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Improving Traffic Efficiency and Safety via Vehicular Communications

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Improving Traffic Efficiency and Safety via Vehicular Communications

A dissertation submitted in partial satisfaction

of the requirements for the degree

Doctor of Philosophy in Computer Science

by

Reuben Vincent Rabsatt

2018

ABSTRACT OF THE DISSERTATION

Improving Traffic Efficiency and Safety via Vehicular Communications

by

Reuben Vincent Rabsatt

Doctor of Philosophy in Computer Science

University of California, Los Angeles, 2018

Professor Mario Gerla, Chair

Vehicles are an integral part of modern life. People depend on vehicles for transportation between work, home, and entertainment. As populations have grown and lower production costs have made vehicle ownership more accessible to more people, the number of vehicles on the road has skyrocketed. The potential for a collision with other drivers increases as more vehicles are added to the roadways. These additional vehicles also create congestion, consuming drivers' valuable time, and contributing to traffic delays.

Huge advances have been made in technology since the introduction of the first vehicle at the turn of the 20th century. Modern vehicles are equipped with sensors, navigation systems, and communication devices that enable data collection and information sharing like never before. This technology can be leveraged to improve traffic efficiency and safety.

The first contribution of this dissertation is the introduction of a framework that uses historical and real-time traffic data to access the risk levels of various routes to provide drivers with the ability to consider their safety when making travel plans.

The second contribution is a protocol that relies on cooperation between vehicles through wireless communication to improve the overall traffic state of all vehicles along a roadway.

The third contribution is a scheme that reduces the load placed on cellular infrastructure that provides vehicles access to Internet content.

The results in this work further the movement of vehicular technology-based solutions, creating safer and more efficient driving experiences.

The dissertation of Reuben Vincent Rabsatt is approved.

Henry J. Burton

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Glenn D. Reinman

Mario Gerla, Committee Chair

University of California, Los Angeles

2018

To my wife, my parents, and my daughter . . .

for your unwavering support

and encouragement

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R. Vince Rabsatt and Mario Gerla, "Multi-lane cooperative shock wave mitigation," 2017 16th Annual Mediterranean Ad Hoc Networking Workshop (Med-Hoc-Net)

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Ishihara, Susumu, R. Vince Rabsatt, and Mario Gerla. "Improving reliability of platooning control messages using radio and visible light hybrid communication." Vehicular Networking Conference (VNC), 2015 IEEE

Ciarán Mc Goldrick, R. Vince Rabsatt, Mario Gerla "Purposing AAL to an Aging Population: AAW (Walking), AAD (Driving) and the IoV (Internet of Vehicles)" IEEE GC 2015 Workshop on Internet of Things for Ambient Assisted Living (IoTAAL)

Susumu Ishihara, R. Vince Rabsatt, Mario Gerla "Secure Autonomous Platooning with Hybrid Vehicular Communication" HotMobile 2015, Santa Fe, New Mexico, February 2015

Lu, You, Mario Gerla, Tuan Le, R. Vince Rabsatt, and Haik Kalantarian. "Community aware content retrieval in disruption-tolerant networks." Med-Hoc-Net 2014, Piran, Slovenia, June 2014

Tuan Le, R. Vince Rabsatt, Mario Gerla"Cognitive Routing with the ETX Metric" Med-Hoc-Net 2014, Piran, Slovenia, June 2014

CHAPTER 1

Introduction

Vehicles play an instrumental part in our daily lives, and have transformed the way we live. Vehicles are used to transport goods as well as people across short and long distances for various purposes. Over the years, the number of vehicles around the world has steadily increased. This trend is especially true in the United States. Figure 1.1 shows the rise in the number of registered vehicles in the US over the past fifty years [Bur16]. Currently, there are over 260 million vehicles registered in the US. The high prevalence of vehicle ownership leads to a high traffic demand along roadways, which in turn leads to several transportation challenges, including high traffic congestion, long commutes, and increased risk of accidents.

Traffic congestion has been a major issue for a number of years, particularly in large cities. This issue contributes to high economic cost with respect to the amount of time people waste commuting, the extra fuel that is expended, and bodily injury and property damage due to collisions. Traffic congestion also generates a large amount of air pollution[WQI09].

Traditionally, the solution to traffic congestion has been to expand the road network to meet the increased traffic demand. However, this solution is becoming unfeasible due to the extraordinary cost of expanding transit infrastructure, and the fact that areas with high population density tend to be clustered around these high-congestion roadways, adding to the complexity of planning and building additional capacity [AS94a]. Unfortunately, the current road infrastructure is not being used to its full potential. In uncoordinated vehicular traffic, a significant amount of road capacity is not used efficiently. Vehicles tend to travel in free flow mode only in low densities and when interactions between vehicles are rare [Ker09].

Another consequence of an increased number of vehicles and high traffic demand is the increased likelihood of vehicular collisions and fatalities [MW10]. Traffic accidents are among
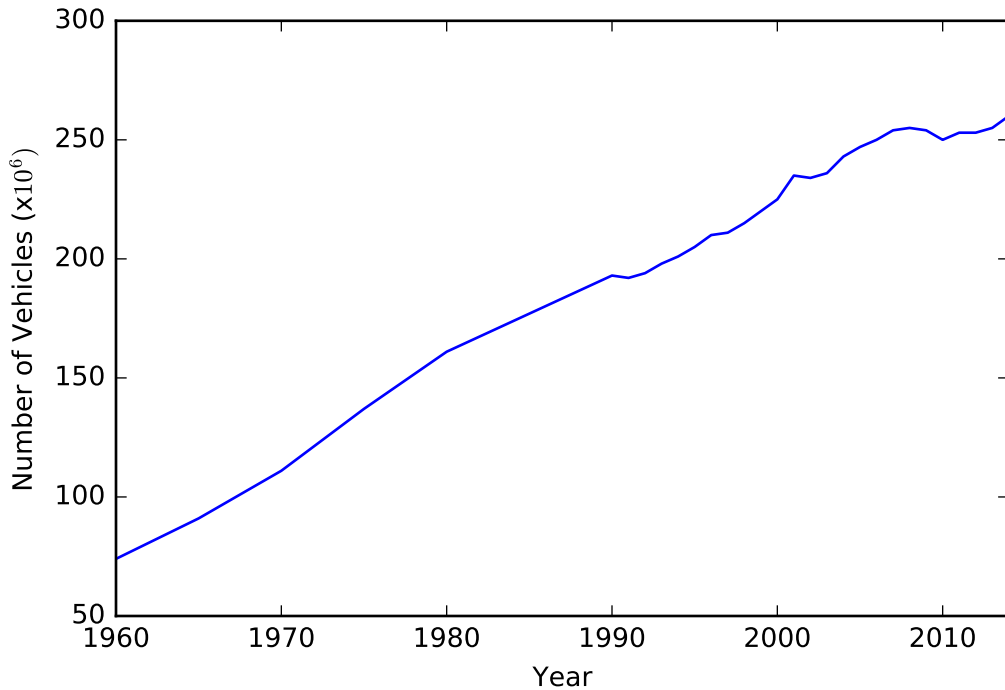
Figure 1.1: Number of registered cars per year in the US

the most critical issues that affect the current transportation system. According to the National Highway Traffic Safety Administration (NHTSA), there were 32,999 fatalities, 3.9 million injuries, and 24 million vehicles damaged in 2010 alone[BMZ15]. In addition to injuries and fatalities, these accidents can damage city infrastructure, create additional traffic congestion, and can lead to litigation, fines or other penalties. While individual accidents are caused by a variety of factors such as unexpected driver behavior, mechanical failures, and distractions on the road [HR95, SNG01, OBS91], the overall rate of traffic accidents is often a function of more predictable parameters such as time of day, weather, and traffic dynamics.

The increasing prevalence of technology has revolutionized travel by providing drivers with a wealth of information about road conditions and traffic state using various sensors embedded in roadways, data from mobile phones carried by drivers, and cars themselves. This has lead to to the realization of Intelligent Transportation Systems (ITS), in which vehicles are equipped with computing power and storage capacity to facilitate vehicular ap-

plications that overcome traffic challenges, such as safety and traffic efficiency. Vehicular communication opens the door for vehicles to form Vehicular Ad Hoc Network (VANET)s, and share the information that they gather, as well as receive beneficial information from other vehicles or infrastructure. While a dedicated communication infrastructure was envisioned for vehicular communication, it is likely that the existing cellular infrastructure will have to be utilized in the interim. However, there is currently a high demand placed on cellular resources by existing applications, therefore vehicles will require an efficient way to use these resources.

In this work we investigate various promising protocols that improve traffic efficiency and safety, as well as the underlining communication technology to support these protocols.

1.1 Contributions

In this work, we develop a framework that provides users with a classification of the risk associated with various travel route options. We also address a traffic phenomenon that contributes to traffic congestion and reduces traffic efficiency. Additionally, we address some of the communication challenges required for vehicles to collect and exchange data.

This work makes the following contributions:

- Develop a framework that has the capability to extend the functionality of current navigation systems, and provide a safety metric to to be included in the route selection process.

- Develop a protocol that enables vehicles to share traffic state information to redistribute traffic and mitigate traffic congestion.

- Propose a heterogeneous network that offloads traffic from a centralized cellular network, and redistributes content locally via Inter-vehicular Communication (IVC)

All of these protocols are essential to ITS, and contribute to the benefits of leveraging technology within its transportation components.

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1.2 Roadmap of the Dissertation

The rest of the dissertation is organized as follows: Chapter 2 presents the background work on technology and applications that enable safe and efficient driving, as well as communication challenges faced. In addition, it reviews previous works related to traffic models, vehicular ad hoc networks, and applications. Chapter 3 presents a framework that assesses the risk of accidents along potential travel routes, and provides risk classifications for travel routes. Chapter 4 describes an application to enable efficient driving along a highway that uniformly distributes traffic across multiple lanes. Chapter 5 presents the utilization of heterogeneous communication technologies to support vehicular applications. Finally, we conclude our work and summarize the work presented in this dissertation in Chapter 6.

CHAPTER 2

Background and Related Work

The focus of this dissertation is to leverage ITS technology to improve traffic efficiency and safety, while also providing an efficient scheme to utilize heterogeneous communication networks. To facilitate the discussion of the topics presented in this dissertation, Section 2.1 presents background materials on addressing traffic safety via ITS. Section 2.2 discusses prior work related to traffic efficiency applications. Finally, related work on heterogeneous communication networks are presented in Section 2.3.

2.1 Safe Driving

Traffic safety is a topic of the utmost importance because it has the potential to impact lives. There are three major factors that contribute to the causes of accidents on roadways: environment, vehicles and drivers, and traffic conditions [OOR05]. Traffic conditions are typically impacted by accidents regardless of the factors that caused it.

Many efforts have been made to improve traffic safety. In recent years, various techniques have been proposed to improve the performance of vehicle navigation using traffic and accident information. These works employ vehicular ad-hoc networks to exchange information between cars, or rely on a widely deployed infrastructure such as a cellular networks to exchange traffic and safety information. In [Kan07], Kanoh et al. propose a genetic algorithm for routing vehicles through diverse, dynamic traffic conditions. Results show superior performance compared to the more primitive routing methods found in GPS devices. In [YIK04], Yamashita et al. propose a vehicle routing system with a centralized server aggregating traffic data from individual nodes. Simulations demonstrated improved travel times

as the number of vehicles reporting data increased, though neither work considered safety issues in routing.

