeon, "A Cooperative Communication Protocol for QoS Provisioning in IEEE 802.11 p/Wave Vehicular Networks," *Sensors*, vol. 18, no. 11, p. 3622, 2018.

[25] B. A. Hamilton, "Safety pilot model deployment-sample data environment data handbook," *US Department of Transportation Intelligent Transportation Systems Joint Program Office*, 2015.

[26] D. Willemsen, M. de Kievit, and F. Faber, "SAFESPOT INTEGRATED PROJECT-IST-4-026963-IP DELIVERABLE," *Update*, vol. 1, pp. 12–05, 2010.

[27] K. Malone, J. Rech, S. Innamaa, S. Hausberger, and E. Al., "Impact assessment and user perception of cooperative systems," tech. rep., DRIVE C2X Consortium, 2014. Link to url.

[28] M. Brännström, E. Coelingh, and J. Sjöberg, "Decision-making on when to brake and when to steer to avoid a collision," *International Journal of Vehicle Safety 1*, vol. 7, no. 1, pp. 87–106, 2014.

[29] R. Schubert, E. Richter, and G. Wanielik, "Comparison and evaluation of advanced motion models for vehicle tracking," in *2008 11th international conference on information fusion*, pp. 1–6, IEEE, 2008.

[30] J. Gunnarsson, L. Svensson, L. Danielsson, and F. Bengtsson, "Tracking vehicles using radar detections," in *2007 IEEE Intelligent Vehicles Symposium*, pp. 296–302, IEEE, 2007.

[31] R. Chen, R. Sherony, and H. C. Gabler, "Comparison of time to collision and enhanced time to collision at brake application during normal driving," tech. rep., SAE Technical Paper, 2016.

[32] P. Cooper, "Experience with traffic conflicts in canada with emphasis on "post encroachment time" techniques," in *International calibration study of traffic conflict techniques*, pp. 75–96, Springer, 1984.

[33] "5G Communication Automotive Research and innovation." https://5gcar.eu, 2019. [Online; accessed 27-May-2019].

[34] Bureau International des Poids and Mesures, *International System of Units (SI)*. Sèvres, France: Le Bureau, 2006.

[35] K. S. Bilstrup, E. Uhlemann, and E. G. Strom, "Scalability Issues of the MAC Methods STDMA and CSMA of IEEE 802.11 p When Used in VANETs," in *2010 IEEE International Conference on Communications Workshops*, pp. 1–5, IEEE, 2010.

A

Appendix 1 - Surrogate Safety measurment functions

A.1 car_points

```
function [car_border_lat, car_border_lon] = car_points(gps_lat,gps_lon,heading)
%CAR_POINTERS Creates a five-point box for a Volvo XC90 car in lat,lon
% This function is developed by Carl von Rosen Johansson, Spring 2019
%  for a Masters Thesis in Communication Engineering at Chalmers University
%  of Technology.
% ------------------------------------------------------------------------
%   INPUT:
%       gps_lat      -   DD.dddddd
%       gps_lon      -   DDD.dddddd
%       heading      -   DDD (degrees)
%   OUTPUT:
%       car_border_lat -    [6x1] DD.dddddd
%       car_border_lon -    [6x1] DDD.dddddd
% ------------------------------------------------------------------------
%
%   4-------------------------5
%   |                         |
%   |           *(in)        1,6 -- (heading) ---->
%   |                         |
%   3-------------------------2
%
% ------------------------------------------------------------------------
% Volvo Cars SUV XC90, width and length of 2008 and 4950 mm
% GPS assumed to be in the center of the car.
% ------------------------------------------------------------------------
distUnits = 'm'; % Meters
front_dist = 4.95/2;
```

```
corner_dist = sqrt((4.95/2)^2+(2.008/2)^2);

% Front point
f_arclen = rad2deg(front_dist/earthRadius(distUnits));
[f_lat,f_lon] = reckon(gps_lat, gps_lon,f_arclen,heading);

% Corner points
b_arclen = rad2deg(corner_dist/earthRadius(distUnits));
b_headings = [heading+22;
              heading+180-22;
              heading-180+22;
              heading-22];
[b_lat,b_lon] = reckon(gps_lat,gps_lon,b_arclen,b_headings);

car_border_lat = [f_lat;b_lat;f_lat];
car_border_lon = [f_lon;b_lon;f_lon];
end
```

