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A Planning Tool to Assess Advanced Vehicle Sensor Technologies on Traffic Flow, Fuel Economy, and Emissions



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# A Planning Tool to Assess Advanced Vehicle Sensor Technologies on Traffic Flow, Fuel Economy, and Emissions

THESIS

submitted in partial satisfaction of the requirements

for the degree of

MASTER OF SCIENCE

In Mechanical and Aerospace Engineering

by

Van T. Wifvat

Thesis Committee:

Professor G. Scott Samuelsen, Chair

Professor Wenlong Jin

Professor Timothy Rupert

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## DEDICATION

For Marie.

Your love defines so much of who I am.

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# NOMENCLATURE

| | |
|---|---|
| AFV | Alternatively Fueled Vehicle |
| BEV | Battery Electric Vehicle |
| CAMP | Crash Avoidance Metrics Partnership |
| CS | Camera System |
| CVIS | Cooperative Vehicle Infrastructure Systems |
| DIAMANT | Dynamic Information and Application for Mobility with Adaptive Networks and Telematics Infrastructure |
| EMIT | Emissions from Traffic |
| FETCH | Fuel Economy and Traffic of Connected Hybrids |
| FCW | Forward Collision Warning systems |
| GHG | Greenhouse Gas |
| H2V | Human to Vehicle |
| HEV | Hybrid Electric Vehicle |
| ITN | Intelligent Transit/Transportation Network |
| LDV | Light Duty Vehicle |
| LDW | Lane Departure Warning systems |
| NHTSA | National Highway Traffic Safety Administration |
| OMNET++ | Objective Modular Network Testbed in C++ |
| PHEV | Plugin Hybrid Electric Vehicle |
| SUMO | Simulation of Urban Mobility |
| US | United States |
| USDoT | United States Department of Transportation |
| V2I | Vehicle to Infrastructure |
| V2V | Vehicle to Vehicle |
| V2X | Vehicle to Vehicle / Vehicle to Infrastructure |
| VRS | Vehicular Radar System |

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# ABSTRACT OF THE THESIS

A Planning Tool to Assess Advanced Vehicle Sensor Technologies on Traffic Flow, Fuel Economy, and Emissions

by

Van T. Wifvat

Master of Science in Mechanical and Aerospace Engineering

University of California, Irvine, 2016

Professor G. Scott Samuelsen, Chair

Light-duty vehicles are responsible for over 16% greenhouse gas (GHG) emissions in the United States. Human driving behavior has a significant impact on vehicle efficiency, the emission of GHG and primary pollutants, and safety. With environmental health in mind, both academia and industry have the opportunity to develop advanced sensor and complementary control technologies to manage the human role.

To explore this hypothesis, the research reported herein began with a comprehensive study of demonstration projects and academic publications which test and evaluate modern technologies to mitigate threats associated with safety and efficiency. The research identified the environmental signals to detect, the corresponding sensors to detect these signals, and the sensor technologies to study in greater depth. Of all the sensor technologies, vehicle-to-vehicle

(V2V) and vehicle-to-infrastructure (V2I) communications technologies emerged as the most promising. A major requirement identified is a planning tool designed to assess advanced vehicle sensor technologies on traffic flow, fuel economy, and emissions.

In response, a major focus of the research was then directed to (1) developing the Fuel Economy and Traffic of Connected Hybrids (FETCH) planning tool, and (2) evaluating the utility of FETCH for a simple V2V-enabled automatic re-routing control on a custom roadway. The major outcomes of the thesis are (1) the FETCH tool, (2) a research plan for utilizing FETCH to explore the variety of scenarios evolving for the advanced control of hybrid vehicles, and (3) an overall perspective for the evolution of advanced technologies to enable safer and cleaner light duty transportation.

# 1 INTRODUCTION

## 1.1 GOAL

The goal of this thesis is to establish the role of advanced vehicle sensor technologies, V2I, and V2V on traffic flow, fuel economy and emissions and, to this end, develop a validated simulation model suitable to support assess the impact of advanced vehicular technology on traffic flow, emissions, and fuel economy of hybrid vehicles.

## 1.2 OBJECTIVES

The subsequent objectives are satisfied to fulfill the goal of this thesis:

1) Identify environmental signals which can be detected to improve vehicular fuel efficiency for hybrid vehicles, and identify state of the art sensor technologies which can be used to detect these signals.

2) Perform a literature review to find studies with relevant research goals, and investigate the tools used and research processes commonly used to solve such research problems.

3) Determine the most appropriate modelling tools for simulating the impact of V2V and V2I technologies for this research.

4) Develop a research process framework and tool to explore the interaction between the selected V2V and V2I simulation tools and the required inputs and outputs of those tools, and develop a corresponding research plan to accomplish the aforementioned research goals.

5) Demonstrate the tool efficacy.

## 2 BACKGROUND

2.1 Role of Light Duty Transportation and Global Climate Change

The Intergovernmental Panel on Climate Change (IPCC), a scientific branch of the United Nations, has concluded that anthropogenic greenhouse gas emissions (GHGs) are higher than ever before, with a near-certainty that carbon dioxide, nitrous oxide, and methane concentrations in our atmosphere are higher than in the past 800,000 years [1]. Domestically, the transportation sector accounts for 27% of the total GHG emissions, and of those, the on-road emissions have increased by 250% from 1970 to 2010, as represented below in Figure 1 [2].

On United States (US) roadways, light duty trucks and passenger cars together (referred from this point on as LDVs) form a majority of GHG emissions per source, as illustrated by the 2006 information from the US Environmental Protection Agency below in Figure 2 [3].

Greenhouse gas emissions attributed to transportation as a whole are expected to rise significantly into the future, driven primarily by increasing energy demand of light-duty vehicles, freight trucks, and air travel, respectively [4]. Such trends of increasing energy demand are illustrated below in Figure 3.

Clearly, improvements to LDV efficiency will help mitigate the large impacts of overall transportation GHG emissions. The following background sections will help to explain some of the most promising contributions in the fight against LDV transit inefficiencies.

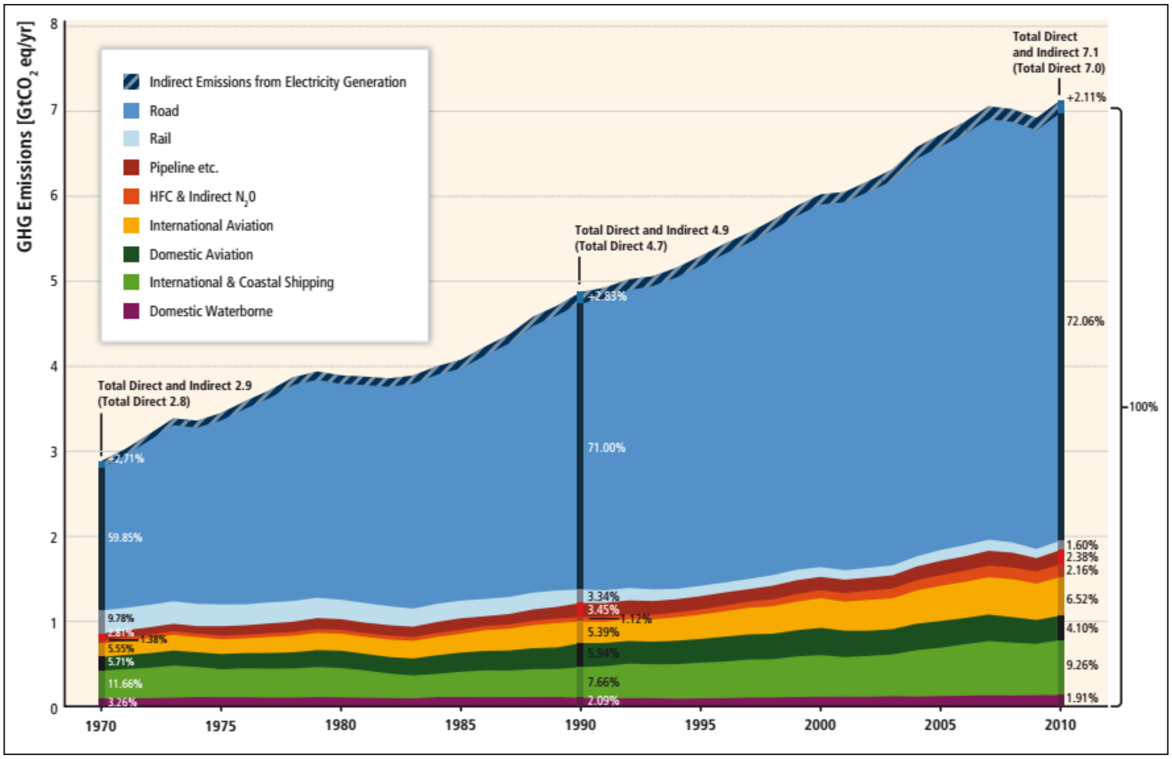


Figure 1: GHG Emissions per Transportation Sector, Mode (From IPCC 2014 Ref. 2 Page 606)

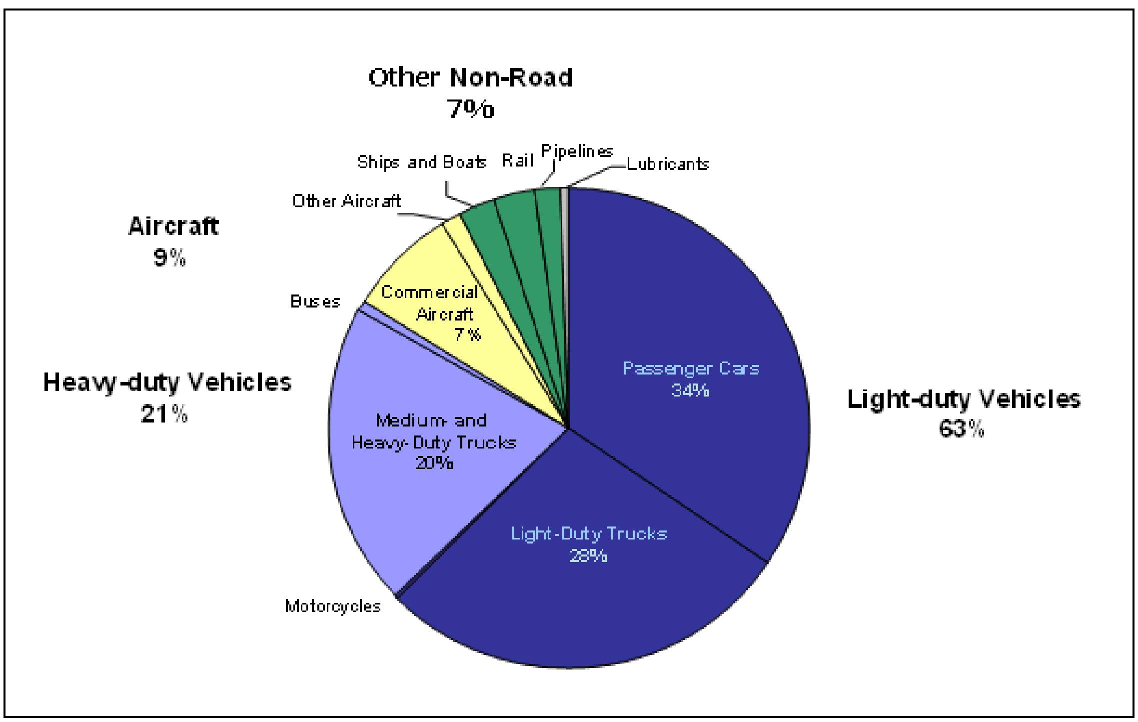


Figure 2: US Transportation GHG Emissions by Source (From USDOT 2006 Ref. 3)

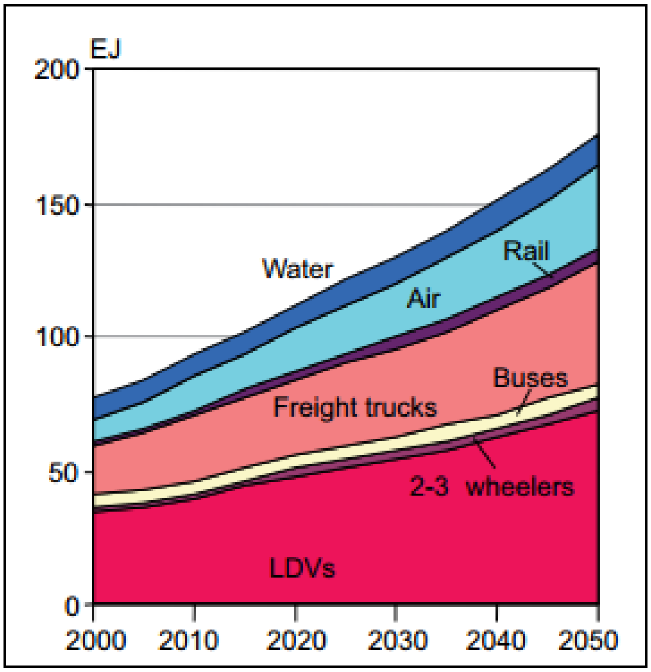


Figure 3: Projected Transportation Energy Consumption (From IPCC 2007 Ref. 4 Page 333)

2.2 Vehicle Powertrain Design as a means of Improving Light-Duty Transit Efficiency

For the purposes of this thesis, the powertrain of a vehicle refers specifically to the power generation components which deliver motive force to the wheels of a vehicle. Because LDV transportation emissions are a significant contributor to the total anthropogenic GHG emissions, efficient vehicular powertrain design can play a critical role in improving the GHG footprint for the light duty transportation sector [5]–[7]. While the vast majority of vehicles in the US are standard gasoline-burning internal combustion engines (ICEs), the overall fuel efficiency of LDV powertrains has improved by nearly 40% from 1960 to 2007 [8]. It is worthy to note that for approximately two decades, the LDV fuel economy per model year decreased in the US, as indicated by the following graph sourced from the United States Environmental Protection Agency [9]:

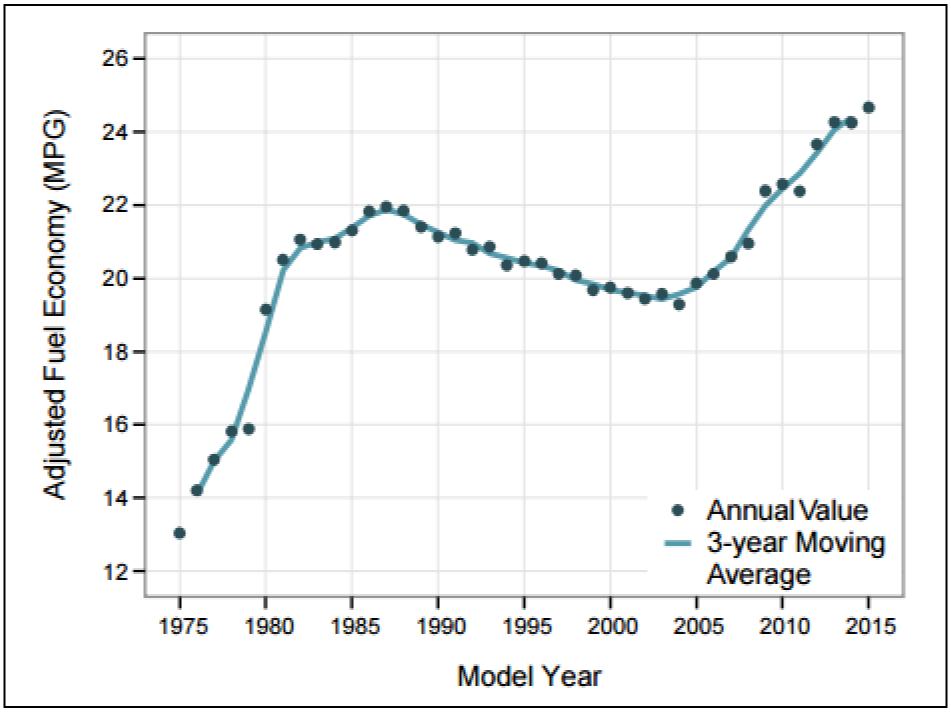


Figure 4: US Light Duty Vehicle Fuel Economy per Model Year (From US EPA 2015 Ref. 9 Page 7)

The model year fuel economy has been steadily improving for LDVs over the past decade, resulting in an approximate 25% increase since the early 2000's [9]. For greater LDV fuel economy improvements in the US, alternative powertrains such as Hybrid Electric Vehicles (HEVs) have been developed. A HEV is a vehicle which can use an electric motor and/or a conventional ICE to supply the motive force to the wheels [10]. There are two predominant configurations for HEVs, as shown in the diagrams below [10]:

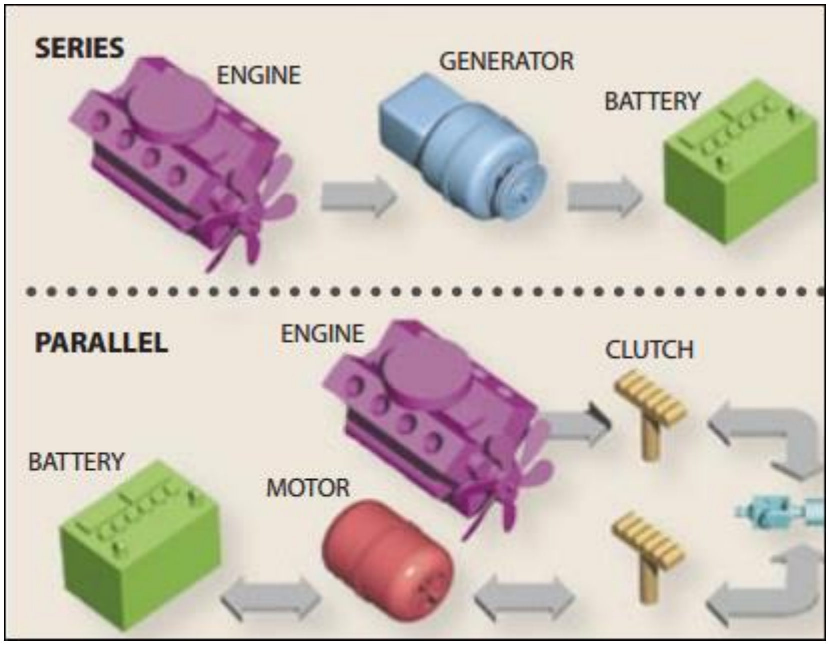


Figure 5: Series and Parallel Configurations for HEVs (From Wouk 1997 Ref. 10 Page 72)

For both of the above configurations, the load given to the ICE will be diminished relative to a comparable ICE-only powertrain vehicle and will therefore reduce the GHG emissions from that vehicle. An advantage to using the electric motor together with an ICE in parallel is that the power delivered to the wheels can be sent from the optimal source for the particular the speed of the vehicle. Electric motors have a peak torque at low RPMs, while ICE's have a peak torque at higher RPMs. By using the electric motor with the ICE, the design of the powertrain can be optimized such that the electric motor and ICE use less energy together in supplying the motive force for transit. For both systems, the design of an HEV can allow for regenerative braking, which is process of using the onboard electric motor to convert the kinetic energy of braking into electricity to be used later [11], [12].

For the fleet-wide scale, the combined city and highway fuel economy improvement is as high as 30% for an HEV fleet using recent technology, compared to a standard ICE powertrain vehicles [13], [14]. There is clearly potential for HEVs to reduce the GHG emissions impact of LDVs, and the impact of HEVs in this regard is well underway. The introduction of the HEV Powertrain on the US market is indicated in the LDV efficiency graph for cars and trucks below [9]:

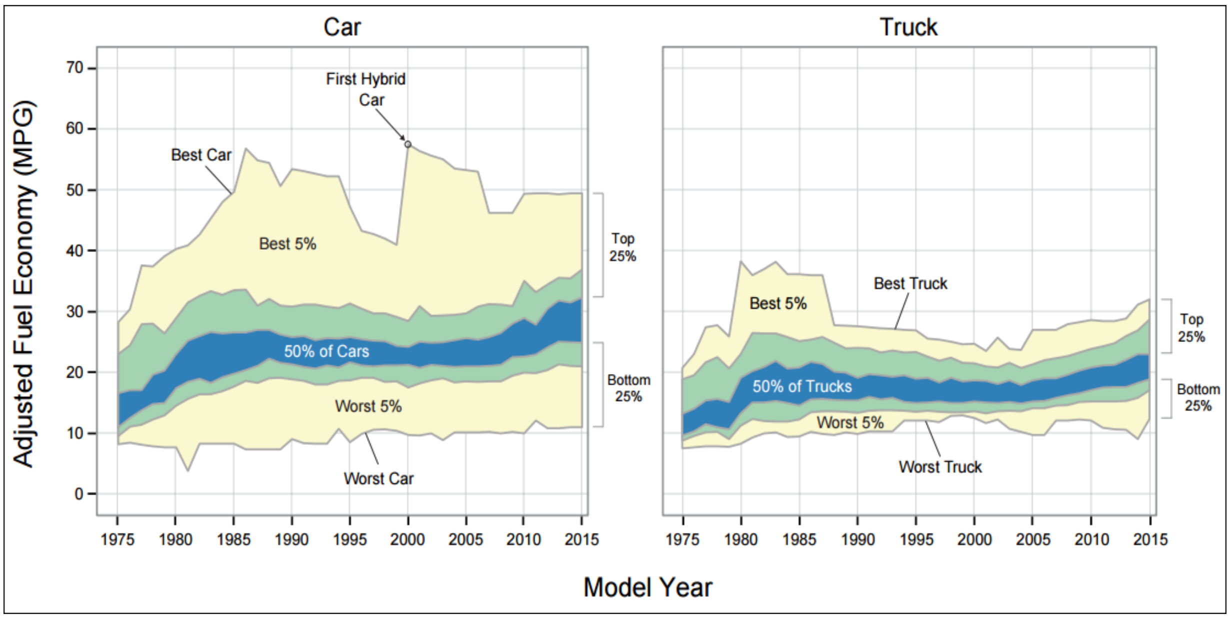


Figure 6: Fuel Economy Dist. per Model Year, Excluding AFVs (From US EPA 2015 Ref. 9 Page 10)

The above information provides a reference for how a larger domestic fleet of hybrid vehicles would raise the average LDV fuel economy. While the above chart gives some context to how the average fuel economy is improving per model year, it does not include data on Alternative Fueled Vehicles (AFVs) or specific information regarding the growing HEV fleet population in the US. The following chart compares these various options, with sales information sourced from the US Department of Transportation (USDoT) [15]:

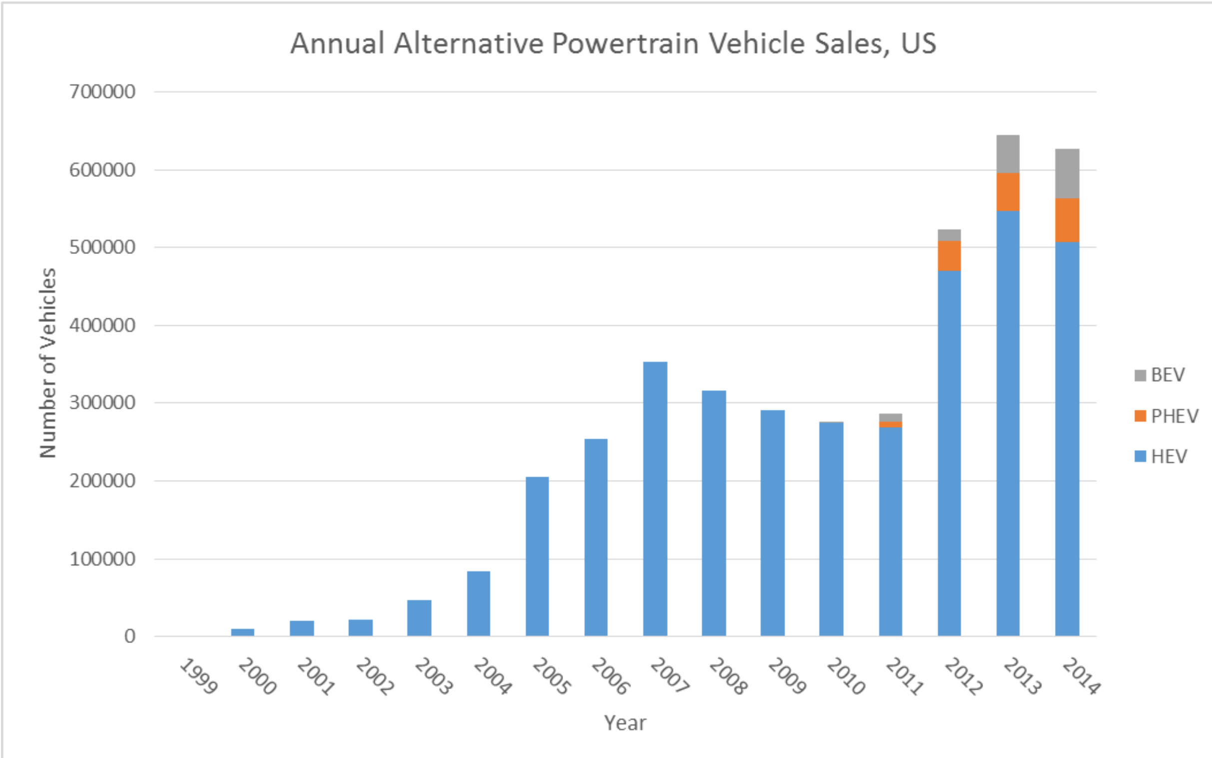


Figure 7: Annual Sales for HEVs, PHEVs, and BEVs, US

The additional context for AFV sales helps to provide an understanding for how large of an impact Battery Electric Vehicles (BEVs) and Plug-in Hybrid Electric Vehicles (PHEVs) are making in the automotive market compared to HEVs. The relatively large adoption of HEVs compared to BEVs and PHEVs is an indication of the large role that HEVs currently play in improving the GHG emissions footprint of the US LDV fleet. While there is growth over these years, there is still much of the domestic LDV fleet to improve as well. As of 2014, there are over 3.6 million hybrid vehicles registered with the US department of transportation, which represents 1.4% of the total registered LDV fleet in the US [16]. In the context of this thesis, HEVs represent a very significant portion of the increasing AFV market, and a LDV option with significant fuel economy benefits.