In [KLW05], Kim et al. explore topics such as optimal departure times, and optimal routing policies under time-varying traffic flows using Markov-based decision processes. The algorithm is evaluated on an urban road network in Southeast Michigan. Another approach by Golding et al. [Gol99] describes a centralized network, rather than distributed system, in which a database aggregates information from individual cars using a cellular network. The centralized database service uses data from individual vehicles to model traffic and travel time. In [FGG04], Fleischmann et al. propose an advanced navigation system which takes into consideration the non-linearity of travel times across streets. A similar approach is described by Ichoua et al. in [IGP03], in which a dynamic speed model is shown to have superior performance. However, none of teh models described above consider safety issues in routing.

Several recent works also address safety issues in vehicular navigation systems, by exchanging relevant information between cars using vehicular ad-hoc networks. Waze [Mob12] is a recent mobile application that functions as a navigation system and alerts drivers to hazards along their path of travel. In [CC05], Chen et al. explore the application of active safety technologies to lower the risk of accidents, using ad-hoc peer to peer networking on vehicles. These features include obstacle warnings, lane change assistance, and adaptive cruise control. A similar work by Biswas et al. [BTD06] proposes collision avoidance technologies using short range radio technologies. In [Sch96], Shreder et al. propose a safety system integrated into a vehicle which includes a suite of safety technologies that use data from on-board inertial sensors to determine unstable vehicle conditions such as skidding or sliding. Another safety-aware routing approach is described in [MRA13], in which the authors present a real-world experiment of an accident-warning system for highway scenarios based on a multihop broadcast algorithm. The authors' results demonstrate that reports of traffic accidents can significantly improve road conditions.

In [SA15], Shi et al. used Random Forest and Bayesian classifiers to identify traffic operation and safety based on various risks. The authors validated their results using a

dataset based on expressways in central Florida. In [XLW13], Xu et al. analyze one particular freeway in northern California and develop a crash risk index based on traffic flow using logistic regression analysis. In [XTW13], Xu et al. model crash severity utilizing real-time traffic data collected with loop detectors in freeways. Among other interesting conclusions, the authors discovered that large differences in speed between adjacent lanes significantly increased risk of accidents.

Lastly, various works [QE14, ECT15, Ali16] describe specific navigation and routing strategies designed specifically for environmental applications. These works generally aim to minimize travel time, optimize fuel economy, or reduce emissions. However, none of these works consider statistical measures of road safety while making decisions related to routing and navigation; addressing this limitation is the primary focus of our work.

2.2   Improving Traffic Efficiency

The increasing number of vehicles on roadways leads to high traffic congestion when the infrastructure cannot fully support the high traffic demands. Traditionally, the method to addresses this issue was to build new roads or expand existing ones. However, this solution is very costly, and currently many metropolitan areas are heavily occupied by transportation infrastructure. High traffic demands lead to traffic inefficiencies.

Improving traffic efficiency has also been an area of interest in research. Intelligent Transportation Systems (ITS), which rely on wireless communication technologies, have been shown to provide traffic benefits. Wireless communication in ITS exist between vehicles, Vehicle to Vehicle (V2V), and from Vehicle to Infrastructure (V2I), enabling the exchange of relevant traffic information [GDD04, PDE09].

In [PKP08], a highway system that relies on Variable Speed Limits (VSL) is proposed. The focus of the paper was to address safety; however, the authors found that placing VSLs along a highway increases the point at which the critical density is reached, enabling higher flows of vehicles. In [VSM02], the authors demonstrate how communication between vehicles enables vehicles to travel with shorter headways, resulting in an increased road capacity.

Managing lane maneuvers in traffic is of interest in our work towards improving traffic efficiency. Wolterink et. al [WHK10] proposed a concept that relies on roadside units (RSU) and vehicle communication to predict vehicles' positions in advance of an on-ramp and relies on RSU to facilitate merging gaps for on-ramp traffic. In [BKS14], the authors propose a traffic model that provides lane fairness through communication in a situation where two lanes merge into one. Vehicles coordinate their actions based on a first-come, first-served basis, allowing vehicles to merge fairly.

Lane changing is considered one of the riskiest maneuvers that drivers perform in a highway system. Jula [JKI00] analyzed collision avoidance for lane changing and merging, which found that a minimum longitudinal spacing should initially exist between vehicles to avoid collisions. In [NZD16] the authors propose a framework for decentralized cooperative lane changing for autonomous vehicles equipped with V2V technology. One of the core models of the framework is the decision module, which determines whether a vehicle should change lanes or remain in the current lane. The decision model is based on the state predictions of surrounding vehicles. In this paper we make a further step to improve traffic efficiency by considering shock wave information in the lane changing decision process.

2.3   Heterogeneous Communication Networks

There are many communication technologies that have been introduced to connect vehicles, such as cellular telecommunication (Long Term Evolution (LTE)), Dedicated Short Range Communication (DSRC), Visible Light Communication (VLC). Each technology performs best in particular situations. Cellular networks are pervasive and are great for pushing and pulling information to or from the cloud, respectively; however, the latency incurred by cellular networks make them a poor candidate for time sensitive applications such as platooning [DBG10]. Cellular networks are widely deployed, and provide vehicles the ability to retrieve data from backend servers, or exchange non-time sensitive information with other vehicles. Short-range wireless communication geared more towards safety applications because it enables distribution of information in a local vicinity in a relatively short time

period. Standardization efforts have taken place with IEEE to define the PHY and MAC protocols for short-range communication in vehicular networks. The standards that have been defined are a variant of 802.11 that is found in WiFi and is referred to as 802.11p. 802.11p utilizes CSMA/CA in the MAC layer, so a saturated wireless channel can lead to long message delays or complete losses of data [JD08]. VLC, on the other hand, is an inexpensive technology that requires line of sight to operate, but is robust to interference from transmissions that are not in its direct line of sight.

In recent years, there has been a tremendous increase in the demand placed on cellular networks due to the widespread surge in mobile devices. A high demand on cellular resources, at the Radio Access Network (RAN) and the core network, results in increased delay and poor QoS for mobile users. The efficiency of wireless links are reaching fundamental limits. Adding additional base stations in already dense deployments is unfeasible[DMW11]. If cellular resources are to be utilized by vehicles, efficient usage schemes need to exist that minimize the load.

Several schemes have been proposed to offload cellular networks in vehicular environments where vehicles are equipped with cellular and DSRC interfaces. Nandan et al. [NDP05] proposed using the BitTorrent concept in VANETs to enable cooperative downloading among vehicles. This scheme describes proximity-based piece selection strategies for obtaining data chunks from peers; however, vehicles do not consider a selection strategy for chunks requested from the backend server by neighboring peers.

Ota et al. [AK06] introduced a max-throughput and min-delay cooperative downloading (MMCD) algorithm, which prioritizes a vehicle's data request by a delivery deadline to minimize the average delay of user requests while maximizing the amount of packets downloaded from a RSU. A major drawback of MMCD is the reliance on RSU to download content. RSUs have a very sparse deployment, which limits the effectiveness of the algorithm.

Vehicles in a VANET tend to generate a wealth of periodic data, or Floating Car Data (FCD), that provides insight about the overall traffic conditions. This data can be utilized locally or propagated to a back-end server for further processing. Various studies consider

the formation of clusters to aggregate this data [HSH17], and the selection of the best vehicle to forward the aggregated data to an LTE base station (eNodeB) [TSB16].

Traffic on the downlink of an eNodeB can be considerable as well, especially when vehicles are downloading similar content related to their trip. Malandrino et. al. [MCC12] proposed a prediction scheme for RSUs to prefetch content for vehicles on the move. The scheme places a high reliability on the RSU to determine a vehicle's route in the future and have the data available for a vehicle at contact time. Shen et. al [SCY14] also address the challenge of data dissemination in a VANET by finding the optimal schedule of slots for data transmission.

In [HSH17], the authors introduce the concept of vehicular micro clouds, which are clusters of vehicles that function as virtual edge servers that aggregate data and transfer it to a backend. However, vehicle clusters are formed around an Access Point (AP) and data traffic is only considered on the uplink. In this work, we extend the Mobile Edge Computing (MEC) to the vehicles as well, forming clusters in a completely distributed manner and optimizing the data segment selection by vehicles in a cluster to efficiently download content.

In this dissertation, we propose a scheme to identify content to download in a distributed manner with minimal communication overhead.

CHAPTER 3

Framework for Safe Travel

A wide range of sensors are being deployed in cars and roadways. These sensors enable the collection of large amounts of information about vehicles dynamics at given locations and various times. When this data is coupled with incident data collected from police officers and highway patrol it provides a rich set of information. Analyzing this data provides insight into the relationships between vehicles' dynamics with respect to time and location and the effects on road safety.

SafeRoute is a framework for classifying potential risk associated with travel routes, based on historical traffic information. In particular, we analyze macroscopic vehicle traffic information collected from Caltrans Performance Measurement System (PeMS), with various machine learning algorithms. We identify the features within this data set that are maximally correlated with accident risk, and provide a model to incorporate route safety in the overall route selection process.

3.1   Introduction

Navigation systems typically suggest directions to drivers based on factors including weather conditions, traffic information, and road hazards. By considering these factors, the system can suggest a route in which travel time is minimized. While minimizing travel time is an important consideration for many commuters, these navigation systems fail to include any meaningful information about the relative safety of different routes. For example, some roads are significantly more accident prone than others and can easily be avoided. By taking alternative paths, individuals can reduce risk, often while adding only minimal time to their

commutes. In this chapter, we develop a model for road safety based on data from the PeMS database. Our model for road safety considers risk using historical accident data based on factors such as the time of day, day of week, average speed, flow, and other traffic features.

There are several factors that contribute to accidents along roadways such as, environment, vehicles and drivers, and traffic conditions [OOR05]. Whenever an accident occurs regardless of the contributing factor, the traffic conditions are directly impacted. This is typically reflected in a drop in the average speed or an increase in density at the accident point of vehicles.

In some cases, the fastest route may not be the safest. For example, a winding road could be particularly hazardous during snow. Moreover, driving on a particular road could be significantly more dangerous during the night when visibility is poor. While drivers may have a vague intuition of safety in different conditions, they lack the data to make consistently optimal choices. By coupling traffic data with accident data the risk associated with various routes at different times of day can be accessed and classified. *SafeRoute* provides a model that enables commuters to determine the additional time a commuter is willing to tolerate for a safer travel route.

3.1.1 Our Contributions

Our objective is to describe a framework for vehicle safety, which can be incorporated into vehicle navigation systems, that estimates the hazards of a particular route based on various factors such as the time of day, traffic conditions, and historical data of previous accidents on the roads comprising a particular route. We also aim to provide a model to prioritize safer routes given a measure of accepted tolerance for potentially adding additional travel time to a route.

3.1.2 Organization of this chapter

The material in this chapter is organized as follows. We describe the *SafeRoute* framework in Section 3.2 as well as the development of the risk model. Section 3.3 details the experiment
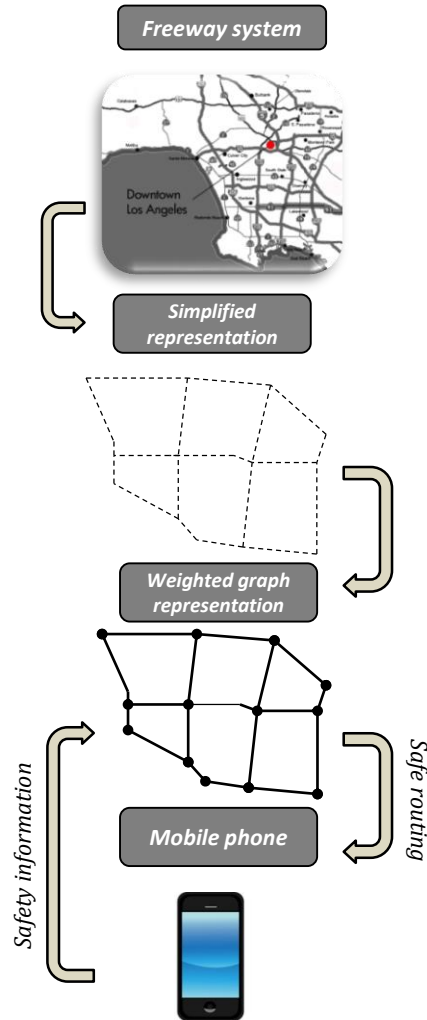
Figure 3.1: Overall System Architecture of SafeRoute

set up and evaluation of the framework. Finally, Section 3.4 concludes the chapter.