A.2 pet_gps_calc

```
function pet = pet_gps_calc(ego,target,visual)
%PET_GPS_CALC Post-Encroachment Time calculator based on your gps coords
%
% This function is developed by Carl von Rosen Johansson, Spring 2019
%  for a Masters Thesis in Communication Engineering at Chalmers University
%  of Technology.
%
% -----------------------------------------------------------------------------
%   INPUT:
%       ego,target  -    [struct] Two structs with the following:
%           lat       -    [DD.dddd] Latitude
%           long      -    [DD.dddd] Longitude
%           speed     -    [m/s]     Speed of vehicle
%         heading   -    [deg]     Heading of vehicle
%           acc       -    [m/s^2]   Longitudional acceleration
%     [opt] yawrate   -    [deg/s]   Yaw rate of vehicle
% [opt] visual      -    [bool] true if you want a plot of intersecting
%                              vehicles at interesting pet (below 5 s)
%   OUTPUT:
%       pet         -    [s] Post-Encroachment Time
% -----------------------------------------------------------------------------
% Calculate PET Based on Slides from TME192 Lecture 2018-09-20 that
% is based on:
% https://www.sciencedirect.com/science/article/pii/S1369847815001540
% B rgman, J., Smith, K., & Werneke, J. (2015).
% Quantifying drivers  comfort-zone and dread-zone boundaries in left turn
% across path/opposite direction (LTAP/OD) scenarios.
```

```
% Transportation Research Part F: Traffic Psychology and Behaviour, 35, 170-184.
% ------------------------------------------------------------------------
% Note: If ego.heading ~ target.heading, PET = TH
% To save processing time,
% TH is calculated if abs(heading-az) < threshold = 10 deg
% ------------------------------------------------------------------------
% Note 2: If target is behinde (abs(heading-az)>100), then PET is not
% calculated
% ------------------------------------------------------------------------
if nargin<3
    visual = false;
end
pet_thr = 4; % Set at what PET time plot should be triggerd

% Quick Time-Headway calc
[ego_border_la, ego_border_lo] = car_points(ego.lat,ego.long,ego.heading);
[target_border_la, target_border_lo] = car_points(target.lat,target.long,target.heading);
[dist,az] = distance([ego_border_la(1:2);ego_border_la(5)],... % Front of ego
                     [ego_border_lo(1:2);ego_border_lo(5)],...
                     [target_border_la(1);target_border_la(3:4)],... % Back of Target
                     [target_border_lo(1);target_border_lo(3:4)]);
D_r = min(dist)*(60*1852); % In Deg *60 -> Nm *1852 -> m

if abs(az(1)-mean(az(2:3))) > 10 || ( ego.lat == target.lat && ego.long == target.long ) % Cars are overlapping (Crash or bad data)
     pet = 0;
elseif D_r/ego.speed > 10 % Quick TH check to avoid calculating PET for long dist.
    pet = Inf;
elseif (abs(ego.heading-az(1)))>100 % Car behinde you
    pet = Inf;
elseif mean(abs(ego.heading-az))<15 && max(az)-min(az) < 5   % Car in same direction, in front of you
    pet = D_r/ego.speed;
    if visual && pet < pet_thr
        ttc = ttc_gps_calc(ego,target);
        figure, grid on, hold on
        plot(ego.long,ego.lat,'g.',...
              ego_border_lo,ego_border_la,'g') % Plot BSM pos & Plot Car borders
        plot(target.long,target.lat,'r.',...
              target_border_lo,target_border_la,'r') % Plot BSM pos & Plot Car borders
        plot_google_map('MapScale', 1,'MapType','satellite','Scale',2,'Resize',2)
```

```
        title(['PET ' num2str(pet) 's, ETTC ' num2str(ttc) ' s'])
        legend('Ego BSM','Ego Car','Target','Target car')
        hold off
    end
else % Do propper PET
    er = earthRadius('m');
    step = 0.5;
    t = 0.1:step:5.1;
    % Define time horizon
    for i=1:length(t)

      % ---- EGO ---- %
        % Update dist, speed, heading & position
        if i == 1
            dist = ego.speed*step + ego.acc*step^2/2; % meters/s;
            ego_speed(i) = ego.speed + ego.acc*step;
            ego_hdg(i) = ego.heading + ego.yawrate*step;
            [ego_lat(i),ego_lon(i)] = reckon(ego.lat,ego.long,rad2deg(dist/er),ego_hdg(i));
        else
            dist = ego_speed(i-1)*step + ego.acc*step^2/2;
            ego_speed(i) = ego_speed(i-1) + ego.acc*step;
            ego_hdg(i) = ego_hdg(i-1) + ego.yawrate*step;
            [ego_lat(i),ego_lon(i)] = reckon(ego_lat(i-1),ego_lon(i-1),rad2deg(dist/er),ego_hdg(i));
        end
        [ego_border_la(:,i), ego_border_lo(:,i)] = car_points(ego_lat(i),ego_lon(i),ego_hdg(i));
        % Create ego polygon
        if i == 1
            ego_path =      [ego_border_la(4,i),  ego_border_lo(4,i);
                             ego_border_la(5,i),  ego_border_lo(5,i)];
            ego_path_tail = [ego_border_la(2,i),  ego_border_lo(2,i);