## 2.3 Sensor technology as a means of Improving Light-Duty Transit Efficiency

In the context of enhancing fuel economy, modern sensor technology can enable a vehicle to detect its surroundings to a greater extent than the human driver behind the wheel, allowing the driver to make more conscientious driving decisions. These technologies usually serve the primary role in enhancing passenger safety. For example, vehicular radar systems (VRSs) are employed on many vehicles today for the purpose of reducing head-on collisions, as signals can be detected hundreds of yards down road, through rain and fog which may otherwise preclude a driver from making safe driving decisions. However, in the same sense that such VRSs can prevent head-on collisions, VRSs can also be employed to prevent unnecessary accelerations towards upcoming traffic jams, or could be used to suggest a proper speed for the driver. Please refer to Section 4.6.1 VRS Overview for more information regarding the use of VRS technology.

This thesis reflects the trend of increasingly greater integration of environmental sensor technologies for LDVs, particularly HEVs. For historical context, the following list of vehicular technologies and corresponding year of integration are helpful to illustrate the relatively rapid pace of recent technological milestones:

- Cadillac offers electric starter as replacement the for hand-crank (1912)
- Mechanical Cruise Control invented (1948)
- First production vehicle with optional anti-lock brakes (1966)
- Electronic Cruise Control invented (1968)
- Electronic Stability Control invented (1987)
- Laser-Based Adaptive Cruise Control offered as an option for first time (1995)

- Lane-Departure Warning System offered for first time (2001)
- Pre-Crash Warning System offered for first time (2003)
- First successful fully autonomous 132-mile desert challenge (DARPA, 2005)
- Google announces fully driverless car project (2010)
- Google driverless test-car able to drive 5 consecutive miles in typical transit situations on public roads (2010)
- Nevada issues first driverless car license plate (2012)
- Google driverless test-car able to drive 1000 consecutive miles in typical transit situations on public roads (2012)
- National Highway Traffic Safety Administration (NHTSA) publishes policy statement for autonomous vehicles (2013)
- Google driverless test-car(s) able to drive 50,000 consecutive miles in typical transit situations on public roads (2014)
- Anticipated year for fully autonomous city-driving taxi service (2020)

While full driving autonomy appears to be just on the horizon, this thesis is primarily concerned with evaluating technologies to for their ability to enhance the fuel economy for human-driven hybrid vehicles in the near-term. Alternatively, this research aims to serve as a bridge between the insulated human-driven transportation paradigm of our past, and the increasingly technologically-connected transportation paradigm of the future.

### 2.4 Intelligent Transportation Network Simulation

In the context of this thesis, an "Intelligent" Transportation network (ITN) is one which uses information garnered from advanced vehicular technologies such as from V2V (described in Section 4.3 Vehicle to Vehicle Communication Systems) and V2I (described in Section 4.4 Vehicle to Infrastructure Communication Systems) to enhance vehicular fuel efficiency. While the most accurate method for learning about intelligent transportation networks is by conducting real-world tests, sometimes real world tests are not feasible in terms of cost and time or are practically impossible [17]–[23]. For the purpose of this research, an ITN will be simulated in the scale over a highway during a realistic rush-hour scenario. Various configurations of V2V and V2I technology will be integrated on vehicles within that simulation, and the results will ultimately show the impact of such technological integration on traffic flow, vehicular fuel economy, and local air quality. Overall, these integrated computer simulations lend themselves to be very well suited to accomplish such research objectives within the time and financial constraints of this project. ITN computer modelling allows the researcher to test various vehicle properties and penetrations, V2X technologies, roadway properties, and control strategies for realistic approximations of resulting efficiencies and environmental impacts. For more details on the research approach described, please refer to Section 5.3 Relevant Research Processes.

The simulation tools to accomplish this research can be explained as several separate components which are eventually integrated together. The first component to identify is the microscopic traffic simulator. The traffic simulator simulates just that, traffic. Additionally, a microscopic simulator is best suited for small-scale (street-level) detail, which allows for researchers to understand and track the behavior of individual vehicles [24]. These tools are commonly used for simulating proposed infrastructure, the interaction between vehicles and new controls systems, and short-term traffic forecasting [25]. Some of the limitations of these tools are that they rely on simple algorithms to model lane-changing and car-following behaviors, little shared standards for evaluating results, and higher computational time compared to less resolute simulation techniques [25]. For the purposes of this thesis, a microscopic traffic simulator was determined to be most appropriate. As a point of comparison, a macroscopic simulator is a less resolved transportation simulation tool best suited for large scale (city-scale) simulations where a lesser degree of resolution is required [24]. For more information regarding the decision of the traffic simulation tool, please refer to Section 6.1 Traffic Simulation Tool.

The next component of an ITN would be the network simulator. Where the microscopic traffic simulator models the interaction between separate vehicles, the network simulator models the wireless communications between each vehicle enabled by V2V and V2I technology [17], [20]–[23]. As with traffic simulation tools, there are many options available for network simulation tools. For the purpose of this research, the network simulation tool was selected according to criteria such as: supporting V2V and V2I operational standards, being capable of simulating realistic interference caused by buildings and other obstacles, and the ability to be easily integrated with a traffic simulation tool, as seen in Section 6.2 Network Simulation Tool.

The final component of this ITN simulation tool is the emissions simulator. To reflect the fact that this research will enable the simulation of vehicular emissions, it is critical to select an appropriate emissions simulation tool for the purposes outlined in this work. Specifically, the emissions simulation tool must match the resolution of the traffic simulation tool. Emissions simulation tools, like traffic and network simulation tools, can have course and fine resolution, and have varying degrees of temporal resolution of pollutants concentrations as well. For the purposes of this research, an emissions simulation tool which has similar spatial and temporal resolution to the microscopic traffic simulator would be sufficient. For more information regarding the selection of this simulation tool, please refer to Section 6.4 Emissions Simulation Tool.

The integration of these models is done to allow the properties and dynamics of vehicle simulators and V2X network simulators affect one another in real time. Overall, this approach of using combined traffic and network models to function as inter-dependent sub-models is an accepted method to simulate ITN's for practical purposes. For more information on the particular architecture of the integrated simulator developed later in this thesis, please refer to Section 5.

### 2.5 Summary

Currently, HEVs offer the most significant contribution towards enhancing LDV fuel economy compared to other AFVs. With hundreds of thousands of HEVs being sold each year in the US, their role in helping to improve the domestic LDV sector will continue for years to come. Concurrently, vehicular sensor technology is becoming less cost prohibitive and more effective at detecting environmental signals which threaten passenger safety and vehicular fuel economy. Enabling HEVs with these technologies will help to improve future LDV fuel efficiency beyond what would have otherwise been possible. In order to learn more about the impact that these technologies will have on HEVs, this research selects the most appropriate traffic, network, and emissions simulation tools to comprise the Fuel Economy and Traffic of Connected Hybrids (FETCH) Tool after conducting a thorough study on environmental signals, sensor technologies, and relevant research initiatives.  The FETCH Tool will also be accompanied by a research plan to aide future researchers to pursue further model development.

## 3 APPROACH

The goal of this thesis is to develop a research framework for the future comprehensive study of the impact of advanced vehicular technology on traffic flow, emissions, and fuel economy of hybrid vehicles using a validated simulation model. The following objectives were completed in order to achieve this goal.

**Task 1: Identify environmental signals which can be detected to improve vehicular fuel efficiency for hybrid vehicles, and identify state of the art sensor technologies which can be used to detect these signals.**

This research begins with a literature review of demonstration projects and academic publications to determine the environmental signals which can be detected for enhancing vehicular efficiency. It was discovered that vehicle response to safety-critical scenarios (such as preventing a forward collision) are also valuable in vehicle efficiency scenarios (such as preventing excessive acceleration and deceleration). Therefore, this literature review begins by primarily searching for demonstration projects and/or academic publications that test and evaluate state of the art technologies which mitigate threats to (1) safety and (2) efficiency.

After exploring these research works and demonstration projects, state of the art sensor technologies could be organized according to the environmental signal to be detected. From this list of sensor technologies, the most relevant and promising technologies in the specific context of enhancing hybrid vehicle fuel efficiency were investigated further. While this is not an exhaustive list of all sensor technologies in development, the technology listed is supported by demonstration projects and often has support of automaker-funded research initiatives. These research initiatives are factors which indicate a degree of technological maturity, which is considered to be a significant factor in selecting particular sensor technologies to investigate further. This section concludes with the selection of V2V and V2I technologies as the primary focus for the following research objectives.

**Task 2: Perform a literature review to find studies with relevant research goals, and investigate the tools used and research processes commonly used to solve such research problems.**

Modelling tools are necessary to research the behavior of complex transportation networks without the expense of large scale testing. The first step towards fulfilling this objective is to apply the information garnered from Section 4.7 Objective 1 , and survey the literature for research studies concerning the simulation of V2V and V2I impacts on transportation networks. This objective identifies 7 (Past and current) research projects directly relevant to the research goal of this thesis. These research works provide insight for the simulation models and the corresponding parameters necessary to successfully complete the goals of this thesis.

**Task 3: Determine the most appropriate modelling tools for simulating the impact of V2V and V2I technologies for this research.**

Following the literature review, the research proceeds to select the appropriate simulation models. Model selection is based on the relevant criteria from previous research initiatives which share relevant research goals to this study, as explained in greater detail in the results sections.

**Task 4: Develop a research process framework and tool to explore the interaction between the selected V2V and V2I simulation tools and the required inputs and outputs of those tools, and develop a corresponding research plan to accomplish the aforementioned research goals.**

After choosing the appropriate models, the necessary model inputs required for these models to function properly are also included, along with potential sources for this information. The research framework was created to illustrate these inputs and outputs of the models themselves, serving as a guide for future researchers to understand the way these different models operate with one another. This research framework is titled: the Fuel Economy and Traffic of Connected Hybrids simulator, or more concisely, FETCH.

When the model selection and model framework objectives are complete for FETCH, a detailed plan to carry out the full research project is provided to assist researchers in future studies.

**Task 5: Demonstrate the tool efficacy.**

The final objective of this research will show the basic functionality of the tool to the extent that a simple V2V or V2I control strategy can be implemented. The result garnered should indicate a change in traffic flow, vehicle fuel economy, or emissions.

# 4 OBJECTIVE 1 RESULTS

**Objective 1: Identify environmental signals which can be detected to improve vehicular fuel efficiency, and identify state of the art sensor technologies which can be used to detect these signals.**

This research begins with primarily searching for demonstration projects and academic publications which test and evaluate state of the art technologies which mitigate major threats to (1) passenger safety and (2) vehicular efficiency. The results of this preliminary study are organized by the signal to be detected.

## 4.1 Environmental Signals

### 4.1.1 Slowing or Stalled Vehicles

Slowing or stalled vehicles pose a safety risk to drivers, and the sensor technologies that can be used to determine if a frontal collision will take place can also be used to mitigate the effects of excessive accelerations and decelerations. A number of research initiatives from academic research institutions and automakers alike have evaluated sensor technologies to avoid the negative impacts slowing or stalled vehicles have on vehicular fuel economy. For example, the Grand Cooperative Driving Challenge was designed to validate theoretical research conclusions that cooperative adaptive cruise control systems (CACC) can increase fuel economy by approximately 10%, in which sensor technologies such as vehicular radar systems (VRS's), camera systems (CS's), LiDAR systems, and vehicle-to-vehicle (V2V) communication systems were evaluated [26]–[28]. The Automotive Collision Avoidance System Field Operational Test was another research initiative involving the National Highway Traffic Safety Administration (NHTSA) and the General Motors Company. Together, these entities investigated forward collision warning systems and adaptive cruise control systems incorporating CS's and VRS's for ability to improve driver safety [29]. The Connected Vehicle Safety Pilot was a US Department of Transportation (USDoT) and automaker collaboration to test V2V and vehicle to infrastructure (V2I) technologies in real-world scenarios for their ability to prevent crashes without distracting drivers [30]. In the Car 2 Car Communication Consortium, over 12 major automakers collaborated in an effort to develop industry standards for an array of connected vehicle technologies such as V2V and V2I [31]. Finally, the Crash Avoidance Metrics Partnership (CAMP) collaborative research effort between a number of automakers has evaluated the capabilities of connected vehicle systems such as V2V and V2I to enhance driver safety in a multitude of driving scenarios [32].

### 4.1.2 Stoplights and Stop Signs

Stoplights and stop signs can create scenarios for fuel efficiency loss when signals change or the location of these signals is unknown to the driver, and such scenarios are preventable with presently available technologies. Research efforts offer more insight as to how these signals can work collaboratively with drivers and vehicular systems and to what extent travel efficiency can be improved. Projects such as the Cooperative Vehicle Infrastructure Systems project (CVIS) have helped to develop a real-world technological platform to enable data transfer between vehicles and the surrounding transit infrastructure with the goal of enhancing driver awareness and transportation efficiency [33]. The Dynamic Information and Application for Mobility with Adaptive Networks and Telematics Infrastructure project (DIAMANT) strived to meet similar goals with regards to using V2V and V2I technology to keep drivers informed of potentially changing traffic patterns [34]. The Safe and Intelligent Mobility–Test Field Germany (SimTD) project performed a real-world test of connected vehicle technologies and determined ways to resolve technical issues surrounding V2I communication [35].

#### 4.1.3 Weather Conditions

Vehicular transit subject to inclement weather conditions can play a significant role in the fuel efficiency of that journey. In this context, it is important for drivers to be aware of the optimal route that should be taken should this environmental signal be detected. For instance, researchers have proposed real time weather notification systems which inform drivers and running control systems by using various sensors placed along roadways and within vehicles [36]. Such research can be thought of as enhancing safety and fuel economy, because adapting vehicle speed to safely avoid natural hazards will also enable vehicles to prevent wasting fuel when approaching these hazards. Similarly, onboard camera systems have been proposed to alert drivers of increasingly hazardous levels of precipitation, allowing drivers to adjust their speed sooner for safer and more efficient travel [37]. This concept has also attracted automaker support, where vehicles can anticipate changing traffic patterns resulting from changes in weather by retrieving weather data from local sources and passing data amongst vehicles using cooperative adaptive cruise control systems [38].

#### 4.1.4 Human to Vehicle Interaction

The influence that a human driver can have over a vehicle is the subject of much study in demonstration projects and in literature alike. Drivers may unknowingly operate their vehicles inefficiently despite concentration on driving tasks. This is the importance of an effective human to vehicle (H2V) interface. Research efforts in this space have spanned many years, and have helped evaluate many different means of human/machine interaction for the greatest improvement to the efficiency of vehicle operation [39]. Demonstration projects have helped evaluate this research, namely, the ecoDriver Project [40], and the eCoMove Project [41].

### 4.1.5 Environmental Signals Summary

The following signals were the subject of demonstration projects and research initiatives conducted in the context of enhancing safety and fuel economy. It was found that where the vehicle has potential to prevent an accident, the vehicle has potential to conserve fuel.

Table 1: Environmental Signals

| **Environmental Signal** |
|---|
| Slowing or Stalled Vehicles |
| Stoplights and stop signs |
| Traffic Conditions |
| Weather Conditions |
| Human to Vehicle Interaction |

## 4.2 Determining Relevant Sensor Technologies

After identifying significant environmental signals, it is important to determine whether or not the sensor technologies used in these demonstration projects are valuable to investigate in detail for this thesis. To further understand the technological maturity of these technologies, the aforementioned research projects funded by industrial automakers were prioritized when selecting additional relevant academic publications. The purpose prioritizing automaker research affiliations is to further verify a significant research effort to advance the state of the art for the vehicular application of these technologies. After this preliminary work is complete, the sensor technologies most relevant to the goals of this thesis will be investigated further for their merit for enhancing vehicular fuel efficiency in Section 4.3 Vehicle to Vehicle Communication Systems. While this is not an extensive list, it does represent what are believed to be the most value technologies to investigate in the timeline and scope of this thesis.

### 4.2.1 V2V, Vehicle to Vehicle Technology

The demonstration projects and research initiatives in the previous section provide a clear indication that Vehicle to Vehicle (V2V) technology is relatively mature (Refer to V2V Demonstration Projects, and V2V Table of Influential Publications). Automaker support of these demonstration projects include General Motors, Daimler, BMW, Ford, Mitsubishi, Nissan, and Volvo. Related literature also indicated a heavy investment in the development of this technology. Note that General Motors and Carnegie Mellon University actively collaborate on both research and demonstration projects, and their relationship is evident in the context of other sensor technologies as well [42]. Bosch and Siemens also collaborate with a number of German automakers, namely Daimler and BMW [32]. Such collaborations indicate a degree of maturity for the V2V communication systems. For more information regarding V2V technology, please refer to Section 4.3 Vehicle to Vehicle Communication Systems.

### 4.2.2 V2I, Vehicle to Infrastructure Technology

Vehicle to Infrastructure (V2I) technology is fundamentally similar to V2V, and it followed that there are certain research initiatives which investigate both technologies simultaneously. However, one difference between V2V and V2I research initiatives is a relatively stronger V2I research investment in from Europe relative to the US. This would indicate that the US market may not be as ready for V2I technology as is the case in Europe. For more information regarding V2I technology, please refer to Section 4.4 Vehicle to Infrastructure Communication Systems.

#### 4.2.3 CS, Camera Systems Technology

While the search for demonstration projects using vehicular Camera System Technology (CS's) were certainly not as strong as those from V2V and V2I (Refer to CS Demonstration Projects), further study into relevant CS publications suggest a fairly strong research investment in vehicular applications. Similar to V2V, vehicular application of CS technology is evident with car manufacturers such as Ford, General Motors, Daimler, and BMW [43]–[46]. For more information regarding CS technology, please refer to Section 4.5 Camera Systems.

#### 4.2.4 VRS, Vehicular Radar Systems Technology

Vehicular Radar Systems (VRSs) are quite mature technologies in the safety context, and VRSs can be found on many vehicles of today (Refer to VRS Table of Influential Publications). This technology can certainly be considered mature, but in the context of enhancing vehicular efficiency there may be greater potential than is obvious. For more information regarding VRS technology, please refer to Section 4.6 Vehicular Radar Systems.

### 4.2.5 H2V, Human to Vehicle Interface Systems Technology

In the context of enhancing hybrid vehicle fuel efficiency, the relatively weak representation of demonstration projects and short project timescale for Human to Vehicle Interface systems (H2V) strong suggest that this technology is beyond the scope of this thesis and may be more appropriate for research for a future time. For more information regarding H2V literature in the H2V Demonstration Projects / Research Initiatives section.

### 4.2.6 LiDAR Systems Technology

Similar to H2V systems, LiDAR systems applied in the context of safety and efficiency were not as strong as those of other technologies. Additionally, much of the LiDAR capability overlaps with camera systems, being that both are susceptible to visual obscurities such as rain, and dust.  For those reasons, LiDAR technologies were determined to be outside the scope of this thesis. The similarly promising, yet more significantly researched technology, Camera Systems Technology, was investigated instead.

### 4.2.7 Infrastructure Data / Mapping

Having advanced knowledge of surrounding infrastructure can help alert running control systems or the human driver to oncoming areas of reduced speed or other hazards. However, similar to LiDAR and CSs, there is overlap between the benefits of including Infrastructure Data / Mapping capabilities to integrating a V2I system with a vehicle. Additionally, there was relatively less automaker support for Infrastructure Data / Mapping research compared to V2I technology. Accordingly, V2I systems are chosen to research in greater depth.

### 4.2.8 Relevant Sensor Summary

After reviewing demonstration projects for environmental signals and sensor technologies, and after investigating the research initiatives behind each sensor technology, this research determined which technologies to include in the report. From this study, V2V, V2I, CS, and VRS technology was determined to be of value. However, LiDAR, Infrastructure Data / Mapping, and H2V technology was determined to not be of significant value to this thesis. Please find this information organized below:

Table 2: Environmental Signals, and Associated Technologies

| **Environmental Signal** | **Associated Technology** | **Technology In Report** | **Future Technologies to Investigate** |
|---|---|---|---|
| Slowing or Stalled Vehicles | V2V Communication<br>Camera systems<br>Radar<br>LiDAR | V2V Communication<br>Camera systems<br>Radar | LiDAR |
| Stoplights and stop signs | Camera systems<br>V2I<br>LiDAR<br>Infrastructure Data / Mapping | Camera systems<br>V2I | LiDAR<br>Infrastructure Data / Mapping |
| Traffic Conditions | V2I<br>LiDAR | V2I | LiDAR |
| Weather Conditions | V2V | V2V | |
| Human to Vehicle Interaction | Various HMI Tech. | Various HMI Tech. | Various HMI Tech |

## 4.3 Vehicle to Vehicle Communication Systems

This section covering Vehicle to Vehicle (V2V) communication systems will introduce the reader to the in-depth surveys of specific sensor technologies. V2V communications technology enables a hybrid vehicle to have an awareness of the status (speed, position, acceleration / deceleration, etc.) of surrounding vehicles, while also being able to broadcast the same information to surrounding vehicles by using wireless communications technology. The fuel economy benefits of installing these systems on standard powertrain vehicles are somewhere between 5-20% [47]–[49], depending on the situation evaluated. There are significant technological similarities to V2I technology, as covered in Section 4.2.2 V2I, Vehicle to Infrastructure Technology.

### 4.3.1 V2V Overview

V2V communication systems anonymously exchange wireless data between vehicles. V2V systems consist of Dedicated Short-Range Communication” (DRSC) using Wi-Fi transmitters using the 5.85-5.925GHz bands, as defined in the Wireless Access in Vehicular Environments (WAVE) standards, in tandem with GPS data. Additionally, IEEE 1609 and ITS-G5 are the specific standards which define the collection and security of V2V and V2I communication [50], [51]. V2V systems enable two-way communication between vehicles where one may transmit a message with location information to be interpreted by surrounding vehicles, as standardized by SAE J2735. A standard message may relay:

- Random vehicle ID

- Sequence number
- Time stamp
- Position coordinates and accuracy
- Motion data (velocity, acceleration, braking status, possibly transmission state)
- Vehicle Size

This technology has promise in the context of enhancing hybrid vehicle fuel efficiency in similar ways to the promise of enhancing occupant safety. Where this technology has the ability to alert for objects to avoid, it may also alert for regenerative braking for traffic jams, stationary vehicles, or other potential hazards ahead as signaled by other vehicles [52], [53].

In this context, V2V technology has the potential to enhance adaptive cruise control and ultimately provide advanced "awareness" of situations where regenerative braking can be applied automatically. In particular, the increasingly advanced cruise control systems (which are currently radar-based) can get additional perspective of the vehicle's surrounding environment (from farther distances, adding to the overall awareness of upcoming obstacles/traffic) to maximize the opportunity for regenerative braking or further optimize vehicular running control in general. The integration of connected vehicle technologies (V2V/V2I) to cruise control systems is altogether known as Cooperative Adaptive Cruise Control (CACC). CACC systems have been found to improve hybrid running control by preventing the traffic speed oscillations (seen in stop-and-go traffic) from occurring and conserving fuel / storing energy when the vehicle encounters such situations [20]. Replacing aggressive human driving behaviors with a CACC has been shown to increase fuel economy by 20%, and a CACC will improve fuel efficiency by somewhere between 5-10% for drivers with more moderate behavior, as evaluated on standard powertrain vehicles [47]–[49].

### 4.3.2 V2V Conceptual Applications

This section details some various unconventional ways of applying V2V technology (or the similar V2I technology) which are not immediately associated with V2V technology itself. Some of these concepts have not been proven in demonstrations, and some have not evaluated fuel economy impacts. However, these concepts have merit of enhancing fuel economy, and may be useful to evaluate in future studies enabled by the later contributions of this thesis.

*Concept 1: V2V / V2I Garnering Weather / Weather Report Data to Enhance Vehicle Perception*

This concept builds on the idea of enhancing a vehicular perception of surrounding environmental signals, including information on changes to weather, by using V2V or V2I technology. This concept has been investigated in terms of safety and in the context of fuel savings as well. The core of this concept is that weather conditions can significantly impact the optimal vehicular performance and route for the vehicle. Weather information can be sourced in a combination of two ways: 1) Vehicles informing other vehicles about weather conditions using onboard sensors [36], [37], and 2) Vehicles receiving information from weather stations, online, or other non-vehicle sources [38], [54].

Table 3: V2V Weather Concept Literature Review

| Organization | Year | Title | Reason | Citations |
|---|---|---|---|---|
| El-Tawab & Abuelela / Old Dominion University | 2009 | Real-time weather notification system using intelligent vehicles and smart sensors | Vehicle-Centric Weather Reporting | 4 |

| Organization | Year | Title | Reason | Citations |
| --- | --- | --- | --- | --- |
| Kurihata<br>Nagoya University, Japan<br>Denso Corporation, Japan | 2005 | Rainy weather recognition from in-vehicle camera images for driver assistance | Vehicle-Centric Weather Reporting Using Camera Systems | 18 |
| Dannheim<br>BMW<br>Objective Software GmbH,<br>University of Hagen, Germany | 2013 | A novel approach for the enhancement of cooperative ACC by deriving real time weather information | Weather Information includes weather stations / online sources | 0 |
| Dannheim<br>BMW<br>Objective Software GmbH,<br>University of Hagen, Germany | 2013 | TEAM - CO2 reduction through online weather assistant for cooperative ACC driving | Weather Information includes weather stations / online sources | 0 |

*Concept 2: Using V2V Data to Predict Vehicle Trajectories and More Efficient Routes*

This concept involves processing raw V2V data to create direct short-term suggestions for the driver, or to add to the perception for the running control of the vehicle. One example suggestion is a fuel efficient velocity profile for the driver to take while in stop and go traffic, which can account for up to 8% fuel economy enhancement for standard powertrain vehicles [55], [56]. The same concept would work in combination with an Adaptive Cruise Control (ACC) System, where the throttle and braking movements are automatically controlled by the vehicle on the highway. V2V technology would enhance ACC by reducing the “string instability” of traffic (the uncoordinated velocity fluctuations of stop and go traffic), by providing a greater environmental awareness to the running control with information on nearby vehicle locations. This particular concept was not found in literature as of the writing of this thesis.