3.2 *SafeRoute:* Framework for Assessment of Road Safety

In this section we present *SafeRoute*, a framework to assess the risk of a route based on a set of variables. Figure 3.1 shows the outline of the proposed system. As this figure illustrates, the supported road system is modeled as a weighted graph. Using a model generated from historical and real-time data from the PeMS dataset, the weights are assigned based on the likelihood of a user being involved in an accident on that roadway given the

day and time of travel. This framework could be useful for a number of systems, such as a mobile application, which can provide turn-based navigation directions to users based on their personal requirements.

3.2.1 Risk Model Development

In this section, we describe some of the different parameters that affect traffic incident rates, based on our analysis of the PEMS dataset.

Mining the PEMS dataset provides valuable insight into the factors that are associated with a higher risk of accidents. Based on our analysis, some of the different parameters that affect the traffic incident rate are Day of the Week, Hour of the Day, and Road Choice.

When considering the median number of accidents per day on a subset of roads in the Los Angeles freeway system as a function of day of the week, we found that on some days the number of accidents are significantly higher, such as Wednesday as compared to others like Saturday or Sunday. However, modeling risk requires an understanding of the number of accidents per vehicle. There is less traffic on weekends because many individuals do not work on these days. Therefore, we normalized this data based on the amount of traffic on a particular day using data collected from the embedded sensors in the roadway as shown in Figure 3.2.

We analyzed the number of traffic accidents along the same subset of freeways as a function of the time of day, by hour. The statistics were not surprising; the results suggest a bimodal distribution with peaks at morning and evening rush hour times. However, three visible peaks appear, rather than two, when the number of traffic accidents per thousand vehicles as a function of time of day are taken into account, as shown in Figure 3.3.

In our work we studied three parallel freeways, I-10, SR-60, and I-210, with traffic flows in the east direction. As shown in Figure 3.4, there appears to be significant variation in risk between the three roads, with I-10 being almost twice as dangerous as SR-60, on average. However, simply taking the SR-60 in all scenarios would be a non-optimal solution as there are many other variables that affect safety; SR-60 may not be safer in all scenarios.

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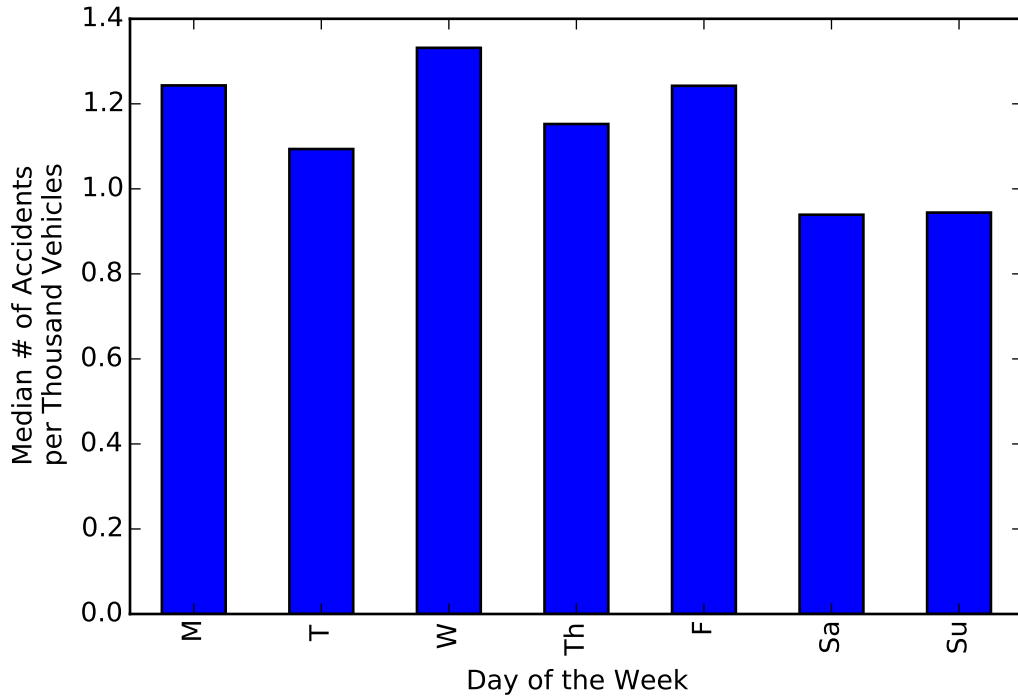
Figure 3.2: Number of accidents per thousand vehicles for each day of the week

We define the sensitivity (s) of the risk function to a variable r over domain x, S_{r_x}, as the average ratio of the three local maxima $(M_1,\ M_2,\ M_3)$ over the global minimum, m. More specifically, this is expressed in Equation 3.1 in which t represents the time of day.

$$S_{r_t} = \frac{M_1 + M_2 + M_3}{3 \cdot m} \tag{3.1}$$

This sensitivity score provides some insight about the relative significance of x when selecting an appropriate variable r during a route. For example, a road with a very low sensitivity score with respect to t (time) implies very little variation in risk throughout the day. Based on the data from Figure 3.4, the risk scores for I-10 E, I-210 E, and SR-60 E are 19.33, 20.25, and 15.4, respectively.
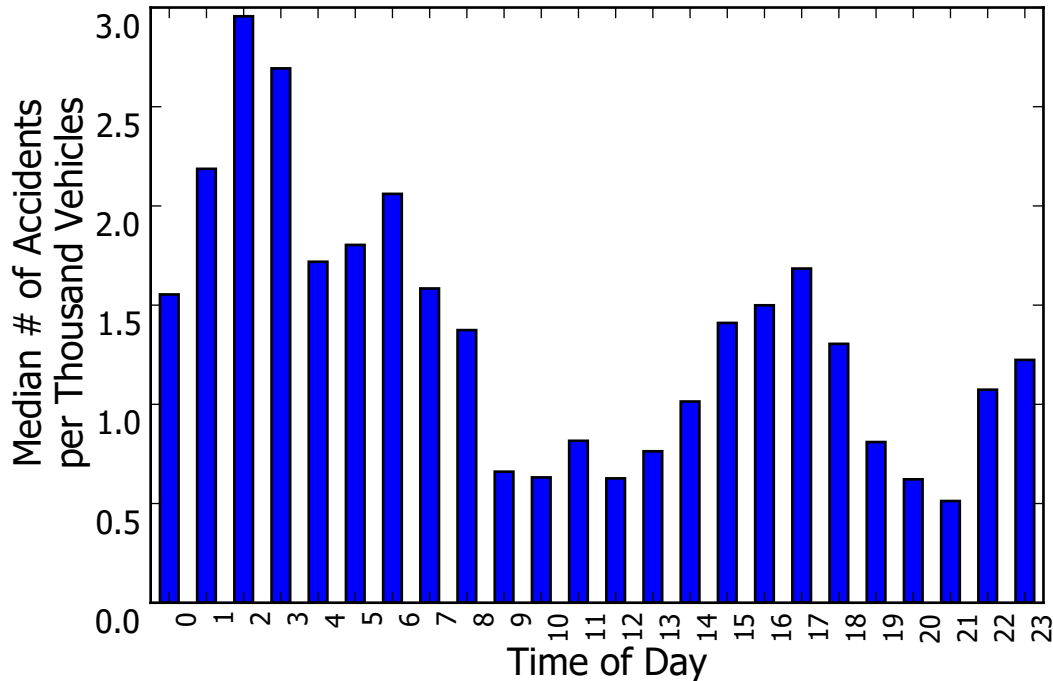
Figure 3.3: Number of accidents per thousand vehicles per hour

3.3 Evaluation

In this section, we evaluate the performance of the proposed risk model. We first describe the datasets used, followed by the metrics we used. Traffic data is paired with accident data obtained from California Highway Patrol (CHP). An accident that occurs on a highway is linked to the nearest downstream traffic sensor, relying on post-mile information of the accident and the traffic sensors. In our study we evaluate the effect of various traffic states over different time periods.

3.3.1 Dataset

Our experiments utilize a very large, near real-world dataset generated by the PeMS that captures near real-time and historical traffic data throughout the state of California. The highway attributes represented in the dataset are velocity, occupancy, and flow, measured every 30 seconds at thousands of sensors distributed across highways in the state. In our experiments, we narrowed our focus to a subset of highways in the county of Los Angeles.

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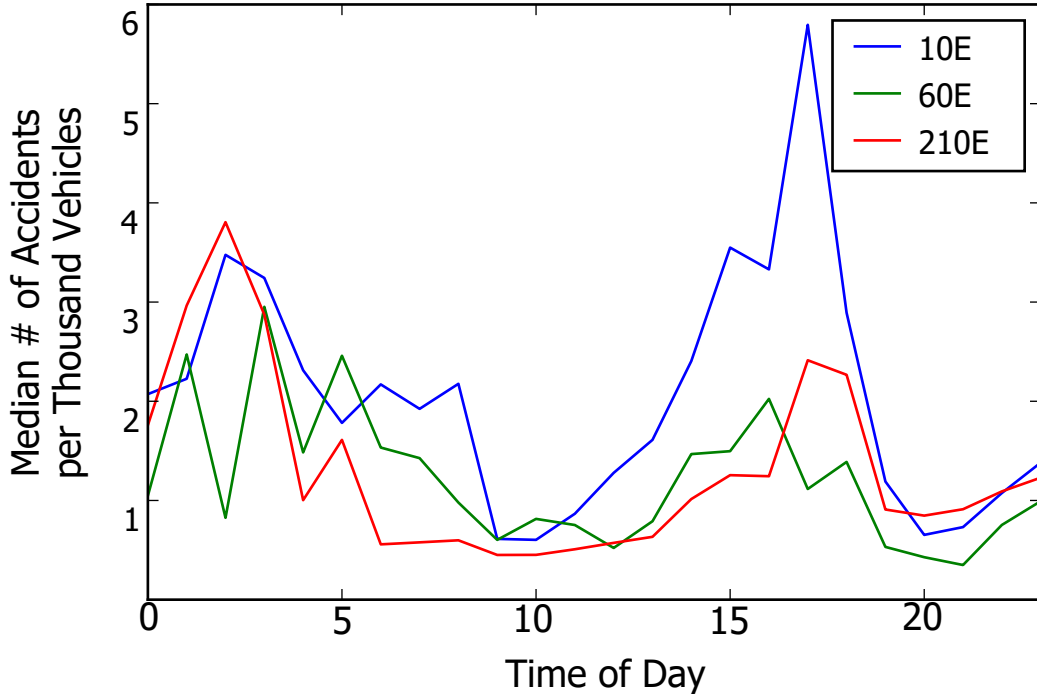
Figure 3.4: Number of accidents per thousand vehicles for each interstate as a function of time of day

Due to the limited deployment of sensors along highways we were unable to establish multiple routes between two locations. There for we selected a twenty mile stretch from three parallel highways I-10, I-210, and SR-60 in our region of interest, as shown in Figure 3.5.