                             ego_border_la(3,i),  ego_border_lo(3,i);
                             ego_border_la(4,i),  ego_border_lo(4,i)];
        elseif i == length(t)
            ego_path =      [ego_path;
                             ego_border_la(5,i),  ego_border_lo(5,i);
                             ego_border_la(2,i),  ego_border_lo(2,i);
                             ego_path_tail];
        else
            ego_path =      [ego_path;
                             ego_border_la(5,i),  ego_border_lo(5,i)];
            ego_path_tail = [ego_border_la(2,i),  ego_border_lo(2,i);
                             ego_path_tail];
        end

      % ---- TARGET ---- %
        % Update dist, heading & position
        if i == 1
            dist = target.speed*step + target.acc*step^2/2; % meters/s;
            target_speed(i) = target.speed + target.acc*step;
            target_hdg(i) = target.heading + target.yawrate*step;
            [target_lat(i),target_lon(i)] = reckon(target.lat,target.long,...
                                                  rad2deg(dist/er),
```

```
    target_hdg(i));
        else
            dist = target_speed(i-1)*step + target.acc*step^2/2;
            target_speed(i) = target_speed(i-1) + target.acc*step;
            target_hdg(i) = target_hdg(i-1) + target.yawrate*step;
            [target_lat(i),target_lon(i)] = reckon(target_lat(i-1),
    target_lon(i-1),...
                                                                  rad2deg(dist/er),
    target_hdg(i));
        end
        [target_border_la(:,i), target_border_lo(:,i)] = car_points(
    target_lat(i),target_lon(i),target_hdg(i));
        % Create target polygon
        if i == 1
            target_path =      [target_border_la(4,i),
    target_border_lo(4,i);
                                target_border_la(5,i),
    target_border_lo(5,i)];
            target_path_tail = [target_border_la(2,i),
    target_border_lo(2,i);
                                target_border_la(3,i),
    target_border_lo(3,i);
                                target_border_la(4,i),
    target_border_lo(4,i)];
        elseif i == length(t)
            target_path =      [target_path;
                                target_border_la(5,i),
    target_border_lo(5,i);
                                target_border_la(2,i),
    target_border_lo(2,i);
                                target_path_tail];
        else
            target_path =      [target_path;
                                target_border_la(5,i),
    target_border_lo(5,i)];
            target_path_tail = [target_border_la(2,i),
    target_border_lo(2,i);
                                target_path_tail];
        end

    end

    % ---- RELATIVE ---- %
    in_sec = intersect(polyshape(ego_path),polyshape(target_path));

    if in_sec.NumRegions > 0
        % FIND all times
        ego_t = []; target_t = [];
        for i = 1:length(t)
            clear('in_e','in_t')
            % EGO
            in_e = inpolygon(ego_border_lo(:,i),ego_border_la(:,i),...
                           [in_sec.Vertices(:,2); in_sec.Vertices(1,2)
    ],...
                           [in_sec.Vertices(:,1); in_sec.Vertices(1,1)]);
              if sum(in_e)>0
```

```
                ego_t = [ego_t; i];
            end
            % TARGET
            in_t = inpolygon(target_border_lo(:,i),target_border_la(:,i),...
                         [in_sec.Vertices(:,2); in_sec.Vertices(1,2)],...
                         [in_sec.Vertices(:,1); in_sec.Vertices(1,1)]);
            if sum(in_t)>0
                target_t = [target_t; i];
            end
        end
        if sum(ego_t) == 0 || sum(target_t) == 0
            pet = Inf;
        else
            t1 = [ego_t(1);target_t(1)]; % Enter zone of conflict
            t2 = [ego_t(end);target_t(end)]; % Exit zone of conflict
            pet = max(t(t1)) - min(t(t2));
            disp(['PET ' num2str(pet) 's'])
            if visual && pet < pet_thr
                figure, grid on, hold on
                plot(ego_lon(1),ego_lat(1),'g.',...
                    ego_path(:,2),ego_path(:,1),'g') % Plot BSM pos & Plot Car borders
                plot(target_lon(1),target_lat(1),'r.',...
                    target_path(:,2),target_path(:,1),'r') % Plot BSM pos & Plot Car borders
                plot([in_sec.Vertices(:,2); in_sec.Vertices(1,2)],...
                    [in_sec.Vertices(:,1); in_sec.Vertices(1,1)]),
                plot_google_map('MapScale', 1,'MapType','satellite','Scale',2,'Resize',2)
                title(['PET ' num2str(pet) 's'])
                legend('Ego','Ego 5 s trajectory','Target','Target 5 s trajectory','Intersecting box')
                hold off
            end
        end
    else
        pet = Inf;
    end
end
end
```