On the whole, V2V / V2I data could also be used to suggest the most efficient route for the driver. This concept was investigated by sending aggregated data from a centralized online source [57]. Using real time V2V data solely from vehicles for this purpose has not been found in literature at the time of this writing. Please refer to the table below for more information:

Table 4: V2V and Vehicle Trajectories Prediction, Efficient Route Citations

| Organization | Year | Title | Reason | Citations |
|---|---|---|---|---|
| Kerper<br>VW<br>University of Düsseldorf | 2011 | Driving more efficiently - The use of inter-vehicle communication to predict a future velocity profile | Fuel Efficient velocity suggestions using V2V tech. | 0 |
| Brakatsoulas<br>RA Computer Technology Institute<br>University of Texas, San Antonio | 2005 | On map-matching vehicle tracking data | Core Publication | 127 |
| Fleischmann<br>DaimlerChrysler AG<br>University of Augsburg, Germany | 2004 | Dynamic vehicle routing based on online traffic information | Core Publication | 96 |

### 4.3.3 V2V Technology Outlook / Maturity

This section provides insight for how soon this technology can integrated onto a modern vehicle to enhance fuel economy. V2V technology is supported by significant study in demonstration projects (V2V Demonstration Projects) and in literature (V2V Table of Influential Publications), while V2V also has current standards to regulate its use on public roads (Table 5: V2V Standards: Current and Pending). However, because V2V technology depends on a level of fleet-wide integration, it will take time before there are enough V2V enabled vehicles to make the fullest potential difference on the roads. This will take relatively longer than the quick integration of systems such as Camera Systems (Section 4.5 Camera Systems) and Vehicular Radar systems (Section 4.6 Vehicular Radar Systems).

*V2V Technological Status*

This technology has been steadily approaching the deployed state, which is made evident in domestic policy proceedings, academic publications and collaborations with automakers, and demonstration projects.

With regard to domestic policy, the U.S. National Highway Transit Safety Administration (NHTSA) released an Advance Notice of Proposed Rulemaking (ANPRM) in August of 2014. The proposal would add a Federal Motor Vehicle Safety Standard (FMVSS #150) to require V2V communication capability for all new light duty vehicles. This proposal is the result of an underlying effort to evaluate and ultimately deploy V2V technology:

> "NHTSA has worked in close partnership in this research both with other [Department of Transportation] DOT agencies, including the Office of the Assistant Secretary for Research and Technology and the Federal Highway Administration, and with several

leading auto manufacturers and academic research institutions, who have invested significant resources into developing and testing V2V technology. The collaboration of government, industry and academia is critical to ensure V2V technology's interoperability across vehicles.” (NHTSA, Feb. 2014)

*V2V Standards: Current and Pending*

In addition to the domestic policy movement, there are accepted domestic standards which regulate the integration of V2V technology on vehicles to be sold in the future. These standards should also help provide additional support for V2V technological maturity.

Table 5: V2V Standards: Current and Pending

| **Organization** | **Std.** | **Title** | **Status** | **Description** |
|---|---|---|---|---|
| IEEE | 1609 | Family of Standards for Wireless Access in Vehicular Environments (WAVE) | Accepted | Defines standard of services, interfaces, and architecture which enables V2V and V2I comm. |
| SAE | J2735 | Dedicated Short Range Communications (DSRC) Message Set Dictionary | Accepted | Message content to relay between vehicles |

*V2V Research Initiatives and Collaborations*

There are a number of domestic research initiatives and demonstration projects which indicate that V2V technology is substantially evaluated. Domestically, there is the Crash Avoidance Metrics Partnership (CAMP), and the Connected Vehicle Safety Pilot. Overseas, there are projects by the likes of the Dynamic Information and Application for Mobility with Adaptive Networks and Telematics Infrastructure (DIAMANT), the Safe and Intelligent Mobility–Test Field Germany (SimTD) project, and the Cooperative Vehicle Infrastructure Systems (CVIS) project. Some of these projects have been conducted in great scale, with the Connected Vehicle Safety Pilot having upwards of 2800 V2V-enabled vehicles, and at great cost. Please refer to V2V Demonstration Projects, and V2V and V2I Demonstration Projects for more information.

#### 4.3.4 V2V Summary

In total, V2V research initiatives and demonstration projects allow this research to conclude that V2V technology is maturing steadily and will be feasible to integrate with a hybrid vehicle for significant fuel economy improvements. Depending on driver behavior, the fuel efficiency of the vehicle can be enhanced between 5% to 20% as evaluated on standard powertrain vehicles [47]–[49]. Conventional applications of V2V technology alert the driver to upcoming traffic conditions or hazards, which in the fuel efficiency context enables that driver to proactively ease the throttle or potentially to engage regenerative braking for hybrid powertrain vehicles. V2V technology can also be integrated with an adaptive cruise control system which could do these functions automatically.  Additionally, there have been concepts investigated by major automakers looking to apply this technology ways that are less straightforward, such as the weather information garnering and the efficient vehicle trajectory research.

The technological maturity of V2V technology is relatively high compared to other technologies such as Camera systems and Vehicular Radar Systems. The demonstration projects discussed conclude that the technology is effective and relatively economically feasible to install.  Domestically, the NHTSA is supportive for mandatory V2V systems in vehicles. However, should a mandate come through, there will be considerable time before there will be enough V2V-enabled vehicles to have a significant impact on fuel efficiency. This is important because there is little use for V2V technology when there are no significant numbers of V2V-enabled vehicles to communicate with each other.

As a result, V2V systems should be expected as a very significant part of the fuel effect vehicle of the future, but in the short-term there may be little impact on fuel economy for a V2V-integrated vehicles.

## 4.4 Vehicle to Infrastructure Communication Systems

Vehicle to Infrastructure (V2I) communication systems can be considered a continuation from V2V Communication Systems. That is, the core technologies of data transfer are largely the same, but the data is transferred between vehicles and infrastructure sources such as traffic lights. This survey will highlight how V2I technology can enable a hybrid vehicle to have an awareness of infrastructure (such as changing stoplights) for a potential fuel economy benefit somewhere between 10-25% for standard powertrain vehicles [58], [59].

### 4.4.1 V2I Overview

Vehicle to Infrastructure (V2I) communication systems anonymously exchange wireless data between vehicles and a centralized source of data, referred to as the “infrastructure.” V2I and V2V systems use the same core technology with regard to data transfer, and operate according on the same standards. However, where V2V systems relay data between groups of vehicles amongst themselves, V2I systems provide vehicles with data from a common source. The similarities and differences between V2V and V2I systems are more evident in each respective application, each offering a particular opportunity to improve fuel economy.

For example, typical applications of V2V technology provide: left-turn assistance (from knowing vehicle position), Pre-collision warning (from knowing vehicle position, and movement information), Lane change warning (from knowing vehicle position), and Emergency electronic brake light (which is an electronic emergency message that a stalled vehicle can send which cannot be obscured with fog or other visual limitations).

Alternatively, some applications of V2I technology may include traffic signal warnings, which can improve vehicle efficiency by activating a regenerative braking system when approaching red stoplight. Similarly, the vehicle can communicate with the signal and "suggest" that the signal change prior to the vehicle reducing speed, or provide information on reduced-speed areas ahead which could also trigger regenerative braking.

### 4.4.2 V2I Conceptual Applications

As in the previous section describing V2V communication, this section illustrates some unconventional applications of V2I technology which are not immediately associated with V2I technology itself.

*Concept 1: Vehicle-Traffic Signal Cooperation*

A vehicle which stops at a red light and accelerates again can produce up to four times the $CO_2$ emissions of a vehicle driving at constant speed [60]. Preventing such situations would have a proportionally significant impact on vehicular fuel efficiency. One way in which V2I technology can prevent this specific transportation inefficiency is by enabling traffic signals to broadcast their status to oncoming vehicles, and for those vehicles to automatically interpret such signals to facilitate (or automatically achieve) more efficient actions. If a vehicle were equipped with the necessary V2I technology and an ACC, that vehicle would have advanced knowledge of signal status and would begin to apply the appropriate velocity curve, or regenerative braking technologies. For the former case interested in standard powertrain vehicles, a study discovered that about 40% fuel savings can be accomplished by eliminating stop-and-go behavior at traffic lights when drivers know the signal status and duration in advance [61].

Table 6: V2I Concept 1 Literature Review Table

| **Organization** | **Year** | **Title** | **Reason** | **Citations** |
|---|---|---|---|---|
| Rakha, H.<br>Transportation Research Board, Washington, USA | 2000 | Requirements for Evaluating Traffic Signal Control Impacts on Energy and Emission Based on Instantaneous Speed and Acceleration Measurements | Tech. Overview | 99 |
| Asadi, B., Vahidi, A.<br>Clemson University | 2011 | Predictive cruise control: Utilizing upcoming traffic signal information for improving fuel economy and reducing trip time | Tech. Overview | 34 |
| Koenders & Vreeswijk<br>Peek Traffic BV | 2008 | Cooperative infrastructure | Publication resulting from CVIS V2I Project | 2 |

Demonstration projects such as CVIS have shown that the concept is able to be supported with available technology, with an overall industry direction moving towards incorporating such V2I technology to a greater extent [62]. Current European research efforts continue the push for such use of V2I technology in the ITS-Europe ecoDrive Project, where fuel savings of up to 25% have been measured in computer simulations of representative traffic through intersections [59].

*Concept 2: Driver Awareness of Future Traffic Light Status / Green Light Optimal Speed Advisory (GLOSA)*

One slightly less advanced application of V2I technology relies solely on the driver to prevent red-light losses in fuel efficiency. Essentially, a driver of a vehicle is approaching an intersection that is about 20 seconds of travel away and the driver receives a message on their dashboard stating that the signal is red while also displaying the recommended speed with which to begin approaching this intersection. In addition, such systems could also display information on how long the traffic light will remain in that particular phase [58], [63]. This concept has been measured to improve fuel economy by 10% when tested on standard powertrain vehicles [58].

This application of V2I technology is also being investigated in the context of safety as the part of a Cooperative Intersection Collision Avoidance System (CICAS), where rather than displaying a message regarding an oncoming intersection and recommended velocity profile, the system would provide an emergency alert to a driver approaching a dangerous intersection, or who may be on a collision course with another vehicle [64].

Table 7: V2I Concept 2 Literature Review Table

| Organization | Year | Title | Reason | Citations |
|---|---|---|---|---|
| van Keulen<br>BMW,<br>Ludwig-Maximilians Univ. Munich, Germany | 2014 | Adaptive traffic light prediction via Kalman filtering | Tech. Overview | 1 |
| Raubitschek,<br>BMW<br>ALTRAN GmbH<br>Dresden Univ. of Tech. | 2011 | Predictive Driving Strategies under Urban Conditions for Reducing<br>Fuel Consumption based on Vehicle Environment Information | Specific Tech. Overview | 18 |

### 4.4.3 V2I Technology Outlook / Maturity

Similar to the past section on technological outlook and maturity study for V2V technology, maturity for V2I is evidenced by demonstration projects such as the IntelliDrive project and various academic studies, and well as at least one standard regulating the technology (Table 8: V2I Standards). However, V2I technology depends on the integration of technology on infrastructure, and the status of infrastructure is the responsibility of local government. There have been significantly more V2I demonstration projects in Europe compared the US, which may indicate that domestic integration of this technology may take more time than abroad. As with V2V systems, though there is a great potential for improving vehicular fuel efficiency, the full benefits of V2I will take longer to achieve than the faster integration of Camera Systems and Vehicular Radar systems.

*V2I Technological Status*

Much like V2V, V2I technology is supported by many academic publications and demonstration projects involving numerous automakers (refer to V2V and V2I Demonstration

Projects, and V2I Demonstration Projects). Accordingly, V2I is approaching the deployed state in a very similar timeframe as V2V technology.

*V2I Technological Status / Standards*

The technological status, the standards, and the publications for V2V and V2I technology are very much the same (please refer to V2V Standards: Current and Pending for more information).

Table 8: V2I Standards

| Organization | Std. | Title | Status | Description |
|---|---|---|---|---|
| ISO/DIS | 26684 | Intelligent transport systems – Cooperative intersection signal information and violation warning systems (CIWS) | Pending | Performance requirements and test procedures |

*V2I Research Initiatives and Collaborations*

There have been four major demonstration projects identified in this report that helped in the development of usable V2I systems. In the IntelliDrive project, 15% fuel savings were found on standard powertrain test vehicles interacting with adaptive traffic lights (meaning, traffic lights which change when vehicles are approaching) [65]. The IntelliDrive Project also investigated similar technology to make drivers aware of traffic signals, which was successfully implemented and has promise for similar results to those of automatically changing traffic lights. For future studies, it was concluded from this project that similar systems can be made with 3G/4G support for more rapid deployment of V2I technology.

Such networking technologies would provide a significant benefit for integrating V2I technology at a faster pace, as there would be less need for installing presently-conventional infrastructure points along roadways to relay messages. As an indication of future work to be conducted domestically, Caltrans has described their vision for future as having intelligent intersections once every 10 miles on California Highways, which might be privately funded with an incentives program [66].

The DIAMANT project was mostly concerned with advancing V2V technology, however the project also installed V2I systems in vehicles. This project was able to conclude that 5/1000 vehicles can give representative understanding of traffic flow when installed with V2I systems [34]. The SimTD demonstration evaluated the overall effectiveness of V2I systems, and project results indicate that drivers with equipped vehicles were quicker to adapt speed, following distance, and behavior to changing traffic speed [67]. The CVIS project tested a number of V2I applications, including: Green light speed advice (where the vehicle issues the driver a recommended speed based on V2I traffic light signals and the traffic sign status on dashboard), social networking to enable ridesharing, and various collaborative safety applications [33].

#### 4.4.4 V2I Summary

For fuel efficiency, V2I technology certainly has much of the same merit to increase fuel efficiency as V2V technology by enhancing driver knowledge of traffic conditions, traffic signal status, and optimal velocity profiles (please refer to Section 4.4.2 V2I Conceptual Applications). In academic literature, these efficiency increases from simulations found in literature range from 10% [58], to 40% [61], for standard powertrain vehicles. Just as with V2V technology, V2I technology can be integrated with an adaptive cruise control system and perform more efficient driving behaviors automatically.

In terms of technological maturity, V2I technology is relatively well proven in the fuel economy enhancement context from demonstration projects. Project conclusions are that V2I technology is practical and effective, with fuel efficiency increases on standard powertrain vehicles ranging from 15%, (Intellidrive project [65]), to 25% (ecoDrive project [59]). These research initiatives support the notion that V2I technology has been steadily maturing.

Most demonstration projects are centered in Europe, and have been given substantial financial support from those local governments and automakers with over €40M total for CVIS, and over €50M for SimTD. In the US there is much less of this type of activity on a relative scale, noting that the Connected Vehicle Safety Pilot had less than $15M USD invested. This is an important distinction, because this technology relies on local government support in order for it to become fully functioning. With this in mind, V2I systems are likely to take longer to implement than other sensor technologies such as Camera Systems (Section 4.5 Camera Systems), and Vehicular Radar systems (Section 4.6 Vehicular Radar Systems).

## 4.5 Camera Systems

This section covers Camera Systems (CSs) which can be installed onto vehicles relatively easily, and at low cost, while operating with less technological complexity than V2V, V2I, and Vehicular Radar Sensors [68], [69]. This in depth survey will cover how CS technology is relatively mature, and enables a standard powertrain vehicle to ultimately have a potential fuel economy benefit of at least 3%, as tested in the euroFOT project, with the potential for more in the future [70].

### 4.5.1 CS Overview

A Camera System (CS) collects and processes the visual information of the surrounding environment, and consists of one or more onboard cameras together with image processing software/hardware. A CS is a passive system, meaning that there is no interaction with the outside environment as is the case with V2V, V2I and Vehicular Radar systems. Compared to these active sensors, CS systems are significantly lower cost, technologically simpler, and easier to install [68], [69]. The core limitations of a CS is the availability of visual information surrounding the vehicle, such information can be obscured by weather conditions (such as heavy rain, snow, and fog) [71].

The innovations in CS's have less to do with the cameras and camera arrangements, which are well studied, and has more to do with the innovations in image processing and increasingly affordable computing power [46], [69]. Camera systems therefore have the advantage to be continually improved at the rate of as image processing and image recognition innovations. For example, early camera systems alerted drivers to potential oncoming hazards by tracking large objects ahead and determining if the large objects pose a hazard to drivers [72], whereas the current state of the art image recognition techniques allow CS's to reliably interpret vehicles based on object/vehicle type (Truck, car, motorcycle, pedestrian etc.) as well as traffic signs [45], [73], [74]. CS's are commonly deployed to enhance safety as a Forward Collision Warning (FCW) systems (where the system objective is to enhance driving safety) and as Lane Departure Warning (LDW) systems (where the CS tracks vehicle position in surrounding lanes and alerts the driver if crossing lane boundary without signaling) [43].

A CS functions by executing two broad steps: By 1) generating a hypothesis of whether object in image is in the background, and what type of object (Automobile, pedestrian, etc.), and by 2) verifying the hypothesis [46]. There are several ways to generate this hypothesis: 1) by using a pre-programmed visual knowledge of object features such as colors, shadows, corners, textures, symmetry, and features such as taillight / license plate position (which can be accomplished with a single camera), by 2) using stereo-vision (requiring multiple cameras), or by 3) using motion-based methods (can be accomplished with a single camera). Motion based methods use the relative motion of processed objects to determine whether or not an object is in the background, and whether this object is approaching (converging) or moving away (diverging) the host vehicle.

In order to verify the generated hypothesis, the CS can operate by using one of two methods: 1) template-based methods, which compares the detected image to a predefined template of expected vehicle characteristics, or by 2) using appearance / pattern methods, which is similar to template-based but relies more on machine learning which can continually improve to define objects in the detected image as vehicle or non-vehicle. Please find the list of references for CSs in 4.5.2 CS Conceptual Applications

For CS technology, there were not as many unconventional applications of CS technology to be found as those from V2V (Section 4.3 Vehicle to Vehicle Communication Systems) and V2I (Section 4.4 Vehicle to Infrastructure Communication Systems). However, this section will offer more insight for how a CS can be integrates with other vehicular systems to provide a fuel economy enhancement.

*Concept 1: Automatic Regenerative Braking from Combined CS and ACC Systems*

CS's such as those from MobilEye are installed to alert the driver to objects of interest on the road with the goal of maximizing safety. These particular objects typically include: approaching vehicles which are too close to the front of the vehicle (the alert would help prevent forward collisions and discourage risky behavior such as tailgating), lane departure warnings, and speed limit alerts. A CS's ability to recognize traffic signs is one of the biggest advantages of the visual information based system over other advanced driver assistance technologies, aside from relatively low cost and ease of installation. Additionally, unlike V2V and V2I systems, a CS would be ready to deploy with the various vehicles and infrastructures of today.

In the context of fuel efficiency, a conventional CS can alert the driver to reduce throttle position depending on the situation, and this type of system could be used to tell the driver to apply regenerative braking. Using standard powertrains, this type of application has been shown to provide roughly a 3% increase in fuel efficiency for vehicles in the euroFOT project [70]. However, a more optimal system could be created which reduces speed and applies regenerative braking automatically based on the information processed by the CS. This more optimal system would consist of a CS (to detect and process speed limit information) working with an Adaptive Cruise Control (ACC) or a standard Cruise Control (CC) system (to execute the change in speed automatically depending on the detected traffic sign information.

As on this writing, the specific concept of a CS/ACC/ Automatic Regenerative Braking has not been explicitly found in academic literature.

### 4.5.3 CS Technology Outlook / Maturity

CS technology demonstrates maturity is demonstrated largely from the successful integration of these systems in the safety context, with many automakers already installing these systems (see list in Vehicular Camera System Technological Status below). Being that these systems are already integrated on vehicles for enhancing safety, using these sensors to enhance fuel economy is likely much closer of a step than integrating V2V systems for fuel economy enhancement.

*Vehicular Camera System Technological Status*

CS technology has been deployed in an array of commercial vehicles in the context of safety in LDW and FCW systems. In particular, the company MobilEye Vision Technologies Ltd. Has been partnering with Continental AG in providing core technologies to a number of automakers, some since 2007: Audi, BMW/Mini, Chrysler, Ford, General Motors, Honda, Hyundai, Land Rover, Mitsubishi, Nissan, Opel, Peugot/Citroen, Scania, Tesla, Volvo, and Yulon.

It is worthy to note that MobilEye in particular has been collaborating with a number of automakers and universities over the year in the development of their technology. Most other automakers have similar camera systems as an option for new vehicles, and while all systems are marketed with the premise of enhancing safety, there is an indirect, and perhaps significant, fuel efficiency impact of CS's which stem from fostering more efficient driving behavior such as driving less erratically and observing speed limits. Because CS technology is becoming increasingly ubiquitous, the relative technological maturity is very high when compared to other sensor technologies.

*Standards: Current and/or Pending*

The standards which regulate CS technology are largely focused on applying the technology to safety systems such as forward collision warning systems (ISO 15623:2013, SAE J3029 (Work in Progress)) and lane departure warning systems (LV NCAP 2010, ISO/DIS 17361, Commission Regulation (EU) No. 351/2012). These standards indicate that CS technology is very much integrated in a number of passenger vehicles today, and that there is certainly potential for these systems to detect other signals such as traffic signs and enhance vehicle fuel economy relatively soon.

*Research Initiatives and Collaborations*

CSs have been evaluated in demonstration projects such as the Automotive Collision Avoidance System Field Operational Test, which largely addressed the image processing challenges of CS technology [29]. Another demonstration project was the euroFOT project, which evaluated many technologies including a forward collision warning system consisting of an integrated radar and camera system [70]. When this system was coupled with an adaptive cruise control (ACC) system, fuel savings were approximately 3% for cars and 2% for trucks using standard powertrain, not including additional efficiencies resulting from improved traffic flow.

#### 4.5.4 CS Summary

CS's are unique amongst other signal detection technologies in that they are relatively cheap, easy to install, and have the ability to interpret visually available information that would normally be detected by the human eye only. The image recognition software at the heart of these systems is continuously being improved, and despite the state of the art being traffic sign recognition, one can imagine the possibilities for this technology as more visually available information can be strategically interpreted and computing power continues to become cheaper. One important concept to note regarding CS's is that they require environmental conditions which are visually clear. Because of this, the addition of a more robust signal detection technology is important (see following section on Radar Technology) to ensure that there will always be baseline object detection available for the driver and running control support.

While there are not as many demonstration projects pertaining to efficiency improvements, CS technology has been demonstrating usefulness in commercial vehicles for a significant amount of time now in the safety context. There are also numerous accepted standards in effect which indicate a healthy presence of this technology on the roads.

Overall, CS's are very mature in the context of enhancing safety and are largely ready for integration on most vehicles to this end. While there are opportunities for image processing to enable CSs to enhance fuel economy, the impact of such systems has not been directly supported.

4.6 Vehicular Radar Systems

This section highlights Vehicular Radar Systems (VRSs), which like Camera Systems is a very mature technology that has been added to vehicles in the safety context (Section 4.6.3 VRS Technology Outlook / Maturity). Radar systems are more robust sensors than camera systems in the sense that VRSs will continue to provide distances and velocities of objects despite visual obscurities [75], [76]. One particular limitation of these radar systems is that they are somewhat crude, solely measuring distances and relative-to-vehicle velocities and not the finer details that camera systems can interpret, as described further in the overview below. This research finds that combining a VRS with a CS is a way to ensure that the overall system is robust, and technologically sophisticated (as with the VRS Sensor Fusion Concept). This section will cover how VRS technology enables a standard powertrain vehicle to a potentially improve fuel economy by as much as 14% [77].

### 4.6.1 VRS Overview

A VRS works by emitting, detecting, and processing radio waves which reflect off objects in the environment and arrive back at the vehicle, granting the perception of the position, and movement of objects in range [78]. Common safety applications for VRS's are for use in forward collision warning systems and for use in adaptive cruise control systems, similar to Camera Systems. The benefits of integrating a VRS over, or in combination with, vision based sensors such as CS's or LiDAR sensors is that the VRS has the capability of detecting objects through weather conditions (such as rain, snow, and fog) or other debris (such as dust or dirt covering the sensor, and road spray) which may compromise sensor effectiveness [75], [76].

Object detection effectiveness for a VRS depends on the following factors [78]:

- Range and precision of object detection
- Range and precision of speed detection
- Angular field of view and resolution

These parameters influence the design of the radar sensor(s) included in a particular VRS, and depending on the desired factors there are several categories of radar sensors [78]:

Table 9: Radar Sensor Categories

| Radar Range | Description |
|---|---|
| Short Range Radar (SRR) | Typical range in the tens of meters yet has a relatively high angular field of view and precise range and speed measurements |
| Long Range Radar (LRR) | Typical range from 100-200 meters with a more narrow field of view and less precision than the SRR. |
| Medium Range Radar (MRR) | Performance characteristics between those of long and short range radars. |

### 4.6.2 VRS Conceptual Applications

Similar to CS technology, there were not as many unconventional applications of VRS technology to be found compared to those from V2V and V2I. Regardless, this VRSs have the potential to combine with other sensors, namely CSs, to improve the overall robustness of environmental perception, and this section will show how this has been accomplished in academic literature (Table 10: VRS Concept Literature Review Table).

*VRS Sensor Fusion Concept*

In the context of enhancing fuel efficiency, VRS's offer a similar contribution to that of other forward collision warning sensors where the leading benefit of the VRS is an advanced perception of oncoming hazards and changing traffic conditions – and informing the driver of these changes and/or making an optimal change in velocity automatically as a part of an adaptive cruise control system. By "smoothing" these velocities with a VRS, up to 14% fuel economy savings have been measured in standard powertrain vehicles [77].

In optimal conditions, CS's will suffice for this purpose while offering the capability to interpret visually available information, such as traffic signs. However, the merit of integrating a VRS in an advanced vehicle is that the VRS operates offers in a wider range of weather and road conditions and produces similar object detection capabilities [77], [79]–[82].