We extracted accident information from traffic incident details collected by the California Highway Patrol (CHP), which is also managed by PeMS. The incident dataset contains a wide range of traffic incidents; traffic accidents are just a subset of the dataset. We considered data from January 1, 2015 to December 31, 2015. In this dataset, there are a total of 5,044 traffic incidents that are labeled accidents. For each traffic collision within our region of interest, we extract the timestamp and the exact location. Within a particular region, we aggregate the number of accidents that occurred during a time window. For our purposes, the length of the time window is set to one hour.
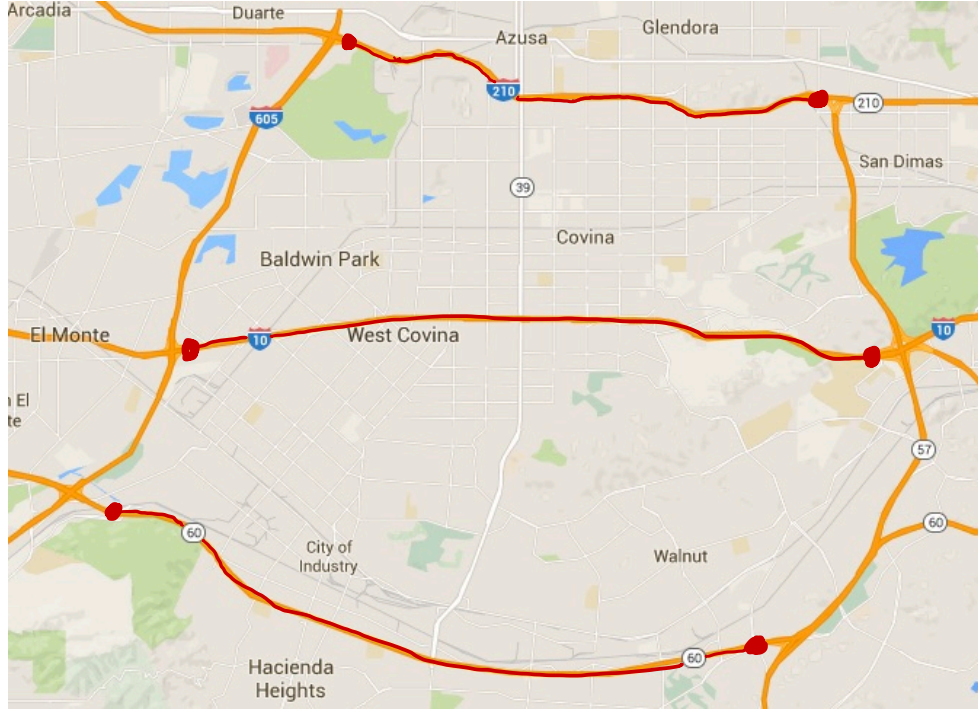
Figure 3.5: Set of highways in region of interest.

3.3.2 Results

In our experiments, we distinguish between two traffic states: minor and severe. A minor traffic state is defined as the case where historically, less than two accidents take place per thousand vehicles within a given hour. All scenarios in which two or more accidents occur per hour, when normalized to traffic flow, is considered a severe traffic state. This particular threshold was selected because it allowed a relatively even distribution of class labels to avoid biasing the classifier towards one particular category. The median number of accidents per thousand vehicles at all times, on all roads, was 1.11. However, the mean value was somewhat higher at 1.54. Two accidents per thousand vehicles was a level of risk that was almost double that of the average road. This value was approximately in the upper 25th percentile.

The maximum risk for a particular road at any hour was 12.72 accidents per thousand vehicles. On the other end of the spectrum, the safest road had 0.15 accidents per thousand vehicles. The 25th and 75th percentiles were 0.61 and 2.03, respectively.

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Table 3.1: Partial List of Selected Features

Rank	Feature Name	Merit
1	Hour	0.246
2	Occupancy	0.21
3	Speed	0.137
4	Flow	0.111
5	Freeway	0.04
6	Day of the Week	0
7	Direction	0

Using a feature subset selection algorithm we identify the set of relevant features that are maximally correlated with the accident risk, and ranked all the features used in our evaluation. These results are presented in Table 3.1, along with the average merit of each feature averaged across all ten cross-validation runs. While all features were used in the final classification model, the feature ranking process provided some qualitative insight about the most important factors in minimizing the risk of accidents.

The feature with the highest merit was the hour of day. Of course, it should be noted that this is a broad feature which encompasses other features such as occupancy, speed, and flow. Day of the week was not directly a strong predictor of accident risk, after normalizing for other factors such as traffic levels and speed. This conclusion was not surprising, give the relative uniformity of the data shown in Figure 3.2.

We performed our experiments using the Random Forest classifier, with a 10-fold cross validation scheme to avoid biasing the dataset. We present our classification results using standard measures of classification accuracy: precision, recall, and F-Measure. These measures are defined in terms of true-positive and false-positive rates in Equation 3.2.
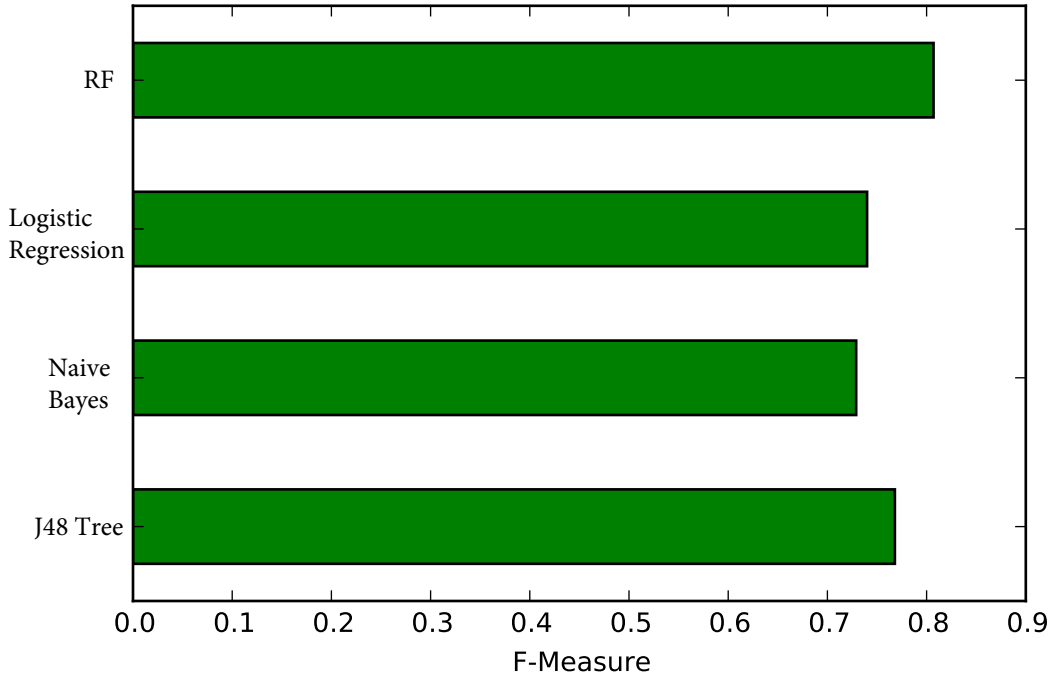
Figure 3.6: Measure of classification accuracy

$$Precision = \frac{t_p}{t_p + f_p}$$

$$Recall = \frac{t_p}{t_p + f_n} \tag{3.2}$$

$$F - Measure = 2 \cdot \frac{Precision \cdot Recall}{Precision + Recall}$$

The confusion matrix of our result is shown in Table 3.2. As shown in this table, precision and recall were approximately 80% using the Random Forest classifier. In Figure 3.6, the F-Measure is compared between Random Forest, J48 Decision Tree, Logistic Regression, and Naive Bayesian classifiers. Highest performance was attained using Random Forest, which uses a bagging technique in which instances are sampled with replacement to avoid biasing the dataset.

Table 3.2: Accident: Confusion Matrix (Random Forest)

	Predicted Class		
True Class	Severe	Minor	**Recall**
Severe	189	42	81.8%
Minor	47	184	79.7%
Precision	80.1%	81.4%	

3.3.3 Route Selection Model

The classification of routes can also be exploited to enable commuters to define the trade-off between travel time and safety in the route selection process. *SafeRoute* accomplishes this using a route selection model. For each route i, we define a risk level r_i and an estimated travel time t_i. We define a time tolerance factor λ, which is used to filter routes that meet our objective in which λ is the ratio of additional time a commuter is willing to accept for a safer route. The set of filtered routes are defined as follows:

$$S = \{j | t_j \leq (1 + \lambda) min(t_i)\} \tag{3.3}$$

The set S encompasses the routes with travel times that satisfy the the time tolerance factor condition. By selecting the route from S with the minimum risk the safest route can be selected:

$$r_s = \min_{i \in S} (r_i) \tag{3.4}$$

3.4 Conclusion

In this chapter, we presented a model based on the PeMS dataset, in which we are able to predict the risk of accidents with a classification F-Measure of 80% using features such as hour, occupancy, speed, flow, freeway, day of the week, and direction. We also qualitatively

described our findings, providing readers with some insight about how risk patterns vary throughout the day and week. For example, we showed that the variation in risk between different times of day is much more significant than the risk from one day of the week to the next. We also defined a route selection scheme that enables users to select the trade-off that is reasonable to accept for a safer route, which may add additional time to a drive.

CHAPTER 4

Improving Traffic Efficiency

In the near future all vehicles will be equipped with communication technology that will enable vehicles to share traffic information, which in turn will open the door for applications that improve traffic efficiency. Currently, drivers react to traffic disturbances when they are within line-of-sight of the disturbance, however when disturbance information is obtained in advance traffic can be redistributed to mitigate the impact of the traffic disturbance.

DRIVE-EX is an event-triggered communication protocol that utilizes wireless communication between vehicles to estimate traffic conditions downstream, and provides drivers with non-intuitive recommendations that will result in overall traffic improvements. In particular, the protocol redistributes vehicles longitudinally, with slow down recommendations, and laterally, with lane maneuver recommendations. We show through simulation that redistributing traffic in this manner improves the overall traffic flow with respect to average speed and average travel time.

4.0.1 Introduction

The past few decades have given rise to a continous increase in the number of vehicles on roadways. However, the existing traffic infrastructure is unable to support the increased volume of traffic efficiently in its current state. Expanding the current infrastructure with additional highways or extending current highways with additional lanes is very costly, and will not solve the problem of traffic congestion [AS94b].