Table 10: VRS Concept Literature Review Table

| Organization | Year | Title | Reason | Citations |
|---|---|---|---|---|
| Barth, A.<br>Daimler | 2009 | Estimating the driving state of oncoming vehicles from a moving platform using stereo vision | Tech. Overview and explores the role of an advanced CS in an integrated Radar/CS system | 36 |
| Gern, A.<br>DaimlerChrysler Research, Stuttgart, Germany | 2000 | Robust vehicle tracking fusing radar and vision | Tech. Overview | 16 |
| Gern, A. | 2001 | Advanced lane recognition - fusing vision and radar | Tech. Overview | 23 |

| Organization | Year | Title | Reason | Citations |
| --- | --- | --- | --- | --- |
| DaimlerChrysler Research, Stuttgart, Germany | | | | |
| Ji, Z.<br>Michigan State University<br>General Motors | 2011 | Incremental online object learning in a vehicular radar-vision fusion framework | Tech. Overview | 6 |
| Stiller, C.<br>Karlsruhe Institute of Technology | 2011 | Information fusion for automotive applications – An overview | Tech. Overview,<br>Provides background information regarding overall concept | 14 |

### 4.6.3 VRS Technology Outlook / Maturity

VRS have already been integrated on many modern day vehicles to enhance passenger safety as a part of forward collisions warning systems. A supporting component of this integration are numerous specific standards pertaining to VRS integration, as seen below in Table 11. Because this technology is already conventional in modern vehicles, applying the sensor technology to enhance fuel economy is more of a short-term initiative than the integration of V2V or V2I systems for fuel economy enhancement.

*Vehicular Radar System Technological Status*

VRS's are a standard component of most vehicles with Adaptive Cruise Control (ACC) systems. This technology has the support of numerous domestic and international standards

(Table 11: VRS Standards: Current and/or Pending), indicating that this technology is very mature and proven in the safety context.

Table 11: VRS Standards: Current and/or Pending

| Organization | Std. | Title | Status | Description |
|---|---|---|---|---|
| ETSI | TR 101 982 | Radio equipment to be used in the 24 GHz band; System Reference Document for automotive collision warning Short Range Radar | Accepted | From ETSI: System Reference Document for 24 GHz Short Range Radar (SRR) to amend technical parameters, consideration of comments and frequency choice information. |
| ETSI | TR 102 263 | Road Transport and Traffic Telematics (RTTT); Radio equipment to be used in the 77 GHz to 81 GHz band; System Reference Document for automotive collision warning Short Range Radar | Accepted | Includes market, technical information regarding the integration of VRS's on the 77-81Ghz Bands |
| FCC | 47 CFR 15.515 | Technical requirements for vehicular radar systems. | Accepted | Defines operating frequency, power for VRS's |

### 4.6.4 VRS Summary

Overall, VRSs have been mainly applied to enhance passenger safety (Section 4.6.3 VRS Technology Outlook / Maturity), provided that VRS's are capable of robustly detecting objects that may pose a threat to passenger safety down road. However, for enhancing fuel efficiency, the information VRS's provide the driver (or running control systems) is relatively crude compared to CSs. Where CS's are subject to weather conditions and debris, the more robust VRS will continue to provide information regarding nearby objects, providing a baseline efficiency improvement that can be as high as 14% for standard powertrain vehicles [77].

### 4.7 Objective 1 Summary

The thesis to this point has explored a variety of sensor technologies which are used to detect environmental signals to enhance safety and/or efficiency. To summarize this work, comparisons are made between the sensors based on potential fuel economy benefit, and technological maturity in Table 12: Summary of Conclusions. The discussion below is a summary of how we reached the conclusions found in the table.

Table 12: Summary of Conclusions

| **Sensor Technology** | **Potential Fuel Economy Benefit** | **Technological Maturity (Years until ready)** |
|---|---|---|
| V2V | 5-20% for conventional vehicle | 10 years out |
| V2I | 10-25% for conventional vehicle | 15 years out (in US) |
| CS | At least 3% for conventional vehicle | Today (Safety)<br><5 years (Fuel Economy) |
| VRS | 14% for conventional vehicle | Today |

Vehicle to Vehicle Communication Systems are evident in many successful demonstration projects (V2V Research Initiatives and Collaborations), and this technology is relatively mature compared to CS and VRS technologies. There is also support from domestic policy, which indicates an eventual mandate of this technology in the US. V2V systems can improve fuel economy of standard powertrain vehicles by as much as 20%. However, these systems rely on other vehicles to be equipped with the same technology, for there to be an improvement to fuel efficiency. Should the proposed mandates for V2V carry through, there will be significant numbers of V2V-enabled vehicles on domestic roadways, and therefore significant opportunities to use this technology for a fuel economy benefit. Because of the high potential to improve fuel economy, V2V technology will be selected to become the focus of greater study for the future sections of this research.

Vehicle to Infrastructure Communication Systems are technologically similar to V2V (Section 4.4.1 V2I Overview), and share much of the maturity of V2V systems. This technology has the potential to improve fuel consumption by as much as 25% for standard powertrain vehicles. There have been significant V2I demonstration projects in Europe, with less of such support in the US. Because this technology is dependent on support from local governments, this may indicate a longer wait until domestic fuel economy improvements will be made. As with V2V technology, V2I technology has a high potential to improve fuel economy, and will therefore be studied in greater depth for the future sections of this research.

Vehicular Camera Systems are very mature in the context of enhancing passenger safety, and can already be found on a number of vehicles already (Section 4.5.3 CS Technology Outlook / MaturityAdvances in image processing allow this technology to now interpret street signs, which can either alert the driver of changing speed statutes or can automatically reduce speed/apply regenerative braking when integrated with the running control of the vehicle in an adaptive cruise control system. This technology is relatively easy to install, and is relatively cheap. However, a drawback of the technology is that the camera system relies on visually available information which can be obscured by weather conditions or dust/dirt near the lens. Camera systems should be considered to be a quite promising technology for (modestly) enhancing the fuel efficiency for hybrid vehicles (by at least 3%) in the very near-term.

Vehicular Radar Systems have been installed on most vehicles which have adaptive cruise control technology, and the technology has been just as or more mature than Camera Systems. These systems are not as sophisticated as camera systems in terms of technological capability. However, these systems are very robust and will continue to relay the driver or running control information pertaining to upcoming threats to vehicle efficiency. A potentially great application of VRSs in support of more sophisticated, yet less robust, camera systems (Section 4.6.2 VRS Conceptual Applications). This “sensor fusion” concept is well studied, and should be considered when deciding which sensors to integrate on a vehicle (VRS Sensor Fusion Concept).

# 5 OBJECTIVE 2 RESULTS

**Objective 2: Perform a literature review to find studies with relevant research goals, and investigate the tools and research processes necessary to solve such research problems.**

The ultimate goal of the remaining research objectives is to study the relationship of roadway communication infrastructure (V2I), vehicle communication technology (V2V) penetration and vehicle control, and their influence on fleet fuel economy, emissions and traffic flow on a roadway. This comprehensive study is referred to as the Research Problem for the remainder of this thesis. The first step in solving the Research Problem is to study the relevant research, tools, and research process of past and current research initiatives.

## 5.1 Relevant V2V/V2I Research Initiatives

The survey for this objective began by identifying seven relevant V2I and/or V2V research initiatives, each offering different insight for how to approach the Research Problem. The table below provides insight as to the various contributions of each work, and illustrates how each of these research initiatives cover some or multiple aspects of the Research Problem:

Table 13: Relevant Research, Goals and Criteria

| **Reference Number** | **Title and Author** | **Research Purpose** | **Research Process Schematic** |
|---|---|---|---|
| 1 | A simulation framework for modelling the impacts of an integrated road-vehicle system on local air quality (Arem, 2008) | To determine the air quality impact of incrementally increasing V2I (Vehicle to traffic signal communications) technology in a realistic, urban setting.<br>**Research Objective → Traffic and Energy Management (T & EM)** | Figure 8 |
| 2 | Cooperative Variable Speed Limit (VSL) Systems: Modeling and Evaluation using Microscopic Traffic Simulation (Grumert, 2013, Thesis) | To investigate the impact of deploying V2I technology and supporting autonomous control system using microsimulation. Results are in terms of the “smoothing out” of traffic flow / vehicle behavior, and reduced emissions.<br>**Research Objective → Traffic Flow** | Figure 9 |
| 3 | Modeling and Simulation of Vehicle to Vehicle and Infrastructure Communication in Realistic Large Scale Urban Area (Noori, 2013, Thesis) | To determine the ability for V2V and V2I systems to improve travel time, fuel consumption and vehicular emissions based on a real city model.<br>**Research Objective → Safety** | Figure 10 |

| Reference Number | Title and Author | Research Purpose | Research Process Schematic |
|---|---|---|---|
| 4 | Cost-Benefit-Based Implementation Strategy for Green Light Optimized Speed Advisory (GLOSA) (Niebel, 2013) | To determine the emissions benefits and cost/benefit ratio of Green Light Optimized Speed Advisory (V2I/~VSL)<br>**Research Objective → Traffic Flow** | Figure 11 |
| 5 | Vehicular Communications for Efficient and Sustainable Mobility (d'Orey, 2014, Partial Thesis) | To create a realistic traffic and emissions model to evaluate heterogeneous V2V and V2I systems (and on to investigate vehicle routing for autonomous taxi system)<br>**Research Objective → T & EM** | Figure 11: Research Process for Reference #4 |
| 6 | A Simulation Tool for Automated Platooning in Mixed Highway Scenarios. (Segata, 2012) | To develop a proof-of-concept an ACC and CACC (V2V) communication simulation for studying strategies and protocols for managing platoons in mixed-vehicle scenarios (scenarios with V2V-connected and non-connected vehicles interacting with each other.<br>**Research Objective → Traffic Flow / T & EM** | Figure 13 |
| 7 | Towards the City-scale Simulation and Performance Assessment of Electric Vehicles. (Masalkina, 2014) | To realistically model city of Nuremberg and transit of 100,000 electric vehicles (EVs), and evaluate the effectiveness of V2I technology to offer rerouting suggestions for nearby charging stations when EV is at low state of charge.<br>**Research Objective → T & EM** | Figure 14 |

## 5.2 Relevant Research Tools

In order to select the best tools to solve the Research Problem, a deeper investigation was conducted on the tools used by the relevant research initiatives to understand why each tools was selected for the various research goals. The Research Problem of this thesis requires researchers to study traffic, wireless communications, and emissions. Learning more about how these simulation tools interact, and which simulation tools are appropriate for what purpose will be essential for selecting the appropriate simulation tools for this thesis. The relevant research initiatives were investigated further to learn more about the tools used to gather more insight, and a detailed table describing these research tools is shown below:

Table 14: Research Tools, Selection, and Criteria

| Reference Number | Title and Author | Simulation Tool Criteria | Tools Considered | Tool Selection and Reason |
|---|---|---|---|---|
| 1 | A simulation framework for modelling the impacts of an integrated road-vehicle system on local air quality (Arem, 2008) | Traffic Tool: High resolution for small, complex, urban scales, must have GUI, model must be capable of intelligent roadside and in-vehicle systems and related communications. Emissions Tool: Street-level emissions resolution Dispersion Tool: Must provide additional spacial and temporal resolution to emissions simulation. | Traffic Tool: VISSIM, AIMSUN, PARAMICS, ITS MODELER Emissions Tool: MOBILE, COPERT, UROPOL, MODEM, VERSIT+ Dispersion Tool: ROADWAY, CAR-FMI, CAR, CARMEN | Traffic Tool: VISSIM + ITS Modeler: Joint simulators chosen for VISSIM traffic detail at traffic signals, and ITS Modeler GUI and V2V/V2I capability Emissions Tool: VERSIT+: Chosen for high spacial resolution to "street level". Dispersion Tool: CARMEN: Chosen for hourly temporal resolution |
| 2 | Cooperative Variable Speed Limit (VSL) Systems: Modeling and Evaluation using Microscopic Traffic Simulation (Grumert, 2013, Thesis) | Traffic Tool: High resolution for realistic urban scales, city-wide modeling capability, model must be capable of V2I/V2V modelling Emissions Tool: Street-level emissions resolution, must use modal vehicle transportation information and not mobile vehicle inventory data | Traffic Tool: VISSIM, AIMSUN, MITSIM, SUMO, DRACULA Emissions Tool: ARTEMIS/HBEFA, MOBILE6, COPERT4, MOVES, CMEM | Traffic Tool: SUMO: Capable of city-wide modelling, high resolution, free and open source, V2I capability, proven in previous research projects. Emissions Tool: CMEM: Uses modal vehicle information, proven to work with SUMO transit information in previous research projects. |
| 3 | Modeling and Simulation of Vehicle to Vehicle and Infrastructure Communication in Realistic Large Scale Urban Area (Noori, 2013, Thesis) | Traffic Tool: High resolution for urban scales, city-wide modeling capability must be free and open source, model must be capable of V2I modelling, determining the difference in transit time for various V2X control strategies. Network Tool: Must be able to set realistic network parameters, support modern V2X technology and standards, must be free and open source. | Traffic Tool: CORSIM, VISSIM, PARAMICS, SUMO, Network Tool: GloMoSim, OPNET, NS-2, NS-3, OMNET++ Combined Tool: VEINS | Traffic Tool: SUMO: Capable of simulating realistic traffic on a realistic street map. Network Tool: OMNET++: Capable of simulating large scale networks with current technology and standards. Combined VANET Tool: VEINS: Framework to connect SUMO and OMNET++, incorporates benefits of each tool, framework is free and open source, as are the individual tools. |
| 4 | Cost-Benefit-Based Implementation | Traffic Tool: High resolution for urban scales, model must be | Traffic Tool: Only considered AIMSUN Network Tool: Only | Traffic Tool: AIMSUN: High street-level simulation detail, allows |

| Reference Number | Title and Author | Simulation Tool Criteria | Tools Considered | Tool Selection and Reason |
|---|---|---|---|---|
| | Strategy for Green Light Optimized Speed Advisory (GLOSA) (Niebel, 2013) | capable of V2I modelling, tool will be used to determine the most efficient investment of capital in V2I network design.<br>Network Tool: No simulation parameters such as range, delay, and technological standards needed. Need basic communication between vehicles and infrastructure.<br>Emissions Tool: Full tool not necessary, just average values of NOx, CO, HC, and PM emissions. | considered the development of a proprietary network simulator.<br>Emissions Tool: Only considered using HBEFA | for development of V2X modules<br>Network Tool: Developed module proprietary for simulation<br>Emissions Tool: HBEFA, handbook of average vehicular emissions. |
| 5 | Vehicular Communications for Efficient and Sustainable Mobility (d'Orey, 2014, Partial Thesis) | Traffic Tool: High resolution for urban scales, capable of lane changing behavior, validated with previous research projects.<br>Network Tool: Must be scalable with size of simulations, must support 4GLTE mobile network simulations, and validated in previous research works.<br>Emissions Tool: Must have been calibrated with real world performance of vehicle types, engine types, and vehicle make, must have high resolution and must have been validated in previous research works. | Traffic Tool: CORSIM, AIMSUN, SUMO, TRANSIMS, VISSIM, DIVERT<br>Network Tool: OMNET++, OPNET, NS-3, JiST/SWANS<br>Emissions Tool: CMEM, EMIT, MOVES, PHEM, IVE | Traffic Tool: DIVERT: Street-level simulation resolution, validated in previous research works, contains a simple V2V model.<br>Network Tool: NS-3: Performance in realistic network simulations, and capability of simulating 4GLTE networks.<br>Emissions Tool: SUMO (as a component of VEINS): Validated with Vehicle type, make, and engine type data, street-level resolution, and previous research works. |
| 6 | A Simulation Tool for Automated Platooning in Mixed Highway Scenarios. (Segata, 2012) | Traffic Tool: High resolution for custom roadway, must be capable of V2I modelling, and change car following properties.<br>Network Tool: Must be able to set realistic network parameters, | Traffic Tool: Only considered SUMO (as a component of VEINS)<br>Network Tool: Only considered OMNET++ (as a component of VEINS) | Traffic Tool: SUMO: Capable of implementing custom made car following model, realistic roadway-level simulation.<br>Network Tool: OMNET++: Capable of realistically simulating modern V2X networks and standards. |

| Reference Number | Title and Author | Simulation Tool Criteria | Tools Considered | Tool Selection and Reason |
|---|---|---|---|---|
| | | support modern V2X technology and standards. | Emissions Tool: No option specified, N/A | Combined VANET Tool: VEINS: Framework to connect SUMO and OMNET++, incorporates benefits of each tool. |
| 7 | Towards the City-scale Simulation and Performance Assessment of Electric Vehicles. (Masalkina, 2014) | Traffic Tool: High resolution for custom roadway, must be capable of V2I modelling.<br>Network Tool: Must be able to set realistic network parameters, support modern V2X technology and standards, and add custom module for evaluating electric vehicle state of charge continually per vehicle in simulation. | Traffic Tool: Only considered SUMO (as a component of VEINS)<br>Network Tool: Only considered OMNET++ (as a component of VEINS)<br>Emissions Tool: No option specified, N/A | Traffic Tool: SUMO: Capable of realistic roadway-level simulation.<br>Network Tool: OMNET++: Allows for custom logic to be implemented, in addition to realistically simulating modern V2X networks and standards<br>Combined VANET Tool: VEINS: Framework to connect SUMO and OMNET++ |

Traffic simulation tools are clearly an essential part of accomplishing the research goals of this thesis. Essentially, these traffic tools are used to mathematically model transportation systems. For the research initiatives, traffic simulation tools are used specifically for experimental studies that necessitate realistic representations of complex traffic scenarios without the time and cost of real-world, full-scale testing. The traffic tools considered by the relevant studies are organized in the table below:

Table 15: Traffic Tools per Research Work

| | **Traffic Tools Considered** | **Research Work** |
|---|---|---|
| 1 | VISSIM, AIMSUN, PARAMICS, ITS MODELER | Arem, 2008 |
| 2 | VISSIM, AIMSUN, MITSIM, SUMO, DRACULA | Grumert, 2013 |
| 3 | CORSIM, VISSIM, PARAMICS, SUMO | Noori, 2013 |
| 4 | AIMSUN | Niebel, 2013 |
| 5 | CORSIM, AIMSUN, SUMO, TRANSIMS, VISSIM, DIVERT | d'Orey, 2014 |
| 6 | SUMO (as a component of VEINS) | Segata, 2012 |
| 7 | SUMO (as a component of VEINS) | Masalkina, 2014 |

Similarly, network simulation tools mathematically model the communication between network entities. Network simulators perform simulations of realistic wireless networks that would otherwise be to time and cost prohibitive to experiment with in the real-world. In order to satisfy the respective goals of the various research initiatives, the following network tools were considered for each study:

Table 16: Network Tools per Research Work

| | Network Tools Considered | Research Work |
|---|---|---|
| 1 | No option specified, N/A | Arem, 2008 |
| 2 | No option specified, N/A | Grumert, 2013 |
| 3 | GloMoSim, OPNET, NS-2, NS-3, OMNET++ | Noori, 2013 |
| 4 | Only considered the development of a proprietary network simulator. | Niebel, 2013 |
| 5 | OMNET++, OPNET, NS-3, JiST/SWANS | d'Orey, 2014 |
| 6 | OMNET++ (as a component of VEINS) | Segata, 2012 |
| 7 | OMNET++ (as a component of VEINS) | Masalkina, 2014 |

Finally, some of these studies required the use emissions tools, which use transit information (including vehicle behavior such as velocity and acceleration) to calculate the amounts of vehicular emissions which result in vehicular transit. Some of these models can also measure the atmospheric dispersion of such vehicular emissions. The emissions tools considered in the relevant research initiatives are organized in the table below:

Table 17: Emissions Tools per Research Work

| | Emissions Tools Considered | Research Work |
|---|---|---|
| 1 | MOBILE, COPERT, UROPOL, MODEM, VERSIT+ | Arem, 2008 |
| 2 | ARTEMIS/HBEFA, MOBILE6, COPERT4, MOVES, CMEM | Grumert, 2013 |
| 3 | No option specified, N/A | Noori, 2013 |
| 4 | Only considered using HBEFA | Niebel, 2013 |
| 5 | CMEM, EMIT, MOVES, PHEM, IVE | d'Orey, 2014 |
| 6 | No option specified, N/A | Segata, 2012 |
| 7 | No option specified, N/A | Masalkina, 2014 |

## 5.3 Relevant Research Processes

### 5.3.1 Research Process Overviews

To ensure that the Research Problem is successfully completed, the simulation model under construction must be capable of simulating traffic, wireless networks, and vehicular emissions. In the same sense that relevant research works have illustrated the need for certain simulation tools, the processes in which these relevant research works assemble their tools and perform their modelling offers insight as to how this research should assemble simulation tools.

In addition to determining the type of models required, examining relevant research processes will provide an outline of how these models can work individually, and with each other, to produce research results. Please refer to the table below for the detailed analysis of relevant research processes identified:

Table 18: Research Process, Tools Used

| **Reference Number** | **Title and Author** | **Research Goals** | **Research Process** |
|---|---|---|---|
| 1 | A simulation framework for modelling the impacts of an integrated road-vehicle system on local air quality (Arem, 2008) | To determine the air quality impact of incrementally increasing V2I (Vehicle to traffic signal communications) technology in a realistic, urban setting. | Traffic Tool (VISSIM + ITS Modeler)<br>↓<br>Emissions Tool (VERSIT+)<br>↓<br>Dispersion Model (CARMEN) |

| Reference Number | Title and Author | Research Goals | Research Process |
|---|---|---|---|
| 2 | Cooperative Variable Speed Limit (VSL) Systems: Modeling and Evaluation using Microscopic Traffic Simulation (Grumert, 2013, Thesis) | To investigate the impact of deploying V2I technology and supporting autonomous control system using microsimulation. Results are in terms of the "smoothing out" of traffic flow / vehicle behavior, and reduced emissions. | Traffic Tool (SUMO)<br>↓<br>Emissions Tool (CMEM) |
| 3 | Modeling and Simulation of Vehicle to Vehicle and Infrastructure Communication in Realistic Large Scale Urban Area (Noori, 2013, Thesis) | To determine the ability for V2V and V2I systems to improve travel time, fuel consumption and vehicular emissions based on a real city model. | Traffic Tool (SUMO)<br>↓<br>Network Tool (OMNET++)<br><br>(Researchers used VEINS integrated Traffic-Network Tool) |
| 4 | Cost-Benefit-Based Implementation Strategy for Green Light Optimized Speed Advisory (GLOSA) (Niebel, 2013) | To determine the emissions benefits and cost/benefit ratio of Green Light Optimized Speed Advisory (V2I/~VSL) | Traffic Tool (AIMSUN)<br>↓<br>Network Tool (Proprietary)<br>↓<br>Emissions Tool (HBEFA) |
| 5 | Vehicular Communications for Efficient and Sustainable Mobility (d'Orey, 2014, Partial Thesis) | To create a realistic traffic and emissions model to evaluate heterogeneous V2V and V2I systems (and on to investigate vehicle routing for autonomous taxi system) | Traffic Tool (DIVERT)<br>↓<br>Network Tool (NS-3)<br>↓<br>Emissions Tool (EMIT) |
| 6 | A Simulation Tool for Automated Platooning in Mixed Highway Scenarios. (Segata, 2012) | To develop a proof-of-concept an ACC and CACC (V2V) communication simulation for studying strategies and protocols for managing platoons in mixed-vehicle scenarios (scenarios with V2V-connected and non-connected vehicles interacting with each other. | Traffic Tool (SUMO)<br>↓<br>Network Tool (OMNET++)<br><br>(Researchers used VEINS integrated Traffic-Network Tool) |

| Reference Number | Title and Author | Research Goals | Research Process |
|---|---|---|---|
| 7 | Towards the City-scale Simulation and Performance Assessment of Electric Vehicles. (Masalkina, 2014) | To realistically model city of Nuremberg and transit of 100,000 electric vehicles (EVs), and evaluate the effectiveness of V2I technology to offer rerouting suggestions for nearby charging stations when EV is at low state of charge. | Traffic Tool (SUMO) ↓ Network Tool (OMNET++) (Researchers used VEINS integrated Traffic-Network Tool) |

By examining these research processes in detail it was found that models typically begin by altering an aspect of the traffic simulation or network simulation, which impacts the way that information is disseminated in a simulation. For example, the resulting information from the traffic and/or network simulator is usually sent to an emissions and/or dispersion simulator to process the air quality impact of the V2X control being tested.

### 5.3.2 Research Process Framework Diagrams

Another way to share the information in the preceding table is to create research process framework diagrams. In addition to showing the interaction between models, these diagrams will illustrate the input and output information required to successfully complete the respective studies. In creating and reviewing these diagrams, researchers can find a common approach to the interface between traffic, network, and emissions simulation tools.

The figure below illustrates the research process associated with the research objective number 1 in Table 18: Research Process, Tools Used (sourced from publication).

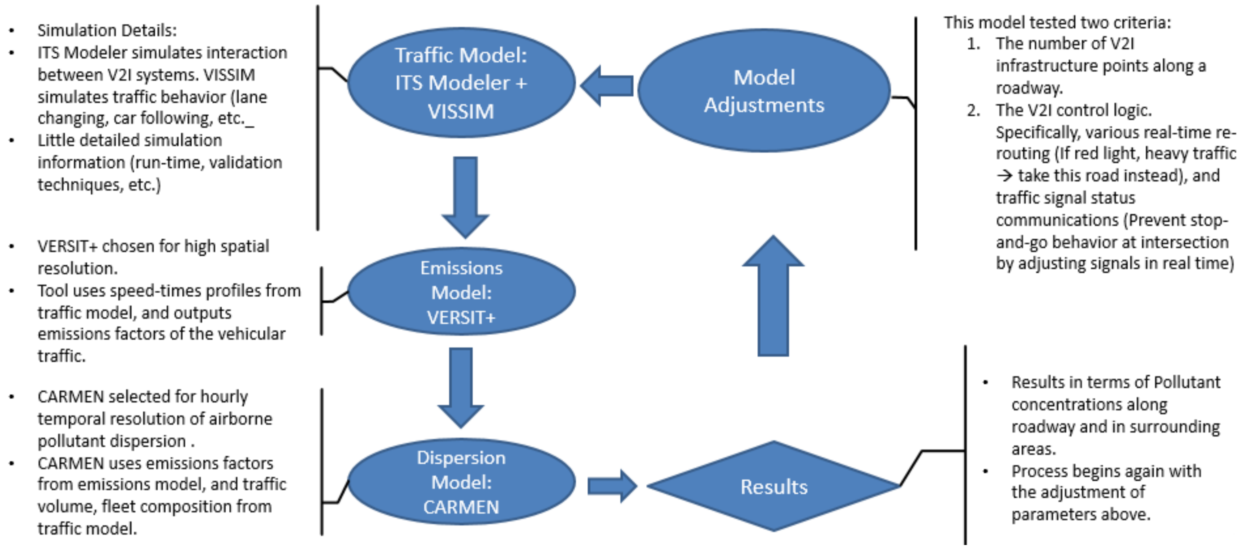


Figure 8: Research Process for Reference #1

The figure below, Figure 9: Research Process for Reference #2, refers to the research process associated with the research objective number 2 in Table 18: Research Process, Tools Used.

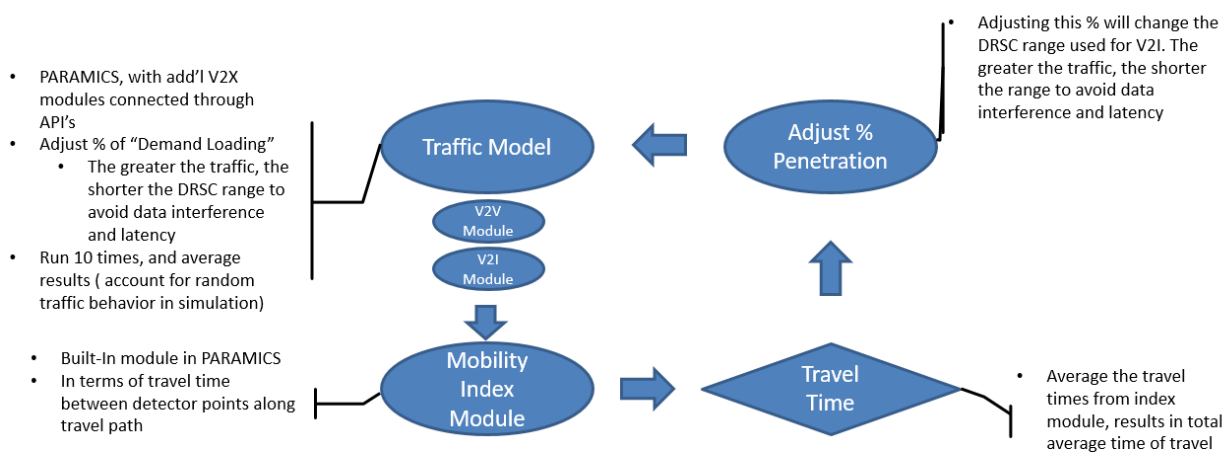


Figure 9: Research Process for Reference #2

The figure below, Figure 10: Research Process for Reference #3, refers to the research process associated with the research objective number 3 in Table 18: Research Process, Tools

Used.

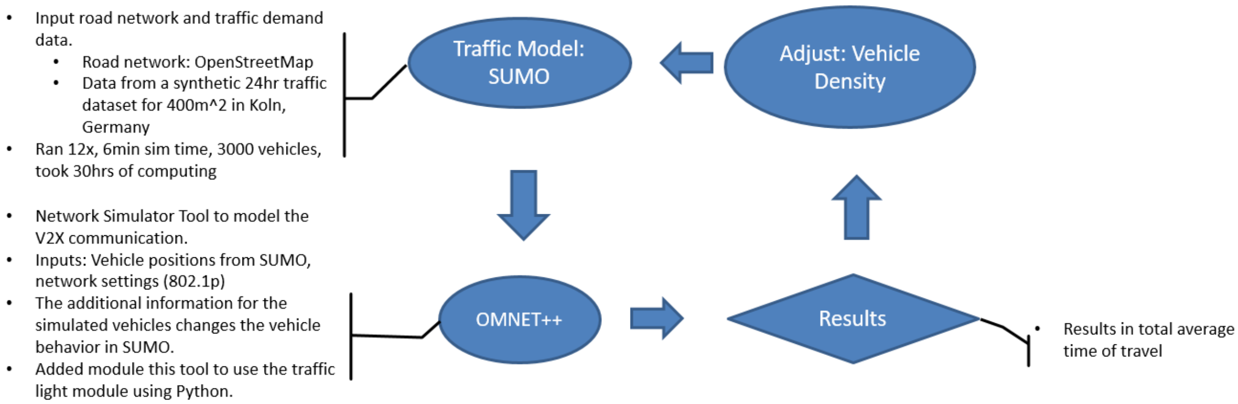


Figure 10: Research Process for Reference #3

The figure below, Figure 11: Research Process for Reference #4, refers to the research process associated with the research objective number 4 in Table 18: Research Process, Tools Used.

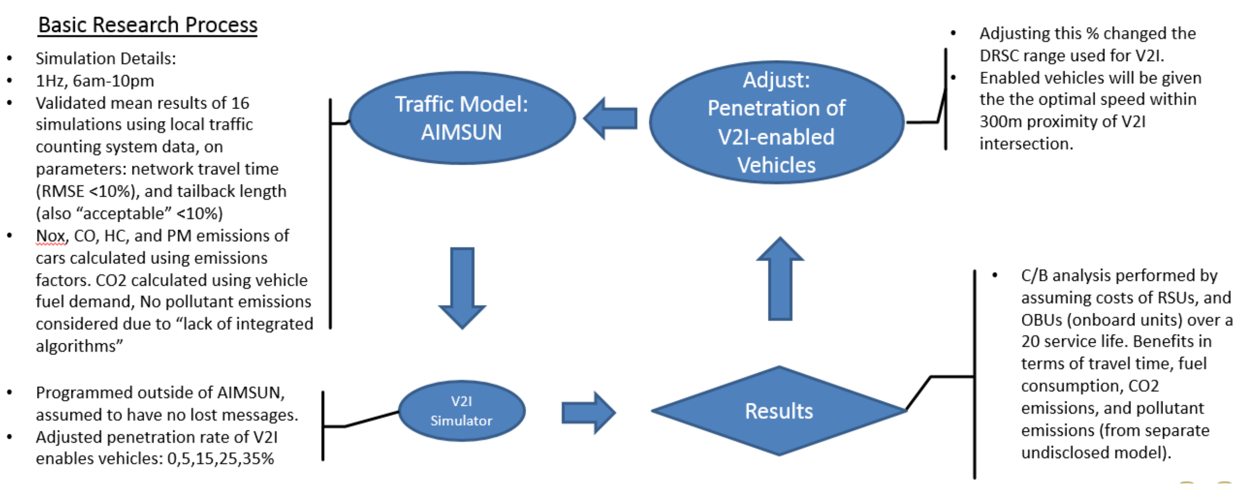


Figure 11: Research Process for Reference #4

The figure below, Figure 12: Research Process for Reference #5, refers to the research process associated with the research objective number 5 in Table 18: Research Process, Tools Used.

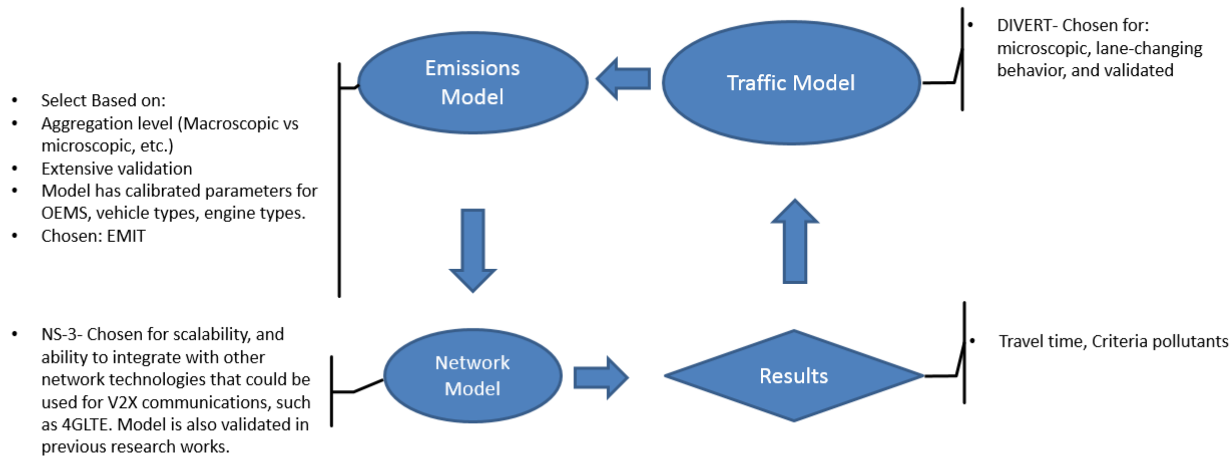


Figure 12: Research Process for Reference #5

The figure below, Figure 13: Research Process for Reference #6, refers to the research process associated with the research objective number 6 in Table 18: Research Process, Tools Used.

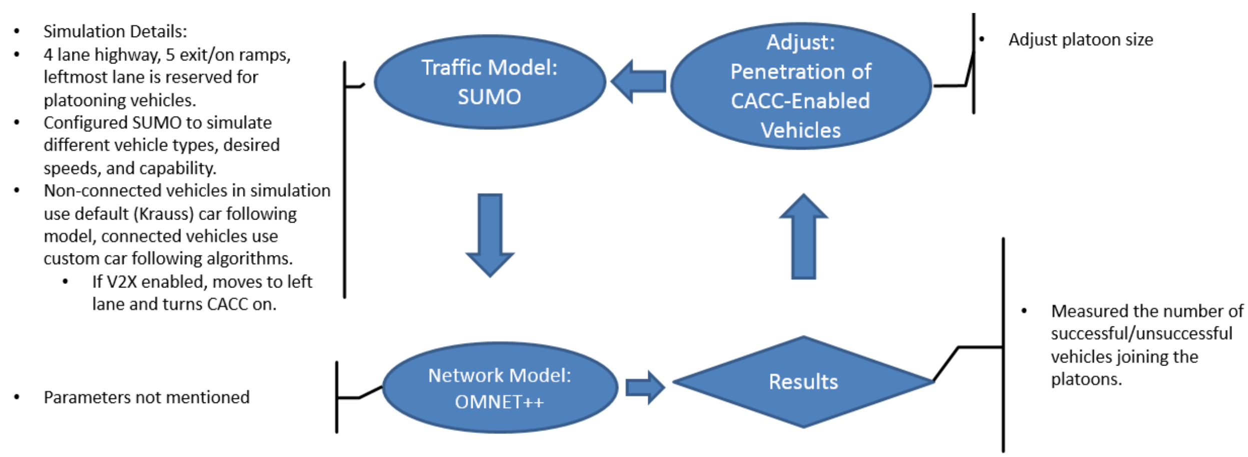


Figure 13: Research Process for Reference #6

The figure below, Figure 14: Research Process for Reference #7, refers to the research process associated with the research objective number 7 in Table 18: Research Process, Tools Used.

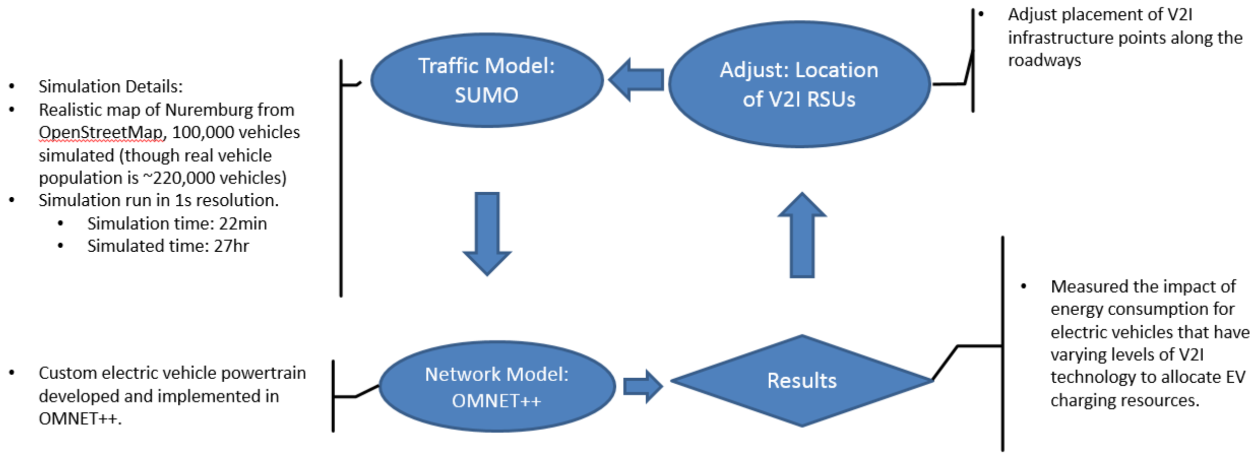


Figure 14: Research Process for Reference #7

# 6 OBJECTIVE 3 RESULTS

**Objective 3: Determine the most appropriate modelling tools for simulating the impact of V2V and V2I technologies for this research.**

## 6.1 Traffic Simulation Tool

This section provides evidence to select the most appropriate simulation tools to solve the Research problem. This section will cover each type of tool separately (traffic, network, emissions), and describe the reason for the tool selection. Pros and cons tables are used to clearly communicate the advantages and disadvantages of each simulation tool option.

Like many simulation tools, the various traffic simulation tools were found to share many similar criteria. In order to clearly see the outstanding pros and cons to these tools, only the unique criteria are listed in the table. The common characteristics are listed outside of these tables to prevent redundancy. Unless otherwise noted, these tools all share the following features:

- Free/Open source

- Allows for integrating other tools without altering source code
- Validated in numerous research initiatives

Table 19: Traffic Simulation Pros and Cons

| **Tool Name** | **Pros** | **Cons** |
|---|---|---|
| SUMO | Frequently used for V2I, (E. Grumert 2014) Chosen for relevant previous uses / larger user base / more available support for independent researchers (Dias 2013) | |
| AIMSUN | Model shown to calibrate well with real traffic data (Niebel 2013) | Licensed |
| PARAMICS | 3D visualization Tools (Noori 2013) | |
| DIVERT | Can be integrated with NS-3, EMIT, at code level (D'Orey 2014) | |
| VISSIM | Highly realistic bicycle, motorcycle, and pedestrian modelling, car following gap model used is relatively flexible (allows for more accurate representation of V2X effect on traffic), More suitable than PARAMICS and AIMSUN for small networks with complex geometry, traffic, and control strategies (B. Arem 2008) | Less suitable than PARAMICS or AIMSUN for modelling large networks with many route choices. Licensed. |

For the purpose of traffic simulator, using a model with a great amount of user support and documentation would be necessary to accomplish the research goals of this project. Additionally, the model would ideally have been proven to be useful for many various scalable V2X studies, but it is not necessary to scale the simulation across a large city or state-wide. These reasons are what gave SUMO the edge when evaluating these traffic models, and SUMO was chosen to be the traffic model to support the completion of the research problem.

## 6.2 Network Simulation Tool

From Section 5.2 Relevant Research Tools, we know that a network simulator is a necessary component of the tool to satisfy the Research problem. Similar to the process used to select the traffic simulation tool, the network simulation tools are organized next to the pros and cons for each tool, with the common features described separately. Unless otherwise noted, these tools all share the following features:

- Free/Open source
- Capability of simulating contemporary V2X networks according to DRSC/WAVE standards

Table 20: Network Simulation Tools Pros and Cons

| **Tool Name** | **Pros** | **Cons** |
|---|---|---|
| OMNET++ | Realistically supports current V2X standards (IEEE 802.11p and IEEE 1609.4 (DSRC/WAVE), accounts for noise, building interference etc. (Noori 2013) | |
| NS-2 | | Does not have IEEE 802.11p standard (Noori 2013) |
| NS-3 | Has 802.11p standard (Niebel, 2013) | |

For the purpose of network simulator, user support, documentation, and a proven track record of various scalable V2X studies are essential to the tool selection, similar to the selection of the traffic model. The fact that OMNET++ supports these points, and supports an array of wireless networking standards, means that OMNET++ is the best model suitable for the research problem.

## 6.3 Combined Traffic and Network Simulation Tools

Another category of research tools related to traffic simulation tool and network simulation tools are combined traffic and simulation tools. Being that a traffic and a network simulator are both necessary components to satisfy the Research Problem, some tools offer a complete package that can be used to simulate V2X communication without requiring the assembly of the two described in Section 5.2 Relevant Research Tools. The benefit of having an integrated tool over having separate tools, is that an integrated tool does not require the development of a framework – simply put, the V2X simulations can be performed and can benefit from the capabilities of each tool, while functioning as a single entity. Similar to the process used to select the traffic and network simulation tools, the integrated traffic and network simulation tools are organized next to the pros and cons for each tool, with the common features described separately. Unless otherwise noted, these tools all share the following features:

- Fully integrated simulation platforms, full "communication" between simulation tools
- Options of traffic simulator and network simulator already determined, and not flexible
- Has benefit of not having to integrate the source codes (D'Orey, 2014)

Table 21: Integrated Traffic-Network Simulation Tool Pros and Cons

| Tool Name | Pros | Cons |
|---|---|---|
| VEINS (SUMO + OMNET++) | Benefits of SUMO and OMNET++, large user base (Noori 2013) | Does not allow for much flexibility with future potential V2X technologies? (4GLTE) (Noori 2013) |
| VSimRTI (VISSIM-SUMO, OMNET++/NS-3, PHEM) | Entirely integrated traffic, network, and emissions models. Professional support, integrated with more simulator options than most other choices - has greater simulation flexibility | Does not allow for future technologies as well, Costs ~$8600, though other pricing options are available. |

For the purpose of a traffic and network simulator, user support, documentation, and a proven track record of various scalable V2X studies are essential to the tool selection, similar to the selection of the traffic and network models. The fact that VEINS combines the benefits of SUMO and OMNET++ and supports these points, means that VEINS is the best model to support the successful completion of the research problem. If future researchers find the conveniences of VSimRTI to justify the cost, the remainder of this thesis is unchanged as the core simulation tools are identical. Also note that this decision does not supersede the previous conclusions for choosing SUMO and OMNET++, but solidifies the decision with the additional benefits of an integrated simulator.

### 6.4 Emissions Simulation Tool

The final category of research tools to consider are emission simulation tools. Being that the air quality impacts of V2X communication are both necessary components to satisfy the Research problem, it is necessary to evaluate these tools and to decide on the best one to integrate with the aforementioned research tools. As in the other sections, the common features of the emissions tools are organized separately, with a table containing the outlying pros and cons. These tools all share the following features, unless otherwise noted:

- Micro-scale emissions models which account for vehicle operation modes (speed, acceleration, gear, engine parameters, etc.)
- Outputs are HC, NOx, CO, CO2 and fuel consumption.
- Street-level detail, using modal vehicle data (idle, accelerating, constant velocities, etc.)

Table 22: Emissions Simulation Tool Pros and Cons

| **Tool Name** | **Pros** | **Cons** |
|---|---|---|
| CMEM | Emissions calculated based on vehicle dynamometer data, temporal resolution on per second basis. (E. Grumert 2014) | |

| Tool Name | Pros | Cons |
|---|---|---|
| EMIT | Obtains instantaneous vehicle behavior data every second. Provides roadway parameter input for roadway characteristics. (D'Orey 2014). | |
| VERSIT+ | Dataset of more than 153 speed-time profiles for 12,000 vehicles. Outputs accurate g/km measurements per vehicle in the traffic scenario (B. Arem 2008) | |
| HBEFA (Aggregate Emissions Inventory, similar to built-in emissions information from SUMO) | Conveniently built in with SUMO, less computationally expensive, good large road networks or in determining the emissions changes to infrastructure changes (Grument 2013) | Uses average speeds, does not directly make use of vehicle modes in travel (inst. Velocity, accelerations) Of interest for this project. (Grumert 2013) |

For the purpose of emissions simulator, the selection depends on user support, documentation, and a proven track record of integration with the aforementioned tool selections – just as was significant criteria for selecting traffic and network simulation tools. Furthermore, the information from SUMO and OMNET++ must in some way be compatible with the emissions simulator. Because EMIT is proven to be implemented with SUMO, has user documentation, and additional inputs which can account for weather events, EMIT is the best model to support the completion of the research problem.

# 7 OBJECTIVE 4 RESULTS

**Objective 4: Develop a research process framework and tool to explore the interaction between the selected V2V and V2I simulation tools and the required inputs and outputs of those tools, and develop a corresponding research plan to accomplish the aforementioned research goals.**

7.1 Research Process Framework - UCI FETCH

Having the selected the appropriate simulation tools,  and with an understanding of the relevant research processes and appropriate model inputs (per 5.3.1 Research Process Overviews and 5.3.2 Research Process Framework Diagrams), it is time to construct the research process that will be used to solve the research problem. When combined together, this simulation package is referred to as FETCH – the Fuel Economy and Traffic of Connected Hybrids. The figure below explains how the research tools combine to form the UCI FETCH model, how information is passed between models, what inputs are set for which models, and what outputs to expect from each of these models:

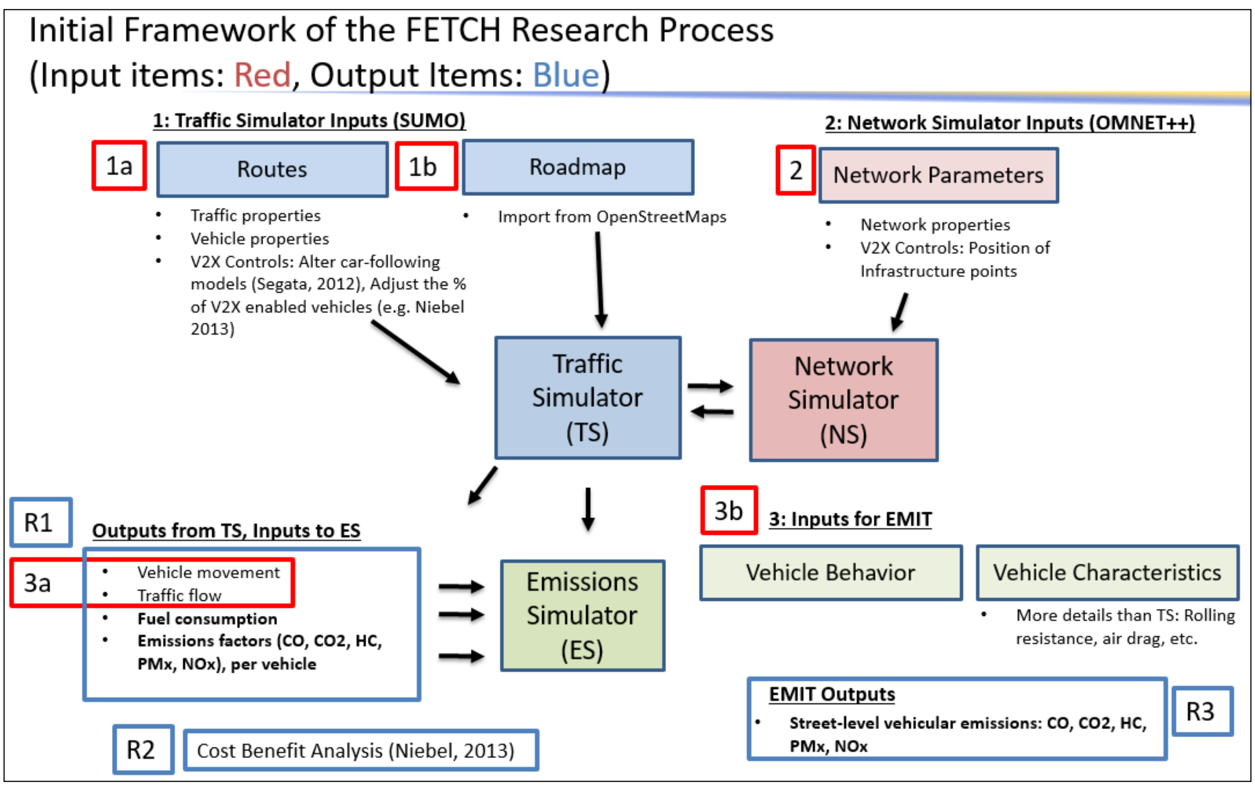


Figure 15: Initial Framework of Research Process

In summary, the FETCH Model can meet the objectives of the research problem in the following ways:

1) When the user desires to change an operating control, the user can either change the vehicle inputs (inputs concerning car following parameters such as following distances, fuel economy, vehicle speeds, etc.) indicated as **1a** in the figure, or change the network inputs (such as the V2X-enabled vehicle penetration rates, beaconing power of V2X modules, range of V2X modules, location of V2X modules, operating standards, etc.) indicated as **2** in the figure.

2) Vehicle control is defined in the Traffic Simulator as a vehicle property, and the penetrations of various vehicle control types can be adjusted within the SUMO simulation package.

3) If the user desires to account for realistic road conditions, such as weather or precipitation on the roadway, this would impact the inputs indicated as **1a and 3b** in the figure, and the user would change properties of the vehicles in the traffic simulator (such as maximum speeds and acceleration) and the emissions simulator (such as rolling resistance).

4) The UCI FETCH model was assembled using the information organized in the pro/cons tables for Traffic simulators, Network simulators, Integrated Traffic-Network simulators, and Emissions simulators described in Section 6 OBJECTIVE 3 RESULTS

## 7.2 Research Plan

Due to the level of complexity of this study, the full FETCH model is planned to develop over 2 years. This research plan is designed to provide some degree of flexibility, but at this point, the first year is planned for phases 1-3 towards FETCH to be complete. Each phase will implement more complexity than the last. The last phase, phase 4, will calibrate FETCH to accurately simulate a real world highway and study a V2X application. The approach to model increasingly complex V2X controls and the corresponding outputs as depicted in the figure below:

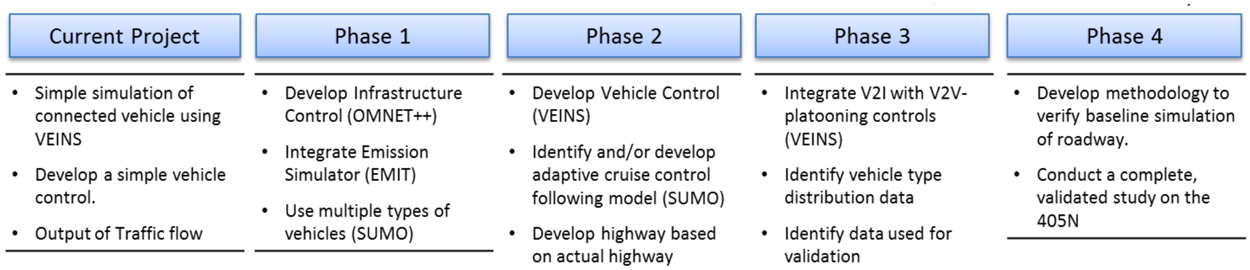


Figure 16: Research Process, Identification of Research Tools per Phase

While this may be enough for a future researcher to surmise the appropriate steps to take, a more detailed plan is necessary in order to best enable future researchers to successfully complete this study. More information regarding how this plan is developed is as follows:

### Phase 0, Current Phase

For the current project, the main research goals were to:

1) Create a simple connected vehicle simulation using VEINS,

2) Develop a simple vehicle control, and

3) Output total transit time.