In recent years Advanced Driver Assistance Systems (ADAS) have become a technology of interest due to their potential to mitigate some of the current traffic issues. ADAS technology

(a) No potential shock wave   (b) Potential shock wave
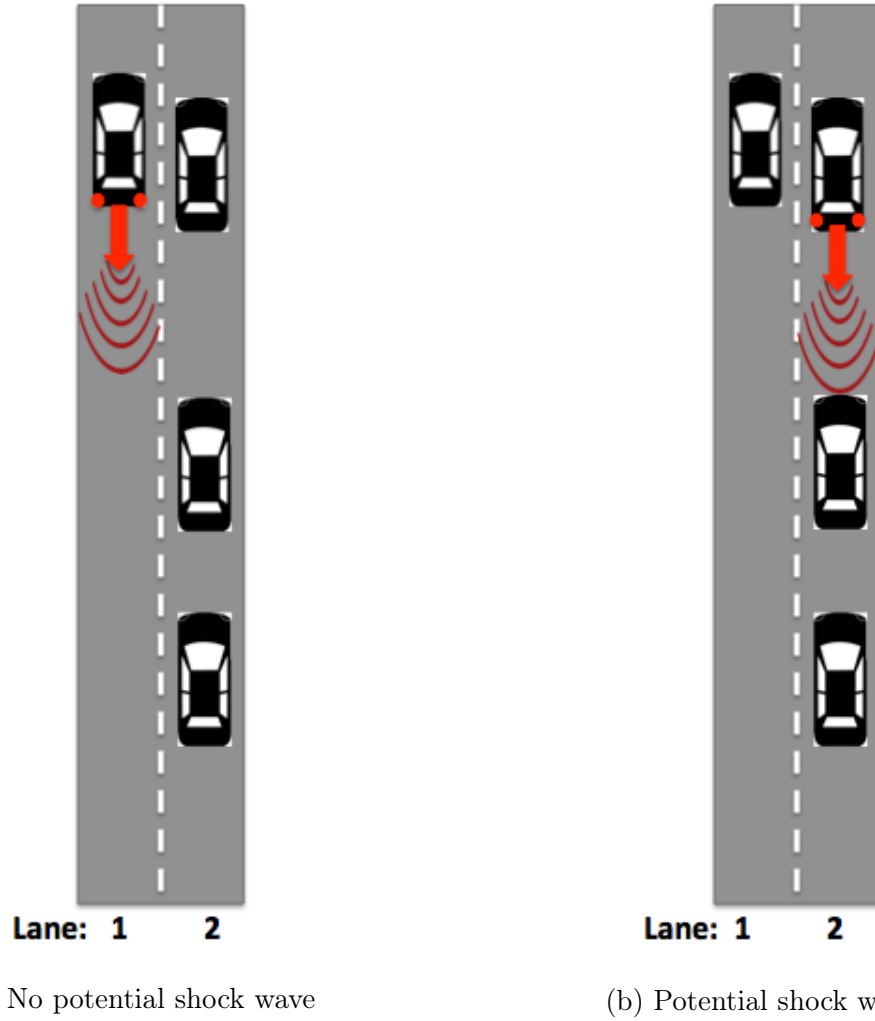
Figure 4.1: Traffic shock wave conditions

is currently used to prevent vehicles from drifting out of their lane and to avoid collisions, which increases a driver's safety and comfort. Adaptive Cruise Control (ACC) is an example of an Advanced Driver Assistance technology that has been introduced in top of the line vehicles. ACC controls the velocity of a vehicle to maintain a desired headway between a vehicle and its predecessor [VE03]. ACC is capable of reacting faster to a disturbance than a human driver, therefore ACC is capable of utilizing smaller time headways. However, ACC relies on radar to detect vehicles ahead. This limits the ability of ACC to line-of-sight, and fails to access the traffic state of adjacent lanes.

In a previous work a protocol, Density Redistribution through Intelligent Velocity Esti-

mation (DRIVE) [FFG14], in which vehicles are connected via VANETs and in the event of a slowdown, vehicles equipped with DRIVE broadcast slowdown information. Vehicles use the information received to learn about the state of traffic downstream. Communicating vehicles are able to use the Lighthill-Whitham-Richard model (LWR) [LW55a], [Ric56a], to estimate the density gradient between them, which is used to estimate the communicating vehicles' velocities and mitigate the occurrence of shock waves. It was shown that by providing vehicles with velocity recommendations, improvements can be made with respect to overall traffic flow and average travel times.

In traffic with small densities, vehicles can often travel at desired maximum speeds without being inhibited by other vehicles. However, in dense traffic situations, the actions of a single vehicle can affect other vehicles upstream, resulting in undesired shock waves, which can lead to congestion [Ker09]. In Figure 4.1a there is a single vehicle in Lane 1, so a temporary reduction of speed by the driver will not necessarily produce a shock wave. However, in Figure 4.1b when the leading vehicle temporarily engages the brakes, all subsequent vehicles will have to apply their brakes as well to avoid a collision. In a dense traffic situation, subsequent vehicles will be required to brake as well, resulting in a phantom jam. The shock wave will persist in traffic as long as the density of vehicles entering the shock wave zone are high.

Typically when drivers experience a reduction in speed in their current lane, they are motivated to change to another lane in order to avoid an undesired slow down. This sudden lane change has the potential to improve a driver's state with respect to the previous lane; however, there is the possibility that the lane the driver is switching to fails to provide an improvement in driving conditions. Also, a lane change can force vehicles in the lane being entered to abruptly slow down, which can lead to shock waves in that lane. The inability of a driver to access the traffic conditions of lanes downstream can lead to frequent lane switching, and continuous braking.

4.0.2 Our Contribution

Traffic inefficiencies arise when the infrastructure can not fully support the high traffic demand, or when drivers are unable to make use of the road capacity available. The key contribution of *DRIVE-EX* is to use vehicular communication between vehicles in multiple lanes allowing vehicles to access traffic conditions, and perform lane change maneuvers when traffic state can be improved, with little to no impact to the target lane.

4.0.3 Organization of this Chapter

The rest of the chapter is organized as follows. Section 4.1 presents the models used to model vehicles' behavior. We then describe the *DRIVE-EX* protocol in Section 4.2. Section 4.3 details our evaluation of the performance of *DRIVE-EX* using simulation. Finally, Section 4.4 concludes the chapter.

4.1 Traffic Modes

A realistic car following model is essential for testing and verifying traffic flow optimization strategies. In this work, we rely on both a microscopic and macroscopic traffic model. The microscopic traffic model simulates individual vehicle behavior, and the properties of the macroscopic traffic model are used to assess the traffic conditions between vehicles.

4.1.1 Krauss Car-Following Model

The Krauss car-following model [KWG97], [Kra98] is a microscopic traffic model, which describes the individual dynamics of each vehicle as a function of the position and velocity of neighboring vehicles. The model is time-discrete and continuous in space, meaning that the model is updated at discrete time steps and the space is not divided into distinct cells.

In each simulation time step, a vehicle attempts to accelerate until the max velocity, v_{max}, is reached. However, a preceding vehicle, $i - 1$, may be traveling at a slower velocity, $v_{i-1}(t) < v_i(t)$, which may prevent the vehicle, i, from accelerating, and require the vehicle

to set its velocity to a safe velocity, $v_{i,safe}(t)$, which maintains a safe gap between vehicles. A randomization phase is also applied during each time step where there is a probabilistic tendency for a vehicle to dally, as is common with human drivers. This randomization phase makes the model more realistic, providing the possibility for velocity differences between vehicles and leading to potential phantom jams. After the velocity is computed for the next time step, $v_i(t+1)$ the vehicle's next position, $x_i(t+1)$, is also updated according to its updated velocity.

4.1.2 Lane-Changing Model

Lane-changing maneuvers are performed for discretionary and mandatory purposes. These maneuvers tend to have an impact on traffic state with respect to the capacity, stability, and breakdown of traffic flows [Erd14]. Lane-changes due to road hazards or on-ramps and off-ramps highly contribute to the break down of traffic flow in dense traffic situations, which can lead to long-lasting shock waves.

The lane-changing model introduced by Erdmann [Erd14] applies to microscopic traffic models with multiple lane roads. This model relies on a multilevel process applied at each time step to determine a driver's behavior. The first level, the Strategic Level, is a mandatory lane-change that a driver must make to reach their destination. This can be triggered due to a dead-end lane or a hazard in the lane. The Cooperative Level is the second level and applies to lane-changes performed by drivers exclusively to assist another vehicle with lane-changing towards their lane. The Tactical Level is a discretionary lane-change that allows vehicles to avoid following slower driving vehicles. In some countries, there are lanes dedicated exclusively for overtaking vehicles in other lanes. Once the slower vehicles are passed, it is required that the vehicle depart from the overtaking lane, which applies to the fourth level.

On multi-lane highways there are two passing rules that apply, depending on the country: symmetric and asymmetric passing rules. Symmetric passing rules are common in the United States and allow vehicles to pass using any lane. Asymmetric passing rules, which are

common in Europe, dedicate a lane for passing and require that the passing lane is used exclusively for that purpose. In this work we consider only symmetric passing rules.
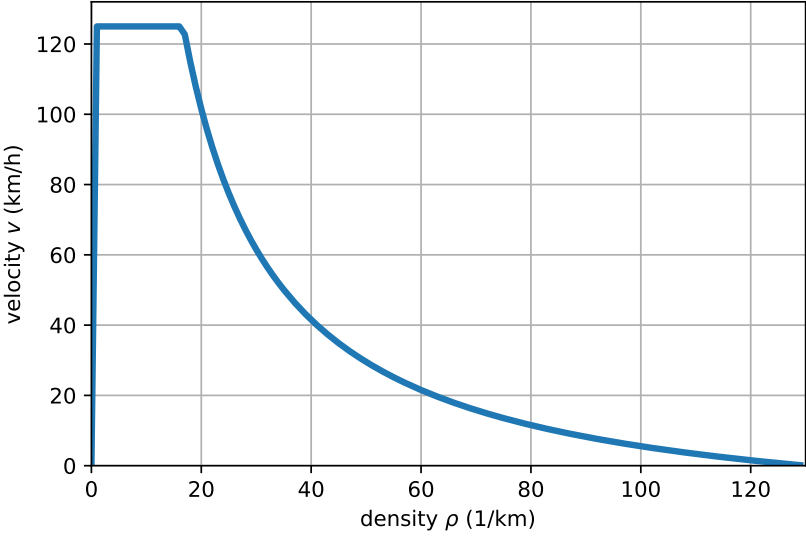
(a) Velocity Density Chart
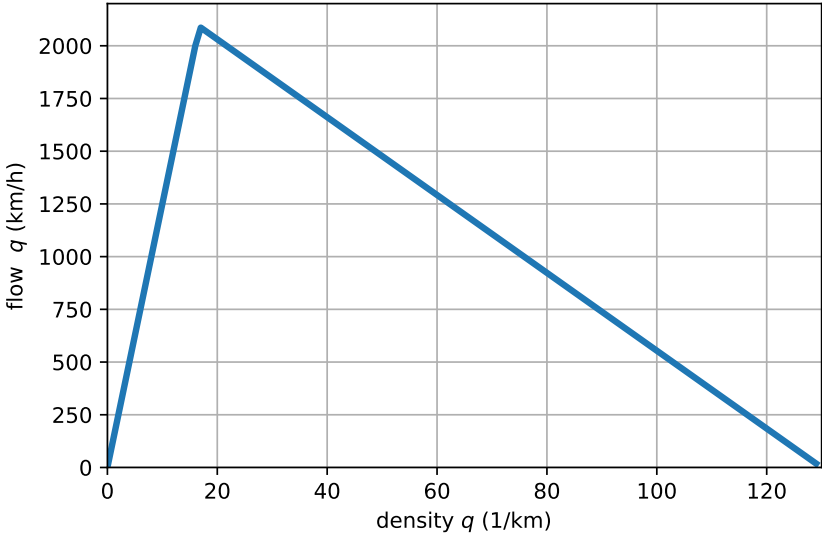
(b) Flow Density Chart

Figure 4.2: Fundamental properties of LWR model

4.1.3   Lighthill-Whitham-Richards model

The Lighthill-Whitham-Richards (LWR) model proposed by Lighthill and Whitham [LW55b] and Richards [Ric56b] falls under the classification of macroscopic models. Macroscopic models treat traffic as a compressible fluid, and the aggregate of vehicles' values are represented by the flow equation:

$$Q(x,t) = \rho(x,t) \cdot V(x,t) \tag{4.1}$$

In this flow equation, the variables are traffic flow $Q(x,t)$, vehicular density $\rho(x,t)$, and average velocity $V(x,t)$.