The research process to accomplish these research goals are illustrated in the figure below:

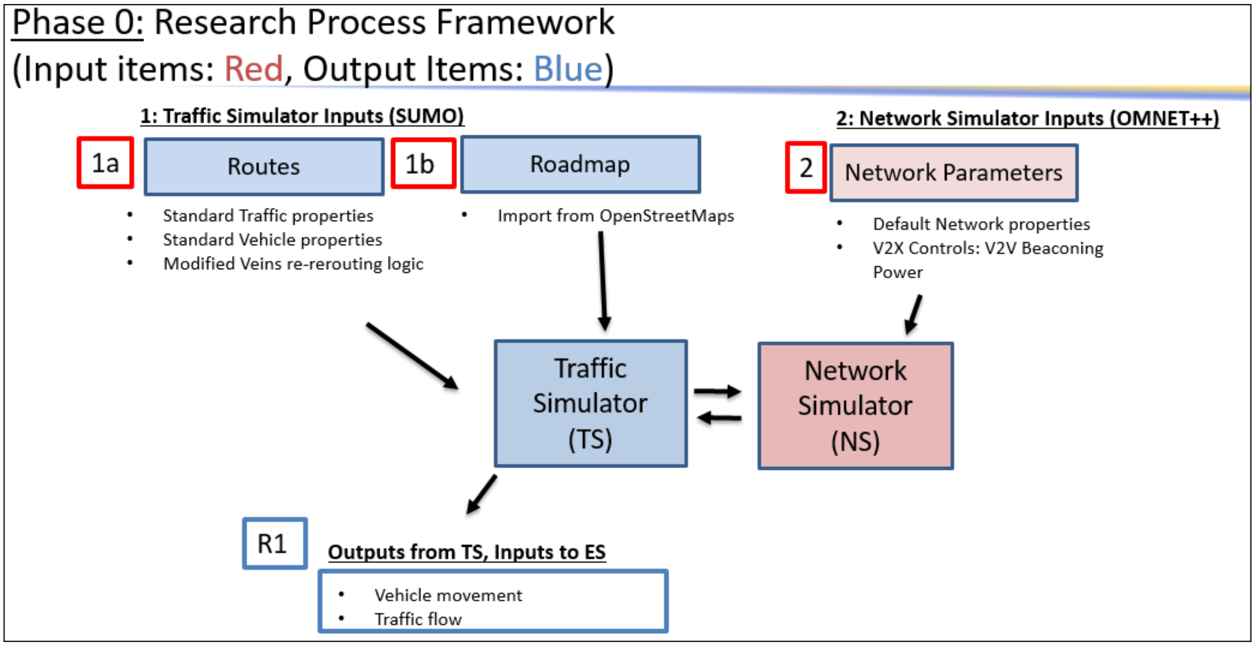


Figure 17: Phase 0, Current Project Research Process

Phase 1

From the current model, the following improvements will be made in Phase 1:

① Develop Infrastructure Control using OMNET++.

② Integrate the emissions simulator tool EMIT.

③ Populate the traffic simulation will various types of vehicle using SUMO.

The resulting infrastructure control will result in the V2I component of Phase 2 and Phase 3.

Following these guidelines, the Research Process Framework becomes the figure below:

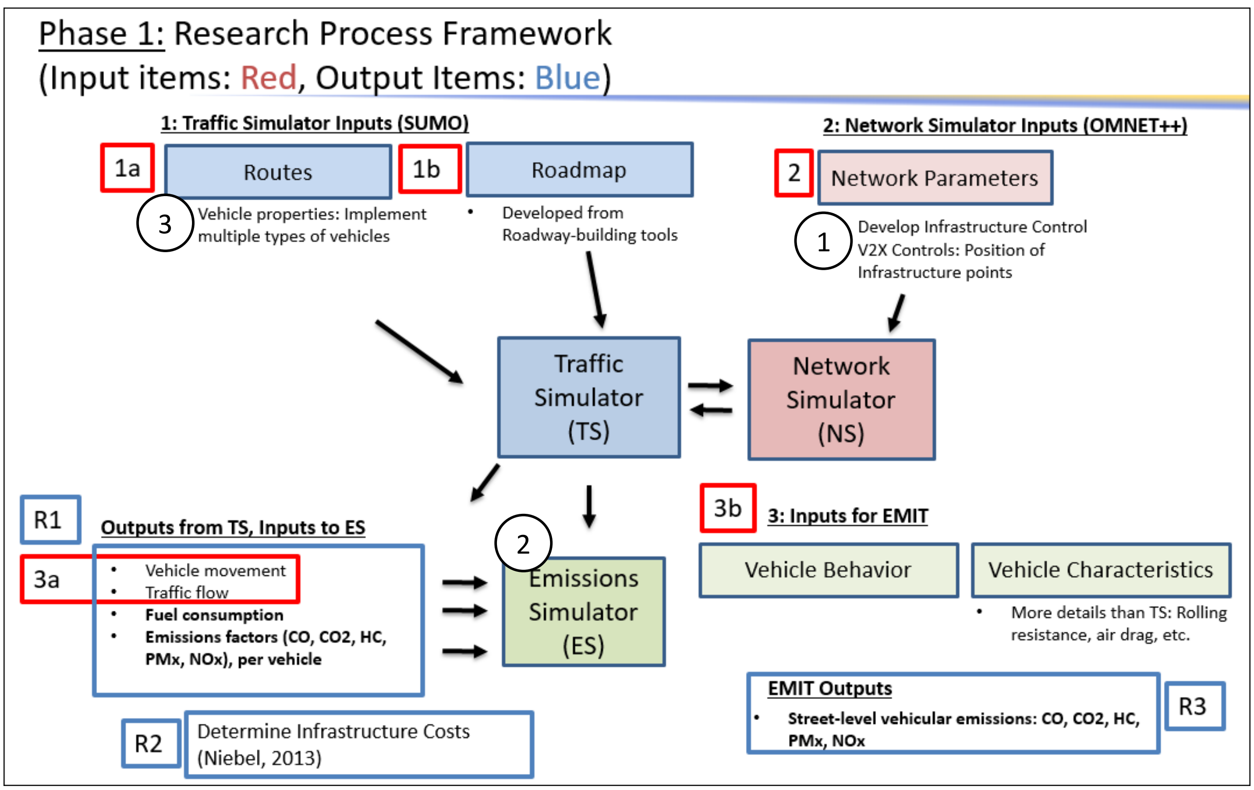


Figure 18: Phase 1 Research Process Framework

Phase 2

From the Phase 1, the following improvements will be made in Phase 2:

① Develop a vehicle control using SUMO. Identify and/or develop adaptive cruise control following model using SUMO.

② Develop highway geometry based on actual highway.

The resulting vehicle control will result in the V2V component of Phase 3 and Phase 4. Following these guidelines, the Research Process Framework becomes the figure below:

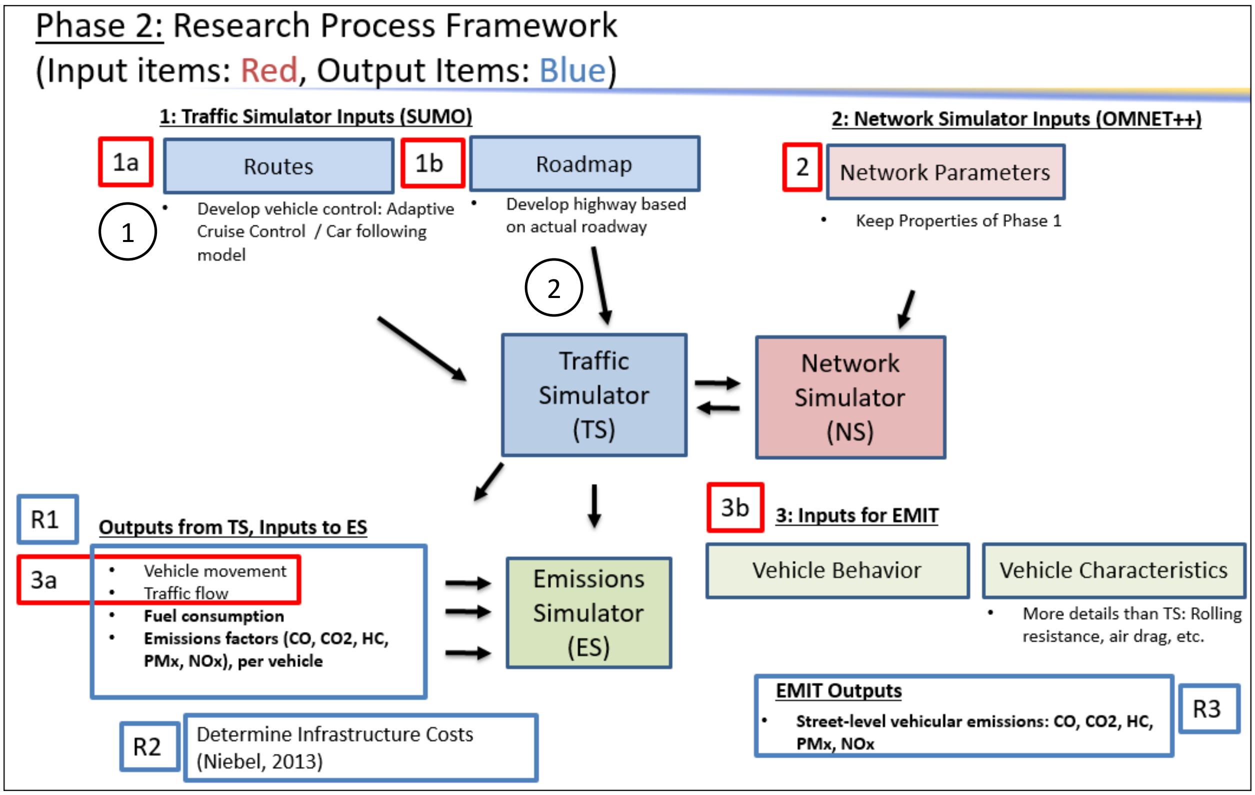


Figure 19: Phase 2 Research Process Framework

Phase 3

From the Phase 2, the following improvements will be made in Phase 3:

① Integrate the Infrastructure controls of Phase 1 with the Vehicle controls of Phase 2 to form a combined V2X control.

② Identify vehicle type distribution data for use in Phase 4.

③ Identify traffic data to be used to validate simulated vehicle behavior for the study in Phase 4.

Following these guidelines, the Research Process Framework becomes the figure below. Please note that the red dashed circle with a (2, 3) inside represents where improvements #2 and #3 will be implemented (where researchers will ultimately apply vehicle type distribution data and traffic data in Phase 4).

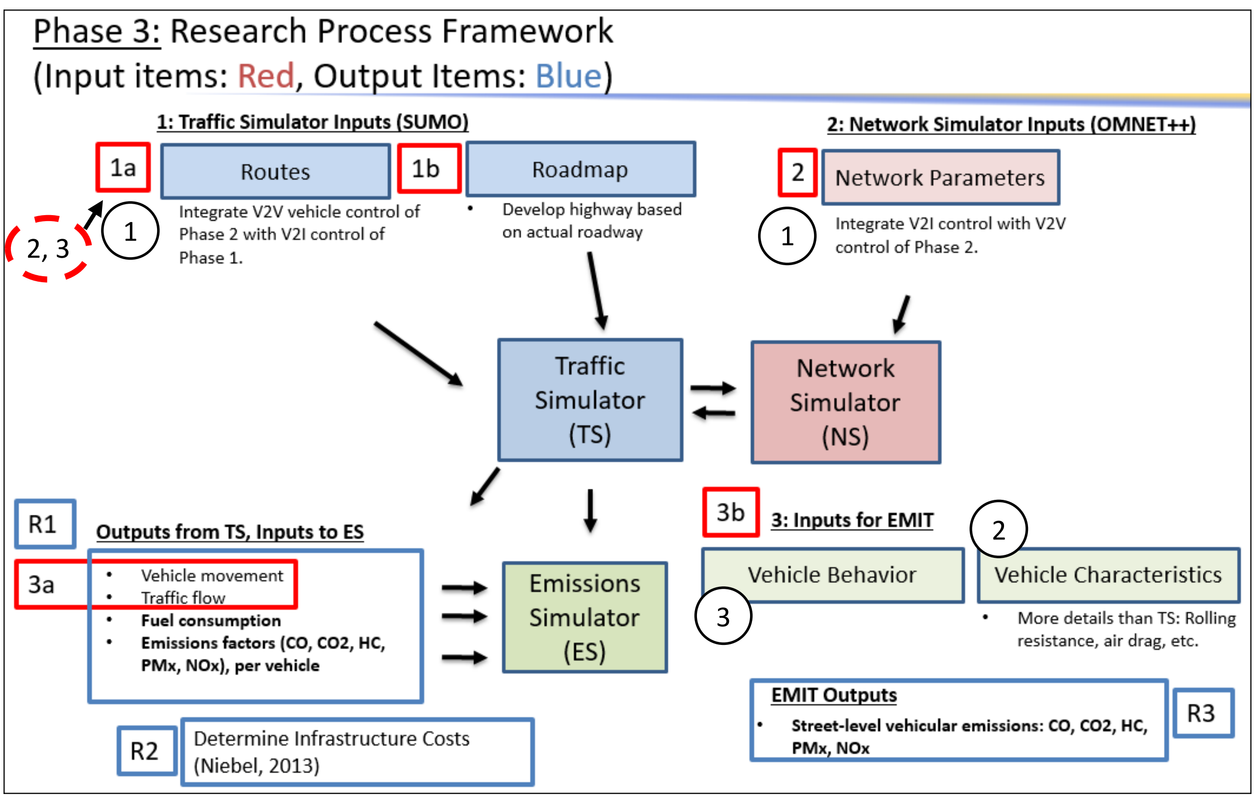

Figure 20: Phase 3 Research Process Framework

Phase 4

From the Phase 3, the following improvements will be made in Phase 4:

① Develop a methodology to verify the baseline simulation of the roadway.

② To conduct a complete, validated study on the 405N/110 Interchange.

③ Report Results

The final phase is the simulated application of the controls and parameters developed in the previous steps, with the goal of achieving an accurate representation of these V2X technologies and controls in action. Following these guidelines, the Research Process Framework becomes the figure below. Please note that the dashed line in this figure with a (1) in it, indicates where the information will be applied when gathered.

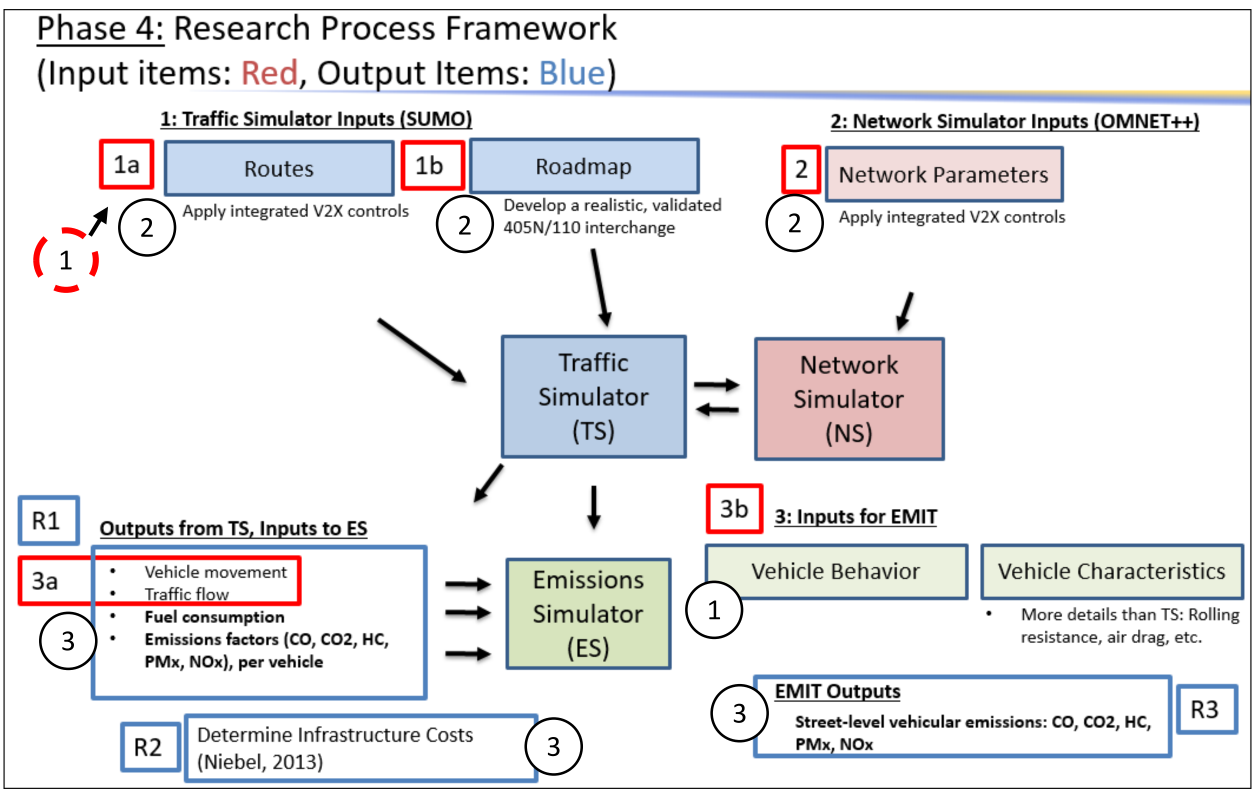


Figure 21: Phase 4 Research Process Framework

## 8 OBJECTIVE 5 RESULTS

**Objective 5: Demonstrate the model efficacy.**

The goal for this section of the thesis is to show the basic functionality of the FETCH model to the extent that a simple V2V or V2I control strategy can be implemented. The result garnered pertains to a change in traffic flow, vehicle fuel economy, or emissions.

8.1 Preliminary Model Setup

The first step in measuring the research result was to develop a preliminary model. This model altered a previously constructed V2X re-routing control using VEINS modelling software [83]. This previous research created a V2X-enabled re-routing control, where V2V messages are set to vehicles up-road if a traffic jam takes place, in order to direct them to change their route for a faster travel time. A schematic showing the operation of this control is below:

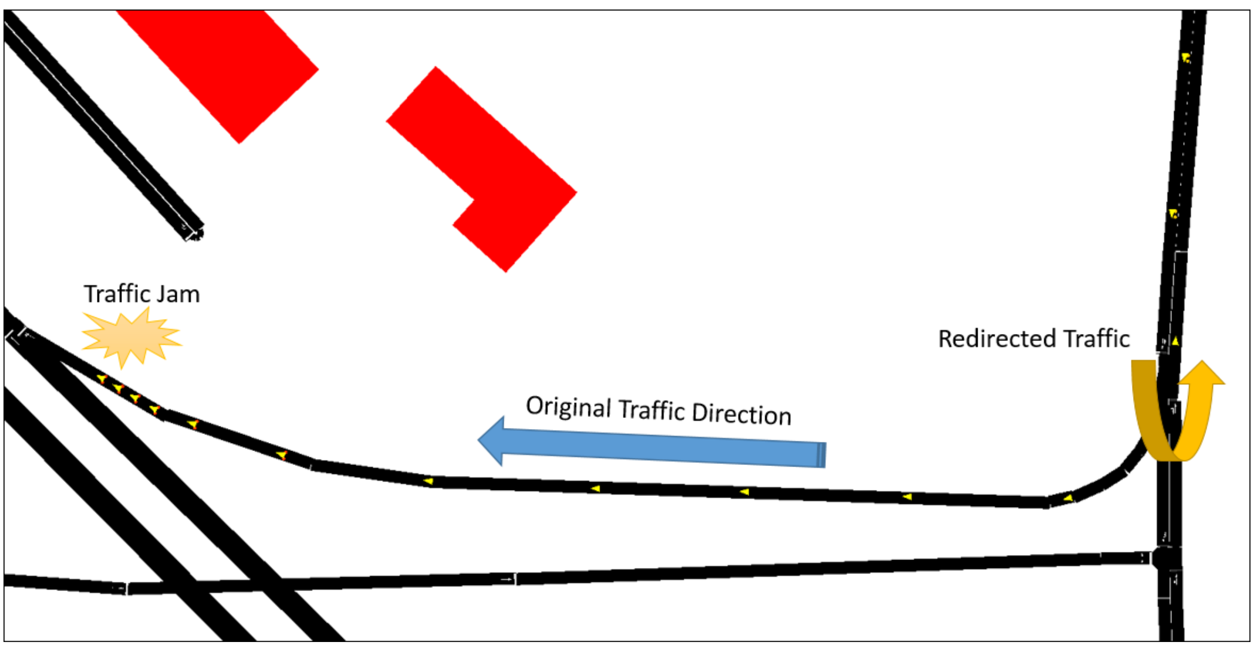


Figure 22: Example V2V Re-Routing Model

It was determined that the preliminary model for this thesis could consist of an altered version of this simple automatic re-routing control run on a custom roadway geometry. The effect of V2V beaconing power on the traffic flow of a multi-path roadway was chosen to be a simple test to demonstrate model capability. Using VEINS traffic and network simulation software, the following steps were taken to form the preliminary model:

1) Importing vehicular map by downloading editing a section through OpenStreetMaps.
2) Assigning Vehicle and Traffic behaviors such as:
    a. Vehicle count: 50
    b. Vehicle Rate of Entry into Simulation: 1 per second
    c. Vehicle maximum speed: 121.3 kph (75 mph)
    d. Vehicle acceleration: 2.6m/s^2 (a 10.3s 0-60 mph time)
    e. Vehicle deceleration: 4.5 m/s^2 (a 5.9s 60-0 mph time)
    f. Vehicle Length: 2.5m (8.2 ft.)
3) Assigning Networking parameters such as:
    a. V2V wireless beaconing power: Varies
    b. Beaconing interval: 1s
    c. Accident duration: 150s

These steps are illustrated below in Figure 23:

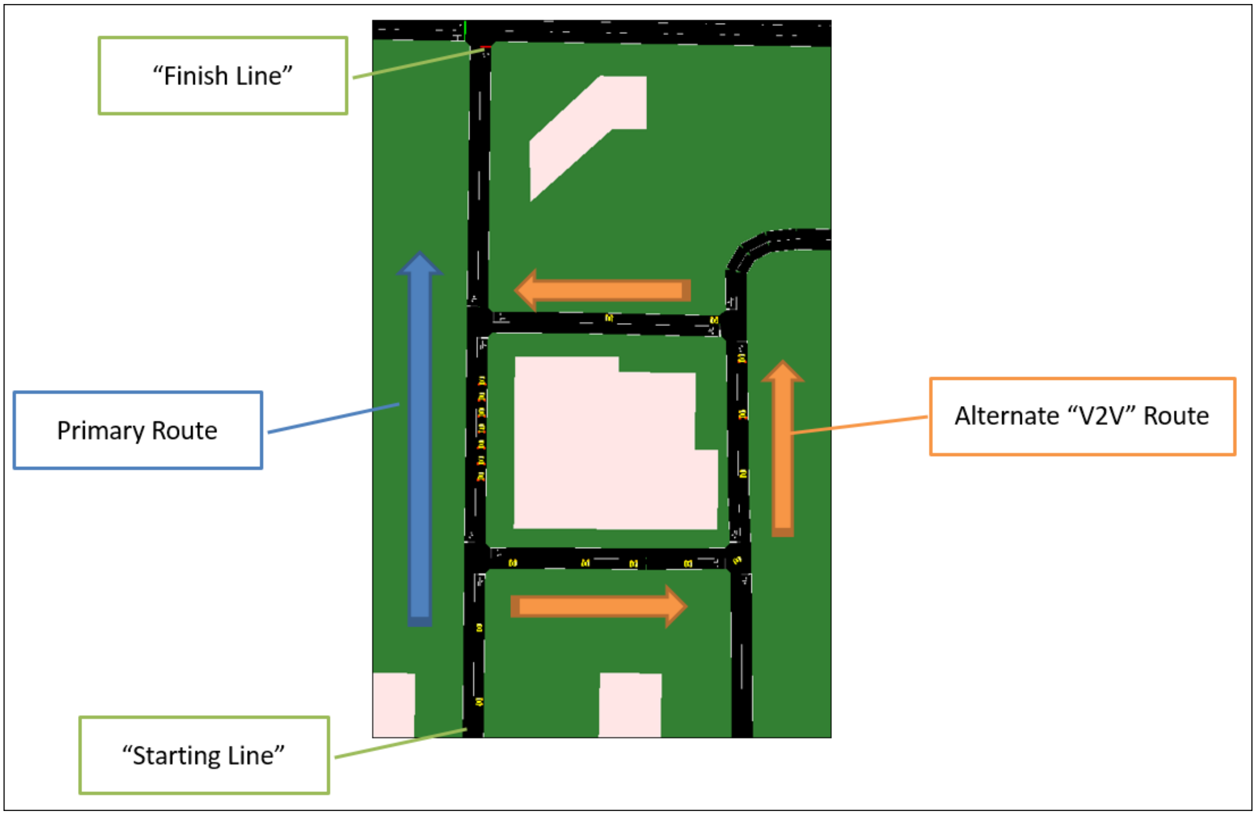


Figure 23: Preliminary Model Traffic Simulation Map

This illustration above describes the traffic behavior assigned in the SUMO traffic model. Both SUMO and OMNET++ combine to form the framework in Figure 24: Phase 0, Current Project Research Process illustrated below. Note that the area indicated by the red star indicates where the changes were made to create Figure 23:

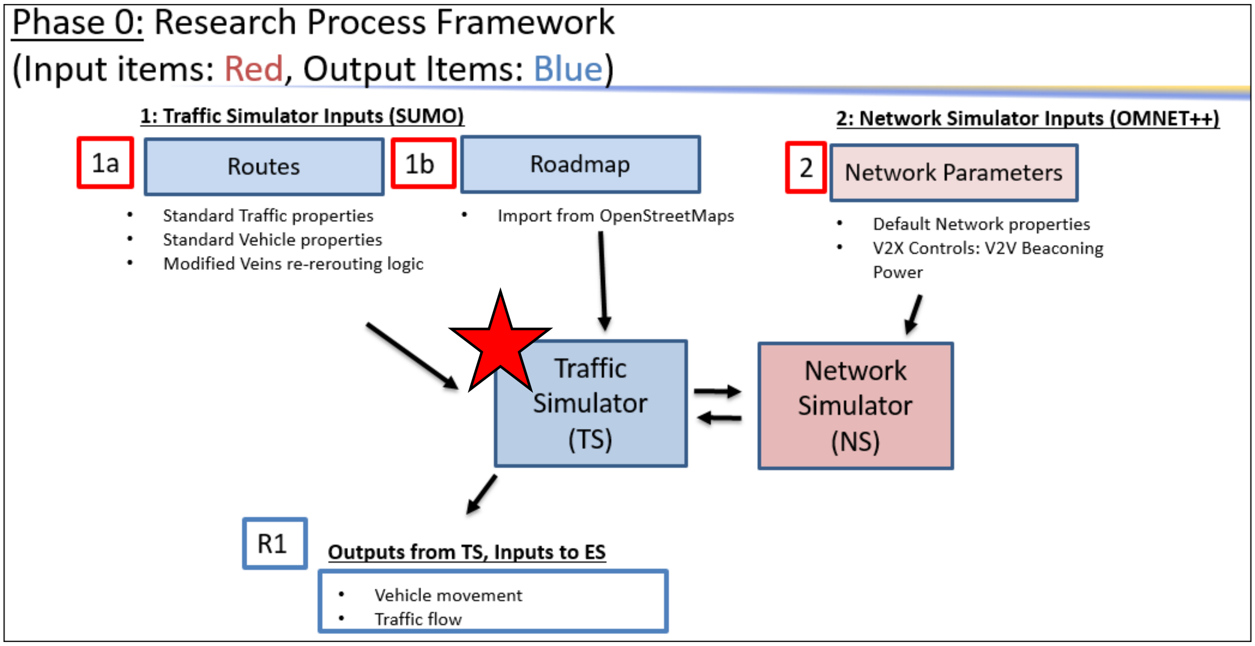


Figure 24: Phase 0, Current Project Research Process

As previously discussed, the preliminary model consisted of a modified an example V2V re-routing example and control logic [83]. The details of this model and control strategy can be clearly conveyed in the following flow diagrams. The diagram on the left, Figure 25: V2V Re-Routing Logic Diagram, is the Re-Routing Control diagram Preliminary, and the flow diagram on the right is the Traffic Model test procedure, shown as Figure 26: Test Procedure Flow Diagram.