LWR is based on the continuity equation. Assuming there is a static relationship between the traffic flow $Q(x,t)$ and the vehicular density $\rho(x,t)$ for a homogeneous road section, where inputs and outputs take place at the borders of the section, the LWR model follows the equation:

$$\frac{\partial \rho}{\partial t} + \frac{d\hat{Q}(\rho)}{d\rho}\frac{\partial \rho}{\partial x} = 0 \tag{4.2}$$

Equation 4.2 describes the propagation of kinematic waves. Substituting the partial derivatives of the traveling-wave ansatz equation, $\rho(x,t) = \rho_0(x - \widetilde{c}t)$ we obtain the shock wave's propagation velocity:

$$\widetilde{c} = \frac{d\hat{Q}(p)}{d\rho} \tag{4.3}$$

This indicates that the velocity of the shock wave is proportional to the gradient in the flow-density chart shown in Figure 4.2b. The propagation velocity of a shock wave can be read as the gradient of the flow-density chart if the two points are in the same traffic phase. In free flow phase, the shock wave moves downstream with the flow of traffic with v_{max}, the maximum velocity, so preceding vehicles are not impacted. However, in the congested phase the propagation velocity is negative; therefore, the shock wave moves upstream in the traffic flow, which impacts the following vehicles with a velocity $\widetilde{c} \approx -18km/h$, causing vehicles to slow down [RKP10].

Figure 4.2 shows that there is a point where the traffic transitions from free flow to congested. This point of transition is defined as the critical density and is defined as:

$$\rho_k = \frac{1}{v_{max}T + (\frac{1}{\rho_{max}})} \qquad (4.4)$$

where the maximum number of vehicles are able to travel at the maximum velocity, v_{max}, with a minimum time headway T, and $\frac{1}{\rho_{max}}$ gives the effective length of vehicles. Prior to the critical density vehicles are capable of traveling at v_{max} and the flow of vehicles increases with density. However, after the point of critical density the velocity and flow of vehicles decreases as density increases.

4.2 Protocol Description

In this section, we present an extension to the DRIVE protocol, DRIVE-EX. DRIVE manages to redistribute traffic within an individual lane longitudinally. DRIVE-EX advances DRIVE by obtaining downstream information from adjacent lanes as well in order to redistribute vehicles across multiple lanes, which avoids long slow downs or high frequency of lane changes in congested areas. The LWR model is used to estimate traffic conditions between communicating vehicles.

The network protocol presented in this work is supported by DSRC. DRIVE-EX is a connection-less protocol that broadcasts messages when a vehicle slows down or the velocity falls below a threshold. Like the original DRIVE protocol, DRIVE-EX consists of three phases: the notification phase, the reception phase, and the forwarding phase. However, the notification and reception phases have been extended to process information from adjacent lanes. We assume that vehicles are equipped with optic sensors so that they can determine which lane they occupy.

In the event that a vehicle must decrease its velocity, a message that contains information about the vehicle is broadcast to neighboring vehicles. Vehicles in receipt of the slow down message that are further downstream from the messaging vehicle broadcast their traffic

state information as well. The vehicle following behind in the same lane as the vehicle that is slowing down either adapts its velocity or switches to an adjacent lane based on recommendations from the DRIVE-EX protocol. Prior to changing lanes, a vehicle uses V2V to coordinate the maneuver with vehicles in the target lane. If coordination is unsuccessful the vehicle aborts the lane change maneuver. However, if a vehicle changes lanes, a message is broadcast to following vehicles in the previously occupied lane to abstain from changing lanes for a predetermined period of time. However, if a vehicle follows the slow down recommendation, the message is rebroadcast until a time to live is reached or until the system determines that there are no additional actions to take.

In the following subsections, the phases of the protocol are further described.

4.2.1 Notification Phase

Vehicles that slow down below a threshold, Δv_n, or traveling below the minimum expected velocity ,v_{min}, trigger the broadcast of a message. Vehicles in adjacent lanes receiving this message broadcast a message as well. A DRIVE-EX message has the following fields:

$$m_h = [id, x, y, t, v, l, f] \tag{4.5}$$

where h $\in$ H is a unique message identifier, and id is a unique identifier of the vehicle originating the message. x and y are the GPS coordinates of the sender. The other values in the message are the time stamp of message creation t, the velocity of the vehicle broadcasting the message v, and the lane number of the lane the vehicle is currently occupying l. f is a flag to represent the message type, where $f \in$ [SLOW,LANE,GRANT,CHANGE]. SLOW is the type of message that is broadcast when a vehicle experiences a reduction in velocity. LANE is the message type that a vehicle broadcasts when it receives a SLOW message from a vehicle that is in an adjacent lane. The GRANT message is broadcast by a vehicle that is in a lane that another vehicle desires to enter. The CHANGE message type is broadcast when a vehicle wishes to change into another lane.

Algorithm Reception Phase

---

c: local vehicle

m: received message

if m_{type} == SLOW **then**

  if m_{lane} == c_{lane} AND $m_{position} > c_{position}$ **then**

    store m in slow down queue

  else if abs(m_{lane} - c_{lane}) == 1 AND $m_{position} \leq c_{position}$ **then**

    broadcast LANE message with c state

  else

    drop m

  end if

else if m_{type} == LANE **then**

  if abs(m_{lane} - c_{lane}) == 1 AND $m_x > c_x$ **then**

    store m adjacent lanes queue

  else

    drop m

  end if

else if m_{type} == CHANGE **then**

  if abs(m_{lane} - c_{lane}) == 1 AND $m_x < c_x$ **then**

    lane change granted

  else

    drop m

  end if

end if

4.2.2 Reception Phase

Upon receipt of a notification message m_h the system determines the type of the message and processes the message accordingly. If a SLOW message is received, the system determines the receiving vehicle's position with respect to the originator of the message. If the receiving vehicle is in an adjacent lane, and in front of the messaging vehicle, a LANE message with the vehicle's state is broadcast. LANE message broadcasts are performed opportunistically to prevent multiple vehicles from responding to the same SLOW message and causing a broadcast storm. If a vehicle is in the same lane as the vehicle that originated the SLOW message and at a position upstream, the message is stored in a Slow Message Queue to be processed by the system. LANE messages are only of interest to vehicles that are in adjacent lanes from the message and in a position following the messaging vehicle. Vehicles that meet this condition store the LANE message in a Lane Message Queue. Vehicles process messages in their respective queues to determine what action should be taken. A vehicle uses the velocity from messages to estimate the traffic densities in each lane:

$$\rho_l = \frac{1}{v_l T + \left(\frac{1}{\rho_{max}}\right)}, \forall l \in \mathcal{L} \tag{4.6}$$

The vehicle then compares the density of adjacent lanes ρ_{adj} with the critical density ρ_c. If a vehicle determines that the density in an adjacent lane is less than the critical density $\rho_{adj} < \rho_c$. CHANGE message is broadcast to vehicles in the adjacent lane to request access. This is based on the fact that at densities below the critical density point vehicles are capable of traveling at desired velocities.

A vehicle in the adjacent lane that receives a CHANGE request message determines if it will be impacted by the lane change maneuver by comparing the velocity of the requesting vehicle, with a time deadline τ_c. The following condition is evaluated at the vehicle in the adjacent lane a using the CHANGE message received from i.

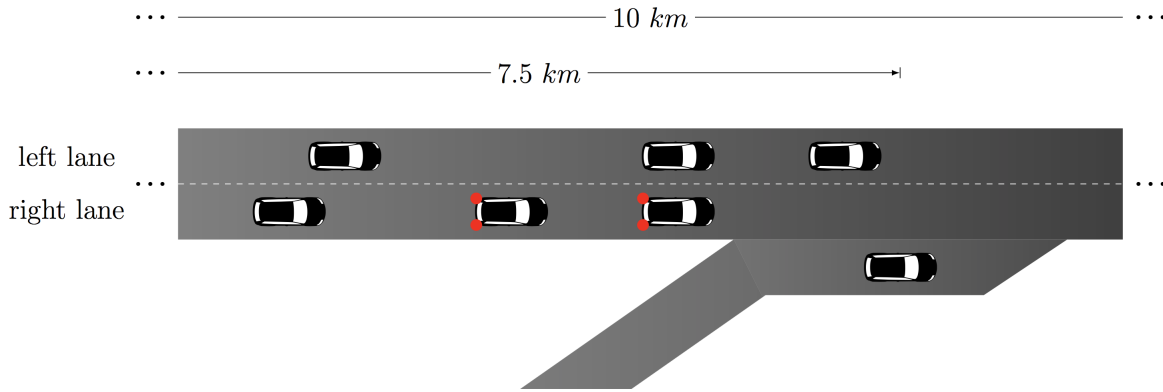$$v_a \leq v_j \ \& \ v_a(T + \tau_c) < \Delta pos \tag{4.7}$$

Figure 4.3: Road Segment

If this condition is true, a vehicle determines that at the current velocities and with the time headway and time deadline a safe distance can still be maintained by the vehicles and a GRANT message is broadcast granting the requesting vehicle access to the lane within the time deadline.

4.2.3 Forwarding Phase

In this phase, if a vehicle follows a slow down recommendation from a SLOW message, the vehicle rebroadcasts the received message at least once; however, if a vehicle switches to a new lane, the vehicle does not forward the slow down message. Instead the vehicle broadcasts a LANE message to other vehicles in its vicinity, informing the vehicles that a lane-change occurred. The system recommends that the vehicle remain in its lane for a set time to prevent a high number of uncontrolled lane-changes.

4.3 Performance Evaluation

In this section, we evaluate the performance of the our proposed protocol via simulation. We first describe the simulation setup, followed by the results.
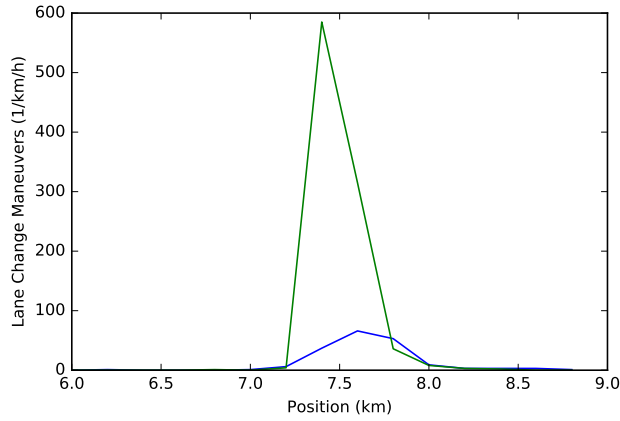
(a) Protocol: None
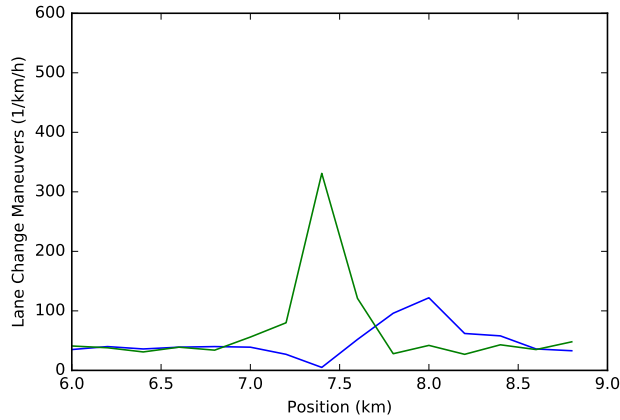
(b) Protocol: DRIVE-EX

Figure 4.4: Distribution of lane changing rate over space

4.3.1 Simulation

Simulations were carried out using Vehicles in Network Simulation (Veins) [SGD11], which couples a network communication simulator with a vehicle traffic simulator. The setup consists of a two lane highway of 10 km with an on-ramp at 7.5 km, as shown in Figure 4.3. The simulation time is a total of 2 hours. The traffic model used is the Krauss car-following model with symmetric lane-changing rules as previously described. Experiments showed that optimal results were achieved with an α value of 0.75, which is used throughout this paper.

The flow at the upstream boundary of the main lane was a constant 1,500 vehicles per
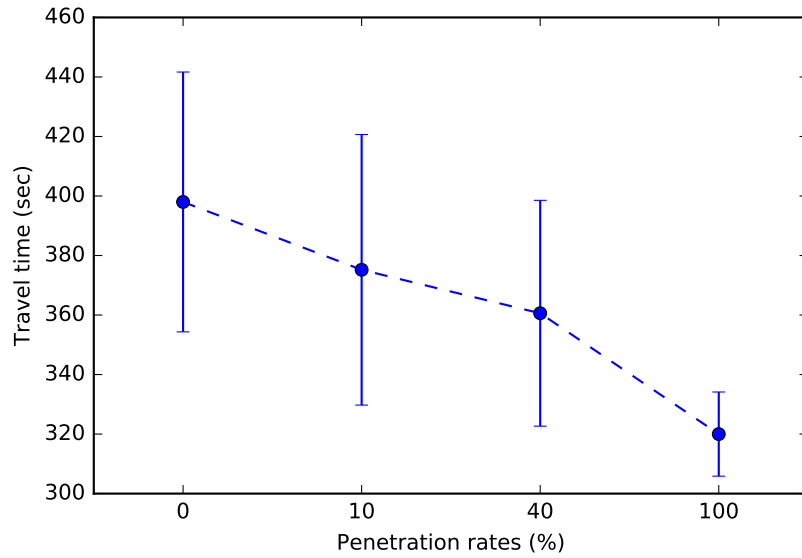
(a) Overall average travel time
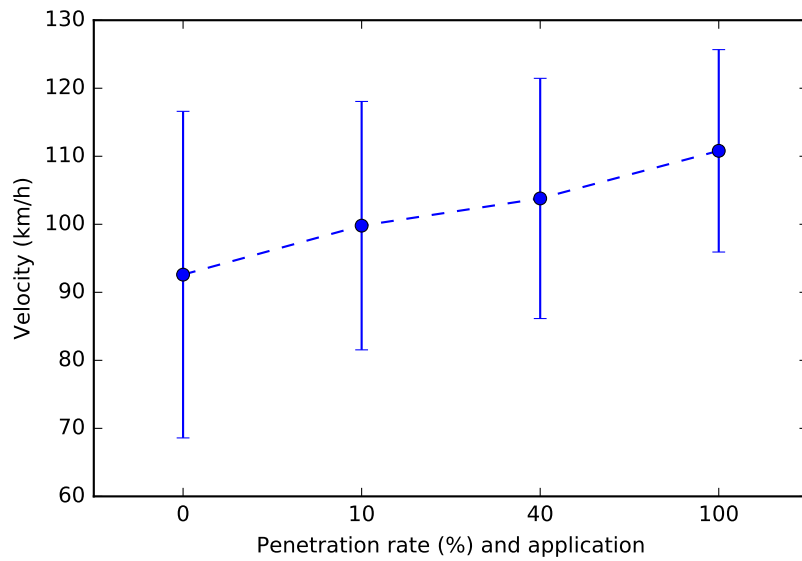
(b) Average velocities

Figure 4.5: Evaluation of overall travel time and average velocities

hour per lane, and the on-ramp flow was a constant 500 vehicles per hour. A single vehicle class was simulated to restrict traffic perturbations to only the on-ramp or driver dallying. Vehicle communication was modeled after the IEEE 802.11p standard with a communication range of 500m.

4.3.2 Results

In this section we present our simulation results. In our analyses, we compare the DRIVE-EX protocol to the DRIVE protocol, and to vehicles that are not equipped with any protocol.

Figure 4.4 demonstrates the lane-changing rate as a function of space. In all scenarios there is a high degree of lane-changing at the on-ramp location. However, DRIVE-EX has a significantly lower number of lane-changes at this point, due to the number of lane-changes that take place prior to the on-ramp position. DRIVE-EX reduces the number of lane-changes at the disturbance by more than 45%, Figure 4.4b, compared to vehicles that are not equipped with the protocol, 4.4a. By distributing traffic in advance, congestion build up is avoided.

Figure 4.5 shows the performance benefits of DRIVE-EX at varying penetration rates in respect to the overall travel time, Figure 4.5a, and the average velocities 4.5b. At full penetration, 100%, the overall travel time is decreased by about 20% compared to vehicles with no protocol, from $T_{0\%} = 398.4s$ to $T_{100\%} = 320.7s$. The mean velocity is also improved, increasing by 20% as well from $V_{0\%} = 92.6km/h$ to $V_{100\%} = 110.8km/h$.

4.4 Conclusion

In this chapter, we presented a protocol that utilizes communication between vehicles to access the traffic state in lanes enabling vehicles to make informed decisions to improve the overall traffic flow. We showed that the lanes impacted by sudden lane changes, and the resulting shock waves can be mitigated with our protocol. We also showed that overall traffic improvements can be realized as the number of vehicles equipped with the protocol increases.

CHAPTER 5

Cooperative Downloading in Heterogenous Vehicular Networks

In recent years, efforts have been focused on making vehicle communication a reality. A standard has been defined for the PHY and MAC layers, IEEE 802.11p, and new cars will be required to be equipped with the technology. Roadside Unit (RSU)s are envisioned to provide vehicles with access to the Internet. However, the deployment of RSUs is costly and scarce. Therefore, relying solely on RSUs will provide vehicles with intermittent or non-existent connections to the Internet. Cellular infrastructure is currently widely deployed and can be used to provide vehicles with access to content on the Internet. However, cellular resources have high demands placed on them, therefore efficient means for accessing them must be considered.

5.1   Introduction

A promising paradigm shift to overcome the challenges placed on overloaded cellular networks is Mobile Edge Computing (MEC) [WZZ17]. MEC places computation and storage resources at the edge of the cellular network near base stations (eNodeB)s in the Radio Access Networks (RAN). Moving these resources closer to the end users enables base stations to satisfy certain user requests, and avoids the necessity of forwarding data traffic through the core network to a remote server. This also leads to additional benefits such as lower latency, higher bandwidths, and location awareness.

Currently, newer vehicles are being equipped with technology to enable wireless communication. This technology includes interfaces to access cellular networks, such as Long-Term

Evolution (LTE), as well as an interface that enables vehicle to vehicle communication directly, using Dedicated Short Range Communication (DSRC), which relies on the IEEE 802.11p standard. When coupled together, the two wireless technologies can complement each other.

LTE has a high penetration rate, wide coverage area, and provides high data rates to users. However, if vehicles rely solely on LTE, it would exacerbate the load on the network. Moreover, certain vehicle applications are unable to tolerate the delay introduced by sending local data to a base station [ACC13]. DSRC is a purely distributed technology that does not require an extensive infrastructure to function. Vehicles have the capability of forming a VANET to exchange data; however, the effectiveness of DSRC is dependent on the proportion of vehicles that are equipped with the technology, the penetration rate [Eic07]. Integrating these two technologies produces a heterogeneous vehicular network that makes it possible to utilize the best network to satisfy a given service, and to augment the MEC by extending computational and storage resources to clusters of vehicles.

In wireless access networks the majority of traffic is attributed to downloading content [PWS09]. An attribute of vehicle networks is that vehicles are constrained by roads, therefore they have similar spatio-temporal properties. This typically results in many vehicles sharing common interest in data, such as maps, advisories, and videos that relate to their shared routes. The contents that vehicles are generally interested in are usually stored at a back-end server. Due to the fact that DSRC is a short-range technology and that there is sparse deployment of DSRC enabled RSU, LTE is the ideal technology to access this content. However, a high number of vehicles requesting related and redundant data can potentially degrade the quality of service (QoS) of the cellular network. MEC mitigates this issue by pushing server capabilities to the edge, however cellular radio resources are still wasted.

5.1.1 Our Contribution

In this chapter, we propose a fully distributed protocol that enables vehicles to form clusters, based on shared routes and interest in content. The vehicles within the cluster request data
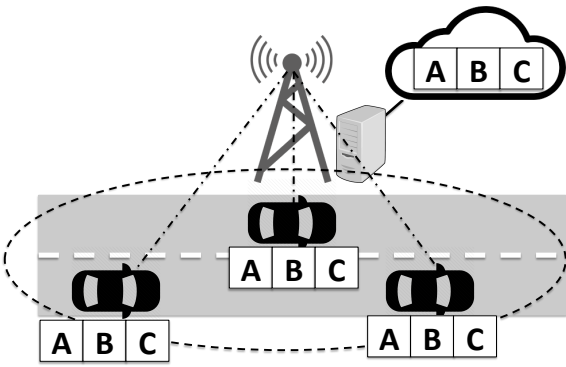
(a) Each vehicle within cluster downloads all data segments.
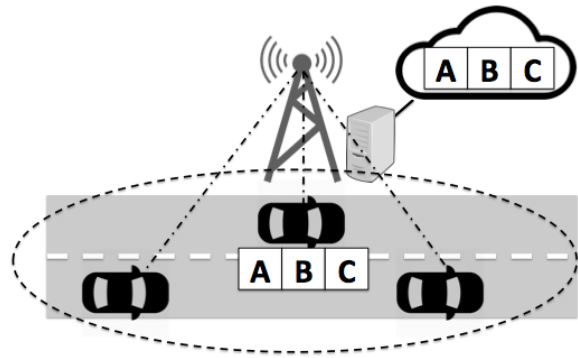
(b) Single vehicle (cluster head) downloads all the content.
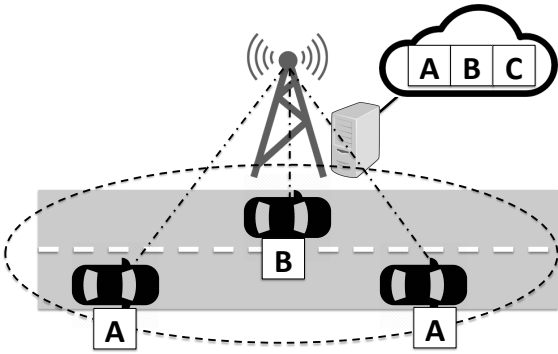
(c) Each vehicle within cluster downloads a random segment of data.
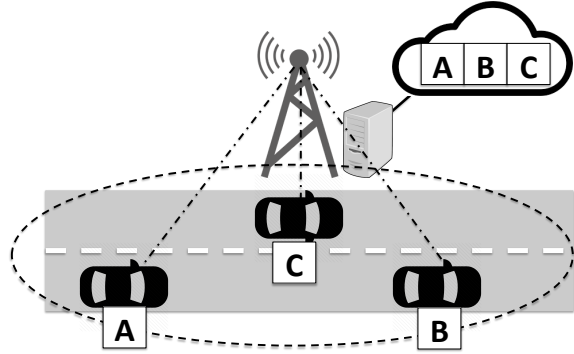
(d) Each vehicle within cluster downloads a unique data segment.

Figure 5.1: System architecture of different scenarios

segments of a file from a back-end server over LTE, and cooperatively exchange the data segments via DSRC to reconstruct the file at all interested vehicles. The goal is to minimize the overlap of data segments requested from neighboring vehicles, in turn reducing the demand on the LTE network by reducing the number of requests for data segments. Furthermore, this approach extends MEC capabilities to the vehicle clusters by storing popular content at cluster vehicles.

5.2 Cooperative Downloading Vehicular Cluster

In this section we introduce a new protocol, Cooperative Downloading Vehicular Cluster (CDVC), a V2V communication protocol that extends the storage capacity of MEC to vehicular clusters. The goal of our work is to minimize the number of requests to the cellular network required by the vehicular cluster to retrieve the segments of a file, and at the same time reduce the cellular resources utilized by vehicles interested in the same content. Vehicles can cache the contents and redistribute data to other interested users. The novelty introduced by CDVC is the ability to form clusters and request data segments in a distributed manner, without the reliance on a cluster head for coordination. Overhead due to frequent broadcasting traditionally required for coordination wastes VANET bandwidth and introduces delays. To reduce the broadcast waste, we achieve coordination of vehicles interested in downloading the same file by constructing a Distributed Hash Table that tracks vehicles' interests.