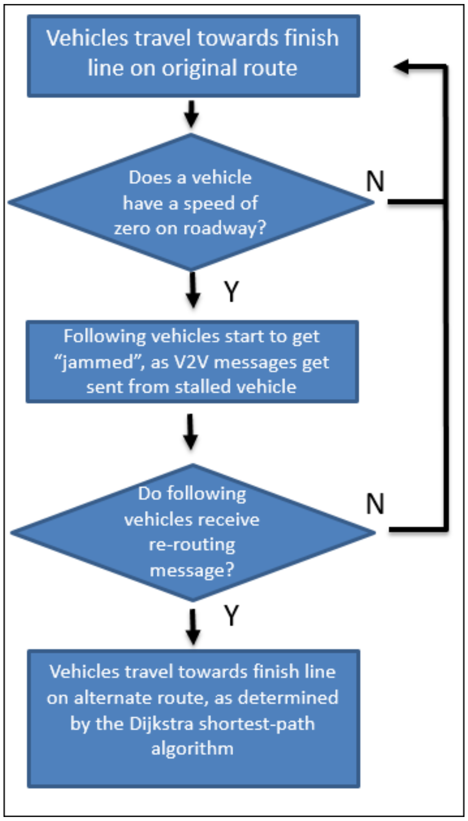


Figure 25: V2V Re-Routing Logic Diagram

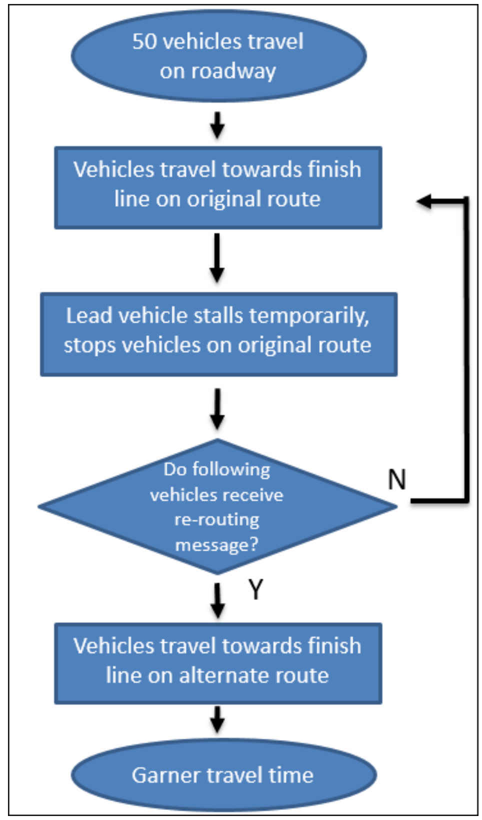


Figure 26: Test Procedure Flow Diagram

The V2V beaconing power on a V2V re-routing logic were altered to provide an appropriate control for the purposes of this preliminary model. This control experiment was carried out as follows:

1) Run trial simulation at standard V2V transmission power (1mW) to establish control traffic flow time. For this simulation, all vehicles in the simulation will be V2V-enabled.
2) Decrease V2V transmission power incrementally (in 0.05mW increments) until the beaconing power reaches zero.

This model is the OMNET++ networking model which corresponds with Figure 27: Phase 0, Current Project Research Process illustrated below, as indicated by the red star:

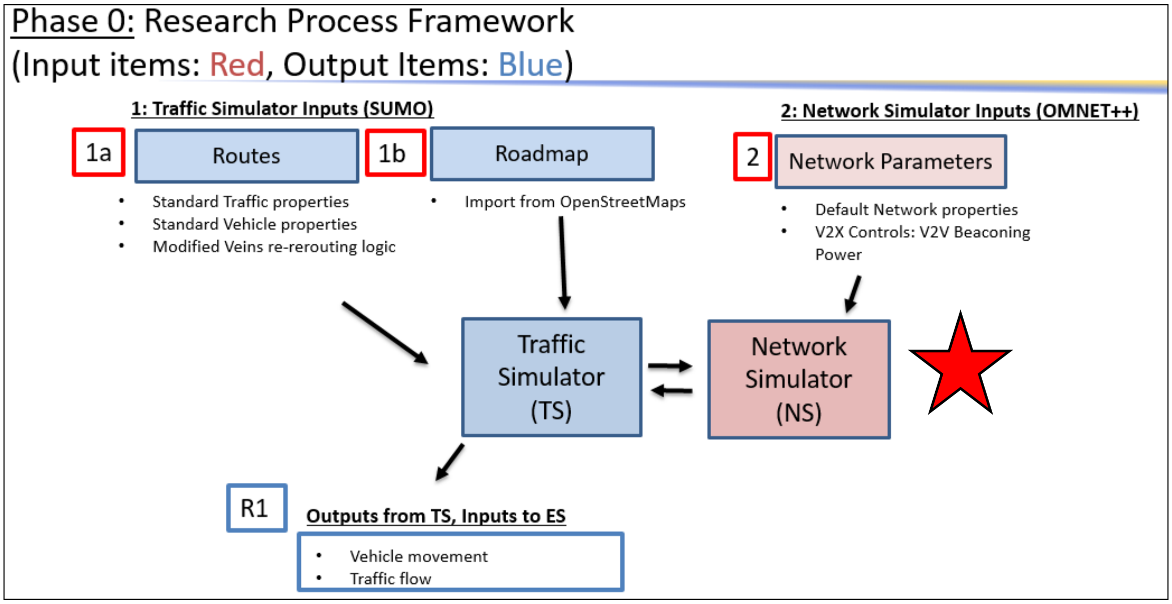


Figure 27: Phase 0, Current Project Research Process

8.2 Preliminary Model Results

It was found that decreasing V2V communication power lower than 0.20mW will affect traffic flow, with an anomaly being present in the data. A graph showing the overall trend is below, in Figure 28:

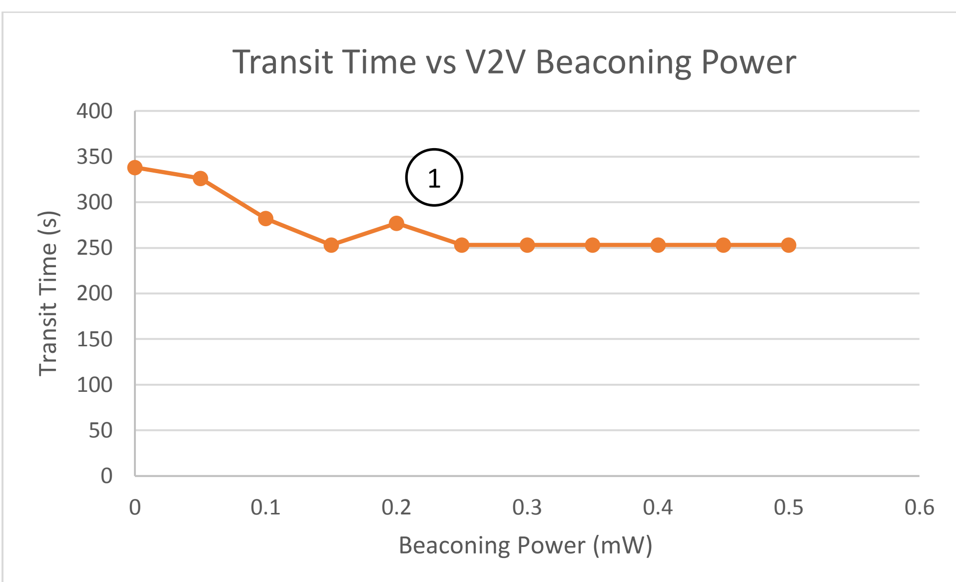


Figure 28: Transit Time vs V2V Beaconing Power

When experimenting with finer power increments, it was more accurately discovered that V2V communication power must be at least 0.205mW to ensure the greatest travel flow possible in this example scenario. However, when the beaconing power is decreased further, the *probability* of upcoming vehicles receiving messages is decreased, but the travel time in *not necessarily* a direct impact. The overall trend in the garnered data is for lower beaconing power to increase the travel time of the vehicles in the simulation. This means that when the V2V beaconing power decreases, the communication becomes less and less effective, resulting in less vehicles using the alternate, "un-jammed" route, and resulting in a greater transit time. However, one may note that this is not a steadfast, direct correlation as denoted by the "bump" at location (①). This lack of direct correlation is associated with the accuracy, rather than the inaccuracy, of the modelling software. The V2X networking simulator is defined to operate under the actual contemporary standards of V2X communication technology, including beaconing interval. In order to determine whether the beaconing interval was not sufficiently "fast" to accommodate all the vehicle dynamics of the simulation, a test was conducted to increase the beaconing rate from 1 Hz to 10 Hz. The resulting travel time at 10 Hz for 0.20 mW of beaconing power was equal to the travel times of the previous 1 Hz at 0.15 mW and 0.25 mW simulations. In other words, the "bump" is a result of a V2X message not reaching a vehicle fast enough, causing a re-routing message to be "dropped" or "lost." By increasing the beaconing interval, the "bump" is eliminated as a result of the beaconing power having the expected impact on transit time for the given network.

Overall, this preliminary model begins to demonstrate the capability of the FETCH model to accomplish the goals of the Research Problem. As the research plan is continued, various scenarios will be developed to evaluate the penetration rate of V2V and V2I technology necessary for impacts to traffic and emissions. When complete, this model will also be able to determine optimal placement of V2I infrastructure points, amongst other V2V or V2I control strategies. As is, this preliminary model illustrates the interplay between the Traffic and Network simulation tools, and follows a significant portion of the research framework illustrated in Section 7.2 Research Plan.

# 9 SUMMARY AND CONCLUSIONS

## 9.1 Summary

A comprehensive study was performed to search for demonstration projects and academic publications which test and evaluate state of the art technologies which mitigate major threats to (1) safety and (2) efficiency. The results of this preliminary study are organized by the signal to be detected. This preliminary study found that these signals include: slowing or stalled vehicles, stoplights and stop signs, traffic conditions, weather conditions, and human to vehicle interactions. Next, the research investigated which state of the art technologies were used to achieve improvements to safety and efficiency. Technologies significant in the surveyed literature include: V2V, V2I, CS, VRS, H2V, Infrastructure Data/Mapping, and LiDAR. It was determined that V2V, V2I, CS, and VRS are the most relevant to the study of this thesis as supported by relevant demonstration projects and research initiatives in Section 4. This information is more clearly conveyed in the table below;

Table 23: Environmental Signals, and Associated Technologies

| **Environmental Signal** | **Associated Technology** | **Technology In Report** | **Future Technologies to Investigate** |
|---|---|---|---|
| Slowing or Stalled Vehicles | V2V Communication<br>Camera systems<br>Radar<br>LiDAR | V2V Communication<br>Camera systems<br>Radar | LiDAR |
| Stoplights and stop signs | Camera systems<br>V2I<br>LiDAR<br>Infrastructure Data / Mapping | Camera systems<br>V2I | LiDAR<br>Infrastructure Data / Mapping |
| Traffic Conditions | V2I<br>LiDAR | V2I | LiDAR |
| Weather Conditions | V2V | V2V | |
| Human to Vehicle Interaction | Various HMI Tech. | Various HMI Tech. | Various HMI Tech |

Next, each of the relevant sensor technologies was evaluated in terms of merit to improve fuel economy and technological maturity. This study yielded the table below:

Table 24: Summary of Conclusions

| **Sensor Technology** | **Potential Fuel Economy Benefit** | **Technological Maturity**<br>**(Years until ready)** | **Cost (relative to other sensors)** |
|---|---|---|---|
| V2V | 5-20% for conventional vehicle | 10 years out | Cheap |

| Sensor Technology | Potential Fuel Economy Benefit | Technological Maturity (Years until ready) | Cost (relative to other sensors) |
|---|---|---|---|
| V2I | 10-25% for conventional vehicle | 15 years out (in US) | Cheap – On vehicle<br>Expensive – Infrastructure Costs |
| CS | At least 3% for conventional vehicle | Today (Safety)<br><5 years (Fuel Economy) | Cheap |
| VRS | 14% for conventional vehicle | Today | Expensive |

The information garnered in the aforementioned study, and as communicated by the above table, yielded the conclusion of V2V and V2I as being the most promising state of the art technologies to improve hybrid vehicle fuel efficiency. Overall, these conclusions guide the thesis to the next stages of research, to develop a tool to help measure the impact of these promising future vehicular technologies. Note that the approach going forward will be inclusive, which is to say that CS and VRS technologies can be evaluated with the developed tool.

The ultimate goal of this research is to study the relationship of roadway communication infrastructure (V2I), vehicle communication technology (V2V) penetration and vehicle control, and their influence on fleet fuel economy, emissions and traffic flow on a roadway. In order to satisfy these research requirements, three major component models (traffic, network, and emissions) were required to estimate the desired outputs (fuel economy, emissions, traffic flow). To select the proper traffic simulator, network simulator, and emissions simulator, this research chose these tools based on criteria such as tool capability, user support, and documentation as shown in Section 6. An existing integrated traffic-network simulator tool, VEINS, was selected in place of individually using SUMO and OMNET++. By using VEINS, the benefits of each tool can be realized in a simpler software package. This thesis section concludes with the selection of specific existing open-source models selected for each of the simulator tools in the table below:

Table 25: Modelling Tool Selection

| **Simulator Type** | **Simulator Selection** |
|---|---|
| Traffic | SUMO (as a component of VEINS) |
| Network | OMNET++ (as a component of VEINS) |
| Emissions | EMIT |

While these simulation tools will enable the research of the present requirements, the overall process used to select these traffic models allows for a degree of flexibility should the goals of this research change. For example, if researchers wish to simulate pedestrians and their interaction with traffic, the researchers can refer to the information gathered on other simulation tools, and make a different decision as necessary.

The UCI FETCH model was assembled using the information organized in the pro/cons tables for Traffic simulators, Network simulators, Integrated Traffic-Network simulators, and Emissions simulators described in Section 6. The aforementioned goals of this research can be satisfied by the FETCH Model by inputting traffic and geographical information into the traffic simulator (SUMO, of VEINS), wireless network parameters in the network simulator (OMNET++, of VEINS), and by integrating the emissions simulator (EMIT) to the traffic simulator. For more information regarding the specific inputs and outputs of these simulation tools, please refer to Section 7.

Next, it was pertinent to create a research plan to be used for accomplishing all research goals beyond those within the scope of this thesis. This plan offers future researchers the ability to clearly see the data required and controls strategies which are necessary to successfully complete each step. The overall goal for these steps is to help ensure the successful completion of future research, as described in Section 7.

Finally, the FETCH Model demonstrated core functionality of V2X controls by implementing a custom roadway on a simple automatic re-routing control model as shown in Section 8. The effect of V2V beaconing power on the traffic flow of a multi-path roadway provided a simple test to demonstrate FETCH capability for measuring the impacts of V2X controls. It was discovered that by decreasing beaconing power, the *probability* of upcoming vehicles receiving messages is decreased, but the travel time in *not necessarily* going to be decreased as well. This occurs because a vehicle along the roadway may be in the messaging range of the stalled vehicle, despite a decrease in power between simulation runs. As a general rule however, the trend is for lower power to increase the travel time for vehicles within the simulation.

## 9.2 Conclusions

- **V2V and V2I communication are the most promising technologies to improve hybrid vehicle fuel efficiency for their ability to detect slowing or stalled vehicles, stoplights, and traffic conditions.**

The identification of promising sensor technologies to improve vehicle fuel economy can guide the direction of both regulation by the government and competition among automakers. Additionally, information on the commercial readiness of these technologies will guide the development required to enable deployment. For example, CS and VRS technologies already exist on many contemporary vehicles. As a result, automakers are already incentivized to integrate these sensors into systems which can be used to maximize efficiency. On the other hand, because V2V and V2I are longer-term investments, governing agencies may be inclined to propose mandates that encourage automakers to undertake the necessary research and development to accelerate the deployment V2V/V2I technologies. Beyond the efficiency discussion, these technologies play a role in safety as well. Consequently, this conclusion could steer engineering resources or policy discussions toward a path that could bring safer, more efficient, and cleaner vehicles on the road at a faster pace.

- **The modelling tools best suited to satisfy the research goal of this thesis are: SUMO (For traffic simulation, as a component of VEINS), OMNET++ (For network simulation, as a component of VEINS), and EMIT (For emissions simulation).**

While these simulation tools will enable the research of the requirements at hand, the overall process used to select the traffic models allows for a degree of flexibility depending on the goal of the research. For example, if researchers wish to simulate the interaction of pedestrians with traffic, additional or alternative simulation tools may be selected. Years in the future, researchers can continue to refer to this work for insight into how to select appropriate simulation tools, even if research in this space has progressed significantly. At this juncture, the simulation tools selected provide the essential components to attain the research goals, namely to establish a simulation model suitable to assess the impact of advanced vehicular technology on traffic flow, emissions, and fuel economy of hybrid vehicles. The tool selection process enables future researchers to achieve a contextual understanding of relevant research, while also developing a research plan that can allow for certain contingencies.

- **The Fuel Economy and Traffic of Connected Hybrids (FETCH) model, established to delineate and evaluate V2V/V2I communication systems, provides a needed resource to assess the roles of advanced vehicle sensor technologies on traffic flow, fuel economy, and emissions.**

  Overall, the FETCH model introduces a planning platform for the development and evaluation of V2X scenarios. FETCH allows the interactions between traffic, network, and emissions simulation tools, and provides government and industry stakeholders thereby with information critical to the design, implementation, and impacts of connected vehicle technologies, technologies which can be integrated into vehicles for the purpose of enhancing vehicular safety and efficiency. The FETCH tool portends an opportunity to enable safer and cleaner light duty transportation.

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# APPENDIX A:  REFERENCED DEMONSTRATION PROJECTS, STANDARDS

V2V Demonstration Projects

Table 26: V2V Communication Demonstration Projects and Research Initiatives

| Organization | Year | Title / Funding (If Available) | Test Criteria | Findings |
|---|---|---|---|---|
| California Partners for Advanced Transportation Technology (PATH)<br><br><u>Automotive:</u><br><br>Daimler, GM, Honda, Toyota, Ford, Nissan, Hyundai / KIA, VW, BMW | 2002-2003 | • Crash Avoidance Metrics Partnership (CAMP) (Technology research collaborations)<br>• Vehicle Infrastructure Integration Consortium (VIIC) (Addresses policy Issues) | Tested V2I ability to provide:<br>• Driver awareness of traffic signal, other hazards near intersection<br>• Traffic signal changes with presence of vehicle | • 15% fuel savings for standard powertrain vehicles with adaptive traffic lights (change for approaching vehicles)<br>• Drivers are aware of signal status, possibly time to next phase<br>• Similar systems possible with 3G/4G cellular networks for more rapid support<br>• Caltrans has the vision to build signalized intersections every 10 miles on California highways. May be privately funded with incentives program |
| Opel (vehicles),<br><br>Continental AG (onboard electronics), Dambach-Werke (Roadside/V2I units) | 2008-2013 | Dynamic Information and Application for Mobility with Adaptive Networks and Telematics Infrastructure<br><br>(DIAMANT)<br><br>€5.2M, Internally funded | One year test period:<br>• Preliminary effort<br>• Test the readiness of V2V / V2I technology<br>• Determine usefulness of data in in context of highway traffic efficiency.<br>• Joined SimTD. | DIAMANT Conclusions:<br>• 5/1000 vehicles with V2I tech. can provide a representative understanding of traffic flow |

| | | | | |
|---|---|---|---|---|
| <u>Automotive</u><br>Daimler, Ford, Audi, BMW/Mini, Opel, VW<br><u>Industry</u><br>Bosch, Continental, Deutsche Telekom<br><u>Research</u><br>Tech. Univ. Berlin<br>Munich Univ. of Tech.<br>Saarland Univ.<br>Univ. of Wurzburg<br>Fraunhofer-Gesellschaft | 2008-2012 | Safe and Intelligent Mobility–Test Field Germany<br>(SimTD)<br>€53M, €30M paid for by German Gov't. Add'l V2I costs covered by State of Hessen, Germany | Create overall system to test the following concepts:<br>• Traffic Sign Assistance<br>• Obstacle Warning Sys.<br>• Electronic Brake Light<br>• Public traffic Mgmt.<br>Field testing: 7/2012-12/2012<br>• 120 Vehicles<br>• 104 V2I / Roadside Units, one connected to traffic light<br>• 500 test drivers, 41,000 testing hours, 1.65M Km | SimTD conclusions:<br>• Drivers with equipped vehicles were quicker to adapt speed, following distance, and behavior to changing traffic speed quicker |
| <u>Automotive</u><br>Fiat, Daimler, Renault, Volvo<br><u>Industry</u><br>BAE Systems, Bosch, Siemens AG, SINTEF, Netherlands Organization for Applied Scientific | 2006-2010 | Cooperative Vehicle Infrastructure Systems (CVIS)<br>€41M, ~€20M paid for by European Union. | • Evaluate a standardized network to facilitate V2V/V2I<br>• Develop dynamic mapping capability<br>• Test V2I equipment and respective toolkits<br>• Testing occurred at 7 | Successful development/ demonstration of V2I features:<br>• Green light speed advice<br>• Traffic sign messages to dashboard<br>• Social networking for ride-share passengers<br>• Collaborative safety applications:<br>○ Safe following distances<br>○ Cooperative Intersection Collision Avoidance Systems (CICAS): Alert drivers on a collision course with another vehicle at intersection |

| | | | | |
|---|---|---|---|---|
| Research (TNO), etc.<br><br><u>Research</u><br><br>British Dept. for Transport, German Aerospace Center, ERTICO - ITS Europe, Forum of European Nat'l Highway Research Laboratories, etc. | | | different testing locations with Automotive, Industry, and Research groups represented | |

V2V and V2I Demonstration Projects

Table 27: Combination V2V and V2I Research Projects

| **Organization** | **Year** | **Title / Funding (If available)** | **Test Criteria** | **Findings** |
|---|---|---|---|---|
| Netherlands Organization for Applied Scientific Research, TNO | 2011,2016 (planned) | Project: Grand Cooperative Driving Challenge<br>Proceedings: Cooperative Adaptive Cruise Control Implementation of Team Mekar at the Grand Cooperative Driving Challenge | Full-scale V2V demonstration project. Implemented CACC system on 8 vehicles from separate teams/countries | CACC, when added to existing ACC system, is technically/ economically feasible |
| <u>Automotive:</u><br>Ford, GM, Honda, Hyundai-Kia, Mercedes-Benz, Nissan, Toyota, VW<br><u>Research:</u><br>Univ. Michigan<br>Transportation Research Institute (UMTRI) | 2012-In Progress | Connected Vehicle Safety Pilot<br>$14.7M | 2836 Vehicles (cars and trucks), Test technical abilities of V2V systems to transmit standardized data packets and efficacy for reducing crashes, tested cars truck, tested V2V and V2I roadside equipment, involved long-term observation of many vehicles in realistic driving saturations. | This project was originally intended to run for 18 months, but is still ongoing. Results have yet to be published. |

| Organization | Year | Title / Funding (If available) | Test Criteria | Findings |
| --- | --- | --- | --- | --- |
| Automotive:<br>Audi, BMW, Daimler, Ford, Honda, Hyundai/KIA, MAN, OPEL, Peugeot, Renault, VW, Volvo, Yamaha<br>Industry:<br>Bosch, Continental, Delphi, etc.<br>Institutions:<br>German Federal Highway Research Institute (BASt), etc. | 2004-2012 | Car 2 Car Communication Consortium | Objective: Collaboratively develop and ultimately deploy V2V / CACC technologies in Europe.<br>Worthy to note that this was initiated by European automakers, is now more diverse. | |

V2I Demonstration Projects

Table 28: V2I Demonstration Projects

| Organization | Year | Title / Funding (If Available) | Test Criteria | Findings |
|---|---|---|---|---|
| Caltrans, BMW, Siemens | 2010 | IntelliDrive: The Benefits of Infrastructure to Vehicle Information Transfer | Tested V2I ability to provide: <br>• Driver awareness of traffic signal, other hazards near intersection<br>• Traffic signal changes with presence of vehicle | • 15% fuel savings with adaptive traffic lights (change for approaching vehicles)<br>• Drivers are aware of signal status, possibly time to next phase<br>• Similar systems possible with 3G/4G cellular networks for more rapid support<br>• Caltrans has the vision to build signalized intersections every 10 miles on California highways. May be privately funded with incentives program |
| Opel (vehicles), Continental AG (onboard electronics), Dambach-Werke (Roadside/V2I units) | 2008-2013 | Dynamic Information and Application for Mobility with Adaptive Networks and Telematics Infrastructure (DIAMANT) €5.2M, Internally funded | One year test period:<br>• Preliminary effort<br>• Test the readiness of V2V / V2I technology<br>• Determine usefulness of data in in context of highway traffic efficiency.<br>• Joined SimTD. | DIAMANT Conclusions:<br>• 5/1000 vehicles with V2I tech. can provide a representative understanding of traffic flow |
| <u>Automotive</u> Daimler, Ford, Audi, | 2008-2012 | Safe and Intelligent Mobility–Test Field Germany | Create overall system to test the following concepts:<br>• Traffic Sign Assistance | SimTD conclusions:<br>• Drivers with equipped vehicles were quicker to adapt speed, following distance, and |

| Organization | Year | Title / Funding (If Available) | Test Criteria | Findings |
|---|---|---|---|---|
| BMW/Mini, Opel, VW<br><br><u>Industry</u><br><br>Bosch, Continental, Deutsche Telekom<br><br><u>Research</u><br><br>Tech. Univ. Berlin<br><br>Munich Univ. of Tech.<br><br>Saarland Univ.<br><br>Univ. of Wurzburg<br><br>Fraunhofer-Gesellschaft | | (SimTD)<br><br>€53M, €30M paid for by German Gov't. Add'l V2I costs covered by State of Hessen, Germany | • Obstacle Warning Sys.<br>• Electronic Brake Light<br>• Public traffic Mgmt.<br><br>Field testing: 7/2012-12/2012<br><br>• 120 Vehicles<br>• 104 V2I / Roadside Units, one connected to traffic light<br>• 500 test drivers, 41,000 testing hours, 1.65M Km | behavior to changing traffic speed quicker |
| <u>Automotive</u><br><br>Fiat, Daimler, Renault, Volvo<br><br><u>Industry</u><br><br>BAE Systems, Bosch, Siemens AG, Netherlands Organization for Applied Scientific Research (TNO), etc.<br><br><u>Research</u><br><br>CNRS (HDS/UTC), Cork Inst. of Tech., British Dept. for Transport, | 2006-2010 | Cooperative Vehicle Infrastructure Systems (CVIS)<br><br>€41M, ~€20M paid for by European Union. | • Evaluate a standardized network to facilitate V2V/V2I<br>• Develop dynamic mapping capability<br>• Test V2I equipment and respective toolkits<br>• Testing occurred at 7 different testing locations with Automotive, Industry, and Research groups represented | Successful development/ demonstration of V2I features:<br><br>• Green light speed advice<br>• Traffic sign messages to dashboard<br>• Social networking for ride-share passengers<br>• Collaborative safety applications:<br>  ○ Safe following distances<br>  ○ Cooperative Intersection Collision Avoidance Systems (CICAS): Alert drivers on a collision course |

| Organization | Year | Title / Funding (If Available) | Test Criteria | Findings |
|---|---|---|---|---|
| German Aerospace Center, ERTICO - ITS Europe, Forum of European Nat'l Highway Research Laboratories, etc. | | | | with another vehicle at intersection |

CS Demonstration Projects

Table 29: Camera Systems Demonstration Projects

| Organization | Year | Title / Funding (If available) | Test Criteria | Findings |
|---|---|---|---|---|
| NHTSA<br>Automotive:<br>General Motors<br>Industry:<br>Delphi<br>Research:<br>Univ. Michigan | 2003-2004 | Automotive Collision Avoidance<br>System Field Operational Test | • Tested efficacy of Adaptive Cruise Control (ACC) and FCW systems (early tech. status) for enhancing safety<br>• 14 vehicles<br>• 66 drivers<br>• 158,000 miles | • Technical challenges (mostly pertaining to image processing errors)<br>• Drivers of equipped vehicles tailgated significantly less (systems believed to be due to increased awareness) |
| ERTICO / ITS Europe<br>Automotive:<br>Lead by Ford (Eur. Research Center, Germany), BMW, Daimler, Fiat, MAN, Volvo, Audi, VW | 2008-2012 | euroFOT<br>€22M | • Tested efficacy for driver assistance technologies to improve driving behavior (safer, more efficient<br>• Mostly evaluated from a transportation-as-a-whole perspective, | • Fuel Implications measured<br>o When FCW coupled with ACC, fuel savings of approximately 3% for cars and 2% for trucks with standard powertrains (not including |

| Organization | Year | Title / Funding (If available) | Test Criteria | Findings |
|---|---|---|---|---|
| Industry:<br><br>Bosch, Continental, Delphi, etc.<br><br>Research:<br><br>Federal Highway Research Institute, Germany (BAST), French Inst. of Science and Tech. for Transport (IFSTTAR ), Netherlands Organization for Applied Scientific Research (TNO), etc. | | | rather than impacts on individual vehicles<br>• Evaluated:<br>  ○ FCW, LDW, ACC, Speed Regulation Systems (SRS), Safe Human-Machine Interface, and Fuel Efficiency Advisor (FEA))<br>• 1000 Vehicles, drivers<br>• 34,000,000km | additional efficiencies resulting from improved traffic flow)<br>• Numerous safety implications with efficiency ties<br>  ○ SRS with standard cruise control reduced speed fluctuations in highway driving |

Below are some domestic and international standards which support the deployment of CS technology in passenger vehicles. The amount of standards should also indicate the maturity / accepted state of CS technology in the public.

CS Standards, Current and Pending.

Table 30: CS Standards: Current and/or Pending

| **Organization** | **Std.** | **Title** | **Status** | **Description** |
|---|---|---|---|---|
| NHTSA | LV NCAP 2010 | NCAP for Light Vehicles | Accepted | Defines performance requirements* for CS used in Lane Departure Warning Systems (LDWs) |
| ISO/DIS | 17361 | Lane Departure Warning Systems - Performance Requirements and Test Procedures | Accepted | Specifications, requirements* and test methods for CS for CS-LDW integration with light and heavy duty vehicles / busses |
| Commission Regulation (EU) | No. 351/2012 | Type/Approval Requirements for the Installation of Lane Departure Warning Systems in Motor Vehicles | Accepted | Defines performance requirements* for CS used in LDWs |
| ISO | 15623: 2013 | Forward vehicle collision warning systems | Accepted | Performance requirements*, test procedures for FCW systems |
| SAE | J3029 | Forward Collision Warning and Mitigation Vehicle Test Procedure | Work In Progress | Test procedure for automatic decorative vehicle systems, includes FCW systems |

*Typical performance requirements include:

- Test Road length, Road curve radius
- Number of trials
- Maximum lane size
- Rate of Lane departure
- False-positive testing
- Warning type, (Visual notification, auditory notification)

- Speed at which system is active
- Whether system can be deactivated / whether system is automatically reactivated with each ignition cycle

## H2V Demonstration Projects / Research Initiatives

Table 31: H2V Demonstration Projects

| Organization | Year | Title / Funding (If Available) | Test Criteria | Findings |
|---|---|---|---|---|
| European counsel for automotive R&D<br>Automotive:<br>BMW / MINI<br>Industry:<br>TOMTOM<br>Research:<br>Netherlands Organization for Applied Scientific Research (TNO), ITS Europe, Forum of European Nat'l Highway Research Laboratories (ERTICO), etc. | 2011 - 2015 | ecoDriver Project<br>€14.5M, €10.7M paid for by European Union. | • Evaluated one main H2V concept<br>○ "Energy Threshold Interpreter"<br>▪ Informs driver of current fuel efficiency as well as best possible efficiency that could be achieved | • Preliminary results confirm academic findings<br>• No specific efficiency results, numbers, given as of the writing of this report. |
| Automotive:<br>Ford, BMW, DAF trucks, Fiat, Volvo<br>Industry: | 2010 - 2014 | eCoMove Project<br>€22.5M, €13.7M paid for | • Studied a number of connected vehicle technologies.<br>• Preliminary Survey Information from 18 | • Results concluded Most drivers prefer a system with that does not attempt to change user experience for greater fuel efficiency |

| Organization | Year | Title / Funding (If Available) | Test Criteria | Findings |
|---|---|---|---|---|
| Bosch, Continental, etc.<br><br>Research:<br><br>Galician Automotive Technology Centre (CTAG), Netherlands Organization for Applied Scientific Research (TNO), etc. | | by European Commission. | Participants pertained to H2V design<br>○ Participants were asked about H2V preferences | ○ That is, systems which change the difficulty of depressing the throttle |

# APPENDIX B: RELEVANT, INFLUENTIAL PUBLICATIONS

V2V Table of Influential Publications

These publications represent the most influential and informative academic works concerning the broad scope of V2V technology. These were selected based on a combination of influence in the subject area (indicated by number of citations) and other technological innovations which can contribute to the future outlook of the technology. Note the domestic collaborations between General Motors and Carnegie Mellon University, this is a recurring collaboration in many sensor groups but is most evident in this technological category.

Table 32: V2V Table of Influential Publications and Demonstration Projects

| Organization | Year | Title | Reason | Citations |
|---|---|---|---|---|
| Hartenstein & Laberteaux (TTC / Univ. of Karlsruhe) | 2008 | A tutorial survey on vehicular ad hoc networks | Tech Overview | 347 |

| Organization | Year | Title | Reason | Citations |
|---|---|---|---|---|
| Lang, Stanger, & del Re (SAE / Johannes Kepler University Linz) | 2013 | Opportunities on Fuel Economy Utilizing V2V Based Drive Systems | V2V Fuel Econ. Merit | 5 |
| Brackstone & McDonald (Univ. Southampton, UK) | 1999 | Car-following: A historical review | Fuel Econ. benefits, Overview of V2V | 342 |
| Lang, Stanger, & del Re (SAE / Johannes Kepler University Linz) | 2014 | Prediction of Preceding Driver Behavior for Fuel Efficient Cooperative Adaptive Cruise Control | Further Explores Fuel Econ. of V2V,CACC | 0 |
| Eichler, S. IEEE Vehicular Technology Conference | 2007 | Performance evaluation of the IEEE 802.11p WAVE communication standard | Tech Overview | 139 |
| Liu, Zhao, & Vaidya (Univ. Illinois, Urbana-Champaign, Microsoft Research) | 2004 | A vehicle-to-vehicle communication protocol for cooperative collision warning | Preliminary Technological Development Publication | 134 |
| Henty, Cooper, & Stancil Carnegie Mellon University / General Motors Research Center | 2008 | A measurement study of time-scaled 802.11a waveforms over the mobile-to-mobile vehicular channel at 5.9 GHz | Performance Characteristics of V2V Waveforms | 40 |
| Kumar & Bai Carnegie Mellon University / General Motors Research Center | 2007 | Bounded-latency alerts in vehicular networks | Investigates Design of Robust V2V communication | 14 |
| Mangharam & Bait Carnegie Mellon University / General Motors Research Center | 2013 | A double decoding scheme to improve the per performance of V2V communications | Research reduces error rate in V2V communication | 0 |
| Michigan Dept. of Transportation / Center For Automotive Research | 2013 | International Survey of Best Practices in Connected and Automated Vehicle Technologies | Up to date review of V2V V2I research activity | 0 |

| Organization | Year | Title | Reason | Citations |
|---|---|---|---|---|
| Gonder, J.<br>NREL | 2012 | Analyzing Vehicle Fuel Saving Opportunities through Intelligent Driver Feedback | Fuel Econ. benefits, Overview of V2V | 6 |

V2I Table of Influential Publications

Where V2V and V2I technologies share much of the same core technology, most of the research efforts involve both V2V and V2I technologies as well. These two publications discuss the main benefits and challenges associated with integrating V2V and V2I technologies. These publications helped to draw the conclusions seen in 4.3 Vehicle to Vehicle Communication Systems and 4.4 Vehicle to Infrastructure Communication Systems.

Table 33: V2I Table of Influential Publications and Demonstration Projects

| Organization | Year | Title | Reason | Citations |
|---|---|---|---|---|
| Hartenstein & Laberteaux (TTC / Univ. of Karlsruhe) | 2008 | A tutorial survey on vehicular ad hoc networks | Tech Overview | 347 |
| CAMP: US DOT/NHTSA<br>Mercedes-Benz, GM, Toyota, Honda, Ford | 2011 | Vehicle Safety Communications – Applications (VSC-A) Final Report | Tech Overview | 13 |

CS Table of Influential Publications

Camera systems have been getting more sophisticated over time with the advancement of image recognition technology and increasingly affordable computing power. These publications offer insight as to how far this technology has come in such a short amount of time, as well as a glimpse into the future of image recognition for vehicular applications.

Table 34: CS Table of Influential Publications

| Organization | Year | Title | Reason | Citations |
|---|---|---|---|---|
| Bertozzi,<br>Univ. Parma, Italy | 2000 | Vision-based intelligent vehicles: State of the art and perspectives | Tech. Overview | 216 |
| Davison<br>Imperial College, London<br>Univ. Oxford<br>Imagineer Systems Ltd.<br>Joint Japanese-French Robotics Laboratory (JRL) | 2007 | MonoSLAM: Real-time single camera SLAM | Detailed Tech. Overview / Reasoning for CS | 847 |
| Sun,<br>Ford<br>Dept. Comp. Sci – Univ. Nevada | 2006 | On-Road Vehicle Detection: A Review | Detailed Tech. Overview | 433 |
| Enzweiler, M<br>Environment Perception Department, Assistance Systems and Chassis, Daimler<br>Univ. Heidelberg,<br>Univ. Amsterdam | 2009 | Monocular pedestrian detection: Survey and experiments | Tech. Overview, specifically covers CS requirements / techniques to recognize pedestrians | 358 |
| Raphael, E.<br>GM,<br>Mobileye Inc. | 2011 | Development of a Camera-Based Forward Collision Alert System | Tech. Overview | 6 |

| Organization | Year | Title | Reason | Citations |
|---|---|---|---|---|
| (SAE) | | | | |
| Dagan, E.<br>MobilEye Vision Tech.<br>Hebrew Univ. | 2004 | Forward collision warning with a single camera | Tech. Overview | 43 |
| LeBlanc, D.J.<br>BMW<br>Univ. Michigan, | 1996 | CAPC: A road-departure prevention system | CS for Lane Departure | 62 |
| Hartmann<br>Univ. Ulm<br>Daimler | 2014 | Towards autonomous self-assessment of digital maps | Independent automaker CS Research | 0 |
| Enzweiler, M.<br>Environment Perception Group, Daimler | 2012 | Efficient stixel-based object recognition | Independent automaker CS Research | 9 |
| Ruta, A<br>Mitsubishi Electric Research Laboratories | 2009 | In-vehicle camera traffic sign detection and recognition | Tech. Overview | 14 |

VRS Table of Influential Publications

Radar systems are becoming ubiquitous on the vehicles of today. The following publications describe the merit for the radar system forward collision avoidance capability to be used in hybrid vehicles (Beg, C.) as well as overviews of the technology (Turner, Kissinger). The Kissinger text was found to be available complimentary of charge online from the publisher.

Table 35: VRS Table of Influential Publications

| Organization | Year | Title | Reason | Citations |
|---|---|---|---|---|
| Beg., C.<br>University of Waterloo, Waterloo, ON, Canada | 2012 | A cost-effective radar system for automotive powertrain control applications | Explores Specific Tech. Application for Hybrid Electric Vehicles, | 1 |

| | | | | |
|---|---|---|---|---|
| | | | Provides Tech. Overview | |
| Turner, J.D.<br><br>Transport Research Laboratory, UK<br><br>Oxford Brookes University, UK | 2000 | Sensors for automotive telematics | Tech. Overview | 20 |
| Kissinger, Dietmar | 2012 | Textbook:<br><br>Millimeter-Wave Receiver Concepts for 77 GHz Automotive Radar in Silicon-Germanium Technology, Chapter 2.4: Automotive Radar | Tech. Overview | N/A |

## APPENDIX C: SIMULATION TOOL NOTES

This appendix briefly covers the research tools mentioned within this thesis. Please refer to the following lists for some short context, and links to find more information if desired.

Traffic Simulation Tools

**AIMSUN:** “Advanced Interactive Microscopic Simulator for Urban and non-urban Networks”. AIMSUN is a licensed transportation modelling software program developed by Transport Simulation Services Inc. AIMSUN is capable of simulating small-scale (microscopic) and large-scale (mesoscopic) traffic on realistic roadway geometries.
[https://www.aimsun.com/wp/?page_id=21]

**CORSIM:** “CORridor SIMulation”. CORSIM is a microscopic traffic simulator developed by the University of Florida. The simulation tool consists of two separate traffic models. One traffic model is used for urban, and one for freeway simulations.
[http://mctrans.ce.ufl.edu/featured/tsis/version5/corsim.htm]

**DIVERT: “**Development of Inter-VEhicular Reliable Telematics”. DIVERT is a microscopic traffic simulator developed my Professor Luis Damas of the University of Porto. Originally built as a stand-alone traffic simulator, new revisions of this tool have added the capability of being combined with a network simulator to model V2X communication.
[http://www.dcc.fc.up.pt/~rjf/vns/]

**DRACULA:** “Dynamic Route Assignment Combining User Learning and microsimulAtion". DRACULA is a microscopic traffic simulator developed by the Institute of Transportation Studies, University of Leeds. DRACULA models traffic flow by means of two modules, one simulating the traffic, and the other simulating the visualization of the traffic movement. [http://www.its.leeds.ac.uk/software/dracula/]

**ITS MODELER:** “Intelligent Transport Systems Modeler”. ITS Modeler is a microscopic traffic model developed at the Netherlands Organization for Applied Scientific Research for the purpose of simulating the impact of V2I communication. [https://www.utwente.nl/ctw/aida/research/publications/TRAIL2008-Mahmod.pdf]

**MITSIM:** “MIcroscopic Traffic SIMulator”. MITSIM is a microscopic traffic simulator capable of studying lane control signals, ramp metering, incident detection, and advanced traffic management systems. MITSIM is an open-source simulation tool chiefly developed by the Massachusetts Institute of Technology. [https://its.mit.edu/software]

**PARAMICS:** “PARAllel MICroscopic Simulation”. PARAMICS is a microscopic transportation modelling tool originally developed by the UK Department of Transportation, and is now available as a licensed tool by the company Quadstone Paramics. [http://www.paramics-online.com/]

**SUMO:** "Simulation of Urban MObility". SUMO is an open source tool developed by the Institute of Transportation Research at the German Aerospace Centre. SUMO is capable of simulating realistic traffic on a realistic street map. [http://sumo.dlr.de/wiki/Main_Page]

**TRANSIMS:** “TRansportation ANalysis SIMulation System”. TRANSIMS was developed by the Federal Highway Administration of the United States Department of Transportation provide a tool for travel forecasts for transportation planning and determining emissions impacts. [https://www.fhwa.dot.gov/planning/tmip/resources/transims/]

**VISSIM:** "Verkehr In Stadten SIMulationsmodell" ("Traffic in cities - simulation model" in German). VISSIM is a licensed microsimulation software package which includes a model from traffic forecasting and analysis and a model for traffic signal optimization and associated traffic impact. [http://www.vissim.com/]

Network Simulation Tools

**GloMoSim:** "Global Mobile information system Simulator". GloMoSim is a software package developed by the University of California, Los Angeles which simulates wired and wireless communication systems. [http://www.scalable-networks.com/pdf/glomosim.pdf]

**JiST/SWANS:** "Java in Simulation Time / Scalable Wireless Ad hoc Network Simulator". JiST/SWANS, developed by the School of Electrical and Computer Engineering at Cornell University, is a combination of a time-discrete event simulator (JiST) and a wireless network simulator (SWANS). [http://jist.ece.cornell.edu/]

**NS-2:** "Network Simulator – 2". NS-2 is an open-source event-discrete network simulator originally developed by the Lawrence Berkeley National Laboratory to simulate network communications. [http://www.isi.edu/nsnam/ns/]

**NS-3:** "Network Simulator – 3". NS-3 is the most recent version of NS-2, and is still an open-source time-discrete network simulator which has been updated to reflect modern network communications. [https://www.nsnam.org/]

**OMNET++:** "Objective Modular NEtwork Testbed in C++" OMNET++ is an open-source, event-discrete network simulation framework and library. [https://omnetpp.org/]

**OPNET:** “OPtimized Network Engineering Tools”. OPNET is a licensed tool to be used for network modeling and simulation. [http://www.riverbed.com/products/steelcentral/opnet.html?redirect=opnet]

7.2.3: Integrated Traffic-Network Simulation Tools:

**VEINS:** “Vehicles In Network Simulation”. VEINS is an open source framework which couples the open-source traffic simulator, SUMO, with the open-source network simulator, OMNET++. The result of VEINS, is that the resulting wireless communications established in the network simulator will impact the travel behavior of vehicles in the traffic simulator. [http://veins.car2x.org/]

**VSIMRTI:** “V2X SIMulation RunTime Infrastructure”. VSIMRTI is a licensed product which combines ope-source and licensed traffic and network models to evaluate the impacts of V2X communications. [https://www.dcaiti.tu-berlin.de/research/simulation/]

Emissions/Dispersion Simulation Tools

**ARTEMIS/HBEFA:** “Assessment and Reliability of Transport Emission Models and Inventory Systems / Handbook Emission Factors for Road Transport”. ARTEMIS/HBEFA refers to the use of the HBEFA emissions inventory, which provides a source of emissions factors (in terms of grams of pollutant per unit distance) as was applied in the ARTEMIS project, which extended the emissions inventory to reflect more accurate factors of vehicle driving cycles. [http://www.ncbi.nlm.nih.gov/pubmed/15504494 / http://www.hbefa.net/e/index.html]

**CAR:** "Calculation of Air pollution from Road traffic" CAR is a dispersion model developed for determining air quality at the street-level. The results of the CAR model have been validated with real-world results. [https://www.researchgate.net/publication/222789808_CAR_International_A_simple_model_to_determine_city_street_air_quality]

**CAR-FMI:** "Contaminants in the Air from a Road – Finnish Meteorological Institute". CAR-FMI is a dispersion model which can calculate the dispersion of criteria pollutants from input information such as: emissions factors, hourly averages of traffic volumes, local meteorology, and source locations. [http://en.ilmatieteenlaitos.fi/open-road-line-source-model]

**CARMEN:** (Acronym unknown) CARMEN is a dispersion model which takes meteorological data, street geometry, and background atmospheric concentrations and outputs an hourly result of pollutant distribution. [https://www.utwente.nl/ctw/aida/research/publications/TRAIL2008-Mahmod.pdf]

**CMEM:** "Comprehensive Modal Emission Model". CMEM, originally developed in partnership between the United States Environmental Protection Agency and the National Cooperative Highway Research Program (NCHRP), is a microscopic emissions modeler suitable for microscopic traffic models. [http://www.cert.ucr.edu/cmem/]

**COPERT4:** "COmputer Programme for calculating Emissions from Road Traffic - 4". COPERT4, originally developed to satisfy the needs of the European Topic Center on Air and Climate Change, is a simulation program designed to calculate vehicular roadway emissions. [http://emisia.com/products/copert-4]

**EMIT:** "EMIssions from Traffic". EMIT is a microscopic emissions models which can be used with the data from a microscopic traffic model, and as a result, has been used in evaluating the environmental impact of intelligent transportation systems. [https://dspace.mit.edu/bitstream/handle/1721.1/1675/A_Statistical_Model_of_Vehicle_.pdf]

**IVE:** "International Vehicle Emissions". The IVE model is designed to estimate vehicular emissions, and help develop effective traffic control strategies and their effect on vehicular emissions. [http://www.issrc.org/ive/]

**MOBILE6:** "Mobile Source Emissions Factor". MOBLE is an open-source model, developed by the United States Environmental Protection Agency, which uses emissions factors to predict the criteria emissions of assorted light and heavy duty vehicles. It is important to note that MOBLE has been replaced by the tool MOVES. [http://www3.epa.gov/otaq/mobile.htm]

**MODEM:** "MODel of vehicle EMission". MODEM is an emissions model which operates based on the premise that the rate of vehicular emissions is how determined primarily by engine power, vehicle speed, and acceleration. [http://virtual.vtt.fi/virtual/proj6/master/rep121.pdf]

**MOVES:** "MOtor Vehicle Emission Simulator". MOVES is an open-sourced software program, originally developed by the United States Environmental Protection Agency, to measure on-road and off-road vehicular/equipment emissions at the national, county, and project level. [http://www3.epa.gov/otaq/models/moves/]

**PHEM:** "Passenger car and Heavy duty Emission Model". PHEM is an emissions model originally developed as a part of the ARTEMIS research project previously mentioned in this section. The PHEM model works by taking inputs such as driving behavior and road characteristics and calculates the resulting vehicular emissions.

[http://www3.epa.gov/ttnchie1/conference/ei18/session6/andre.pdf]

**ROADWAY:** "Roadway Construction Emissions Model". The ROADWAY model is a tool consisting of multiple Microsoft Excel spreadsheets which can help the user estimate off-road vehicle emissions based on previously defined emissions factors.

[http://www.airquality.org/ceqa/]

**UROPOL:** "Urban ROad POLlution". UROPOL is an emissions dispersion model which tracks the movement of localized pollutant concentrations based on local meteorology and topology.

[http://ntl.bts.gov/lib/jpodocs/repts_te/6563.pdf]

**VERSIT+:** "VERkeers SITuatie Model". VERIST+ is a model that has evolved from a theoretical approach and has been validated through empirical testing. VERSIT+ simulates vehicular emissions using speed-time profiles of a large sample size to accurately simulate diverse vehicular fleets. [https://www.tno.nl/media/2451/lowres_tno_versit.pdf]