In this work, we assume that files are divided into data segments of equal size, which can be located at a back-end server or cached at the edge of the network. Vehicles are equipped with GPS to obtain their location, DSRC interface to share data with other vehicles directly, and an LTE interface for cellular communication to retrieve data over the Internet.

The periodic exchange of messages between vehicles that provide cooperative awareness has been standardized as Cooperative Awareness Message (CAM) in Europe [ETS11] and Basic Safety Message (BSM) in the U.S. [Com09]. CDVC relies on these messages. It extends them to include a field indicating a vehicle's interest in content and a bit vector to indicate the data segments cached at a vehicle. Vehicles use this information to facilitate peer to peer data segment exchange.

The system architecture is shown in Figure 5.1 with four different downloading scenarios. A file is segmented by the server, however the distribution of the file is managed by users requesting the segmented data. A, B, and C represent different segments of a file. Each vehicle can request the complete file by requesting all of the segments (Figure 5.1a), however if multiple vehicles in a geographical area are all interested in the same file, this can place an

excessive load on the cellular base station. A single vehicle in the vicinity can download the entire file (Figure 5.1b) and share the contents with interested peers. However, one vehicle uses all of it's cellular resources while the other vehicles benefit, which is unfair. If vehicles randomly request data segments, this can lead to vehicles within a cluster requesting the same data segments, making additional requests necessary (Figure 5.1c). If vehicles request unique data segments from the eNodeB and share their data segments via DSRC, vehicles can cooperatively download while reducing the cellular resources used (Figure 5.1d). However, managing the selection of data segments in a distributed manner is a challenge.

The back-end server could manage the distribution of data segments to vehicles interested in the same content within a geographical area, however this solution would place an excessive overhead on the server. Another option is for vehicles to coordinate which data segments each vehicle will request from the server, however this approach would add significant message overhead on the DSRC as well as coordination delay.

We argue that each vehicle should select which data segment to request from the server in a fully distributed manner. One possible approach is to have each vehicle request a random set of data segments from the server and have the vehicles share the segments needed by other vehicles. This approach relieves the cellular network from having to track which data segments are cached at which vehicle. The eNodeB simply serves each user request. This approach also reduces the amount of coordination messages on the DSRC channel. However, it does not prevent multiple vehicles in the same geographic area from randomly selecting the same data segments to request. This overlap will require vehicles to make additional requests, degrading the cooperative downloading process. A more suitable approach to requesting data segments is to use consistent hashing within a cluster so that vehicles can determine which data segments to request.

CDVC is executed in three phases: *interest phase*, *download phase*, and *distribution phase*. In the following subsections we describe each phase in detail.

5.2.1 Interest Phase

Vehicles interested in data are enabled to express their interest to neighboring vehicles. Instead of introducing a new message to the existing VANET messages, the BSM is extended with a field to represent the files a vehicle is interested in, and a bit vector to specify the data the vehicle is carrying. A file is divided into a sequence of segments, where each bit position corresponds to a data segment. BSM includes a wide range of information about a vehicle such as latitude, longitude, time, angle, speed, acceleration, etc. In CDVC, the information of interest is latitude, longitude, time, and angle. The latitude and longitude information is used to determine the road that a vehicle is traveling along, the angle is used to determine if the receiving vehicle is heading in the same direction as the sender, and the time-stamp of the message is used to maintain the vehicular clusters. If a vehicle, say A, is traveling on the same road at approximately the same angle as the sender, say B, a new vehicular cluster is born. The next vehicle will join if it can hear both A and B, and has affinity with them (say same direction, similar interests, etc). Eventually, a cluster is formed that includes nodes with affinity that can hear each other. The cluster is assumed to persist long enough to allow construction of Distributed Hash Table (DHT) and parallel downloading.

Vehicles use the data interest announced by cluster members to populate a Local Dynamic Map (LDM) [ETS14], which maintains information about traffic objects, such as vehicles, that are maintained locally by each vehicle. If a period of time, Δt, expires without a beacon being received from a cluster member, the vehicle is removed from the LDM.

5.2.2 Download Phase

Vehicles periodically check their LDM to determine what data is available within their cluster. If a vehicle discovers a data segment of interest within its cluster, the vehicle can request it directly from one of its neighbors. However, if vehicles are interested in data that is not present within their cluster, requests are made periodically to an eNodeB. Consistent hashing is applied to the unique vehicle identifier of each vehicle within the LDM to identify which data segments to request from the eNodeB. The DHT maintained across the cluster
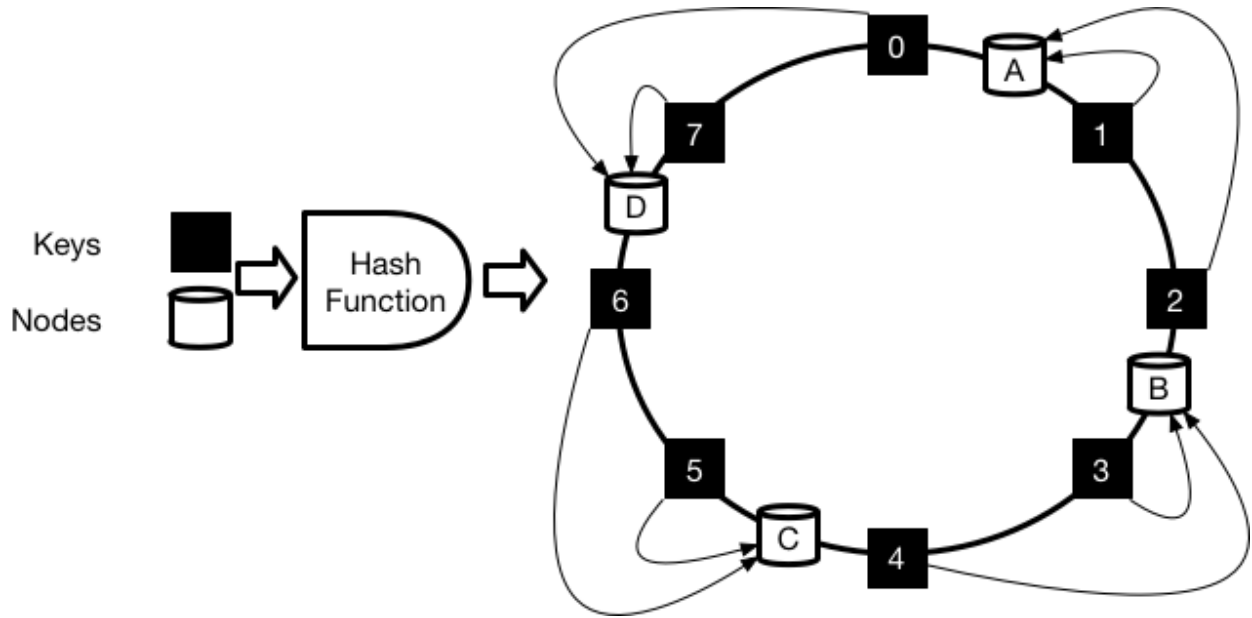
Figure 5.2: Consistent Hashing of data and mapping to nodes.

members is indexed by the vehicle identifier to determine which other vehicles are trying to download the same file over LTE, and coordinate parallel segment downloading.

Consistent hashing [KLL97] is a distributed hashing scheme that virtually maps data elements and nodes to positions along a hashing ring, using a hash function such as SHA-1 [EJ01]. For nodes, the hash function is typically applied to a node's identifier, such as an IP address or in our case, license plate number. For data elements, a key value pair combination is used, where the hash is applied to the key of the data element. Consistent hashing is not influenced by the number of nodes or data elements, however the number of nodes is generally significantly less than the number of data elements. Data elements are mapped to the node immediately adjacent in the counter clockwise position on the hashing ring.

Figure 5.2 shows a hash ring with eight data elements and four nodes A, B, C, and D. Each data element will be stored at the node counter-clockwise to it, with data elements 1 and 2 both being stored at node A, in this example. This method distributes the data elements that a node is responsible for. If a node happens to leave the network, all of the keys do not have to be remapped, only the subset of keys on the hash ring that were associated

with the departed node are removed.

Data segments are originally all stored on a server located at the edge or the core of the cellular network. The goal is to enable vehicles to use consistent hashing to identify the data segments that each vehicle will initially be responsible for. Each vehicle will cooperate in constructing and maintaining a local hash ring from their LDM. We assume that the number of data segments are known by all vehicles, which can be obtained from the server, and data segments are identified by their sequence number. Vehicles use information such as vehicle identifiers and desired data segments not present within the cluster to construct a local hash ring. Vehicles only request the data elements from the eNodeB that map to their position on the hash ring. The hash ring approach eliminates the need for a distributed broadcast based synchronization approach to instruct vehicles which unique data segments they must download. Request to the LTE network are made periodically if a period of time ,*request period* period, passes without a vehicle being able to receive any data from a cluster member.

5.2.3 Distribution Phase

Once a vehicle receives its requested data segments, cluster members will be notified in subsequent beacon messages. Vehicles within the same cluster may request desired data from peers, enabling cooperative downloading. Request for data within a cluster are broadcast. To prevent multiple vehicles from responding to the same request, a message suppression technique is applied that prioritizes data segments from vehicles further away from the requester, which is reflected with a short back-off timer. The rationale behind this message suppression technique is that vehicles further from the requester may have greater potential to reach more vehicles that may be interested in the same data segment, and therefore reduce the number of possible subsequent requests.

Table 5.1: Simulation Parameters

Parameter	Value
Simulation Area	800m x 800m
Average Density (veh/km/lane)	12
Simulation Duration	300s
DSRC Technology	802.11p
DSRC Transmission Power	20mW
Beacon Frequency	1Hz
LTE sheduler	MAXCI
eNodeB Transmission Power	45dBm
UE Transmission Power	26 dBm
Number of RBs	15
Data Segment Size	64KB
Request Period	3s
Total file size	20MB

5.3 Evaluation

5.3.1 Simulation Setup

To evaluate the performance of our CDVC protocol we used Veins LTE [HDS14], a vehicular networking simulator with an LTE extension.

We model an urban traffic scenario with a realistic Manhattan grid with two lanes per road. The average speed of vehicles is $40km/h$, which is common in urban environments. The average density per road is $24veh/km$. This represents actual traffic situations where the maximum lane capacity is reached at a density between 13-17 vehicles per kilometer and lane [Ric56c]. The traffic model used is the *Krauss car-following model*. All simulations are repeated 10 times with an independent random seed for each run.

We assume that our target area of interest is covered completely by an LTE eNodeB. All

vehicles are equipped with LTE and DSRC interfaces. The applicable simulation parameters can be found in Table 5.1.

We evaluate the performance of our cooperative downloading protocol with consistent hashing, referred to as Hashing, by comparing it to a cooperative downloading scheme where vehicles randomly request data segments from the server, referred to as Random. We also evaluate a single cluster head scheme, where a single vehicle downloads all data segments and redistributes the data to neighboring vehicles, and a pure LTE only scheme in which vehicles do not use cooperative downloading at all, with all vehicles requesting data directly from the server via LTE.

5.3.2 Evaluation Metrics

We use the following metrics for evaluation:

- Average Download Time: the average time required for a vehicle to download the complete file

- Data Segments from Server Ratio: the proportion of data segments that are obtained from the sever out of the total data segments comprising a file

- Jain's Fairness Index: the fairness of data segments obtained from LTE with respect to peers

5.3.3 Results

For cooperative downloading to be effective, it is imperative that vehicles have peers in their DSRC transmission range that they can collaborate with to download data. Therefore, a vehicle's number of peers has an impact on the protocols performance, and ability to offload traffic from the cellular network. However, due to the random access nature of the underlying 802.11p protocol, there is a trade off between the number of peers and the observed download times.

Figure 5.3 shows that when LTE is used exclusively, the number of peers a vehicle has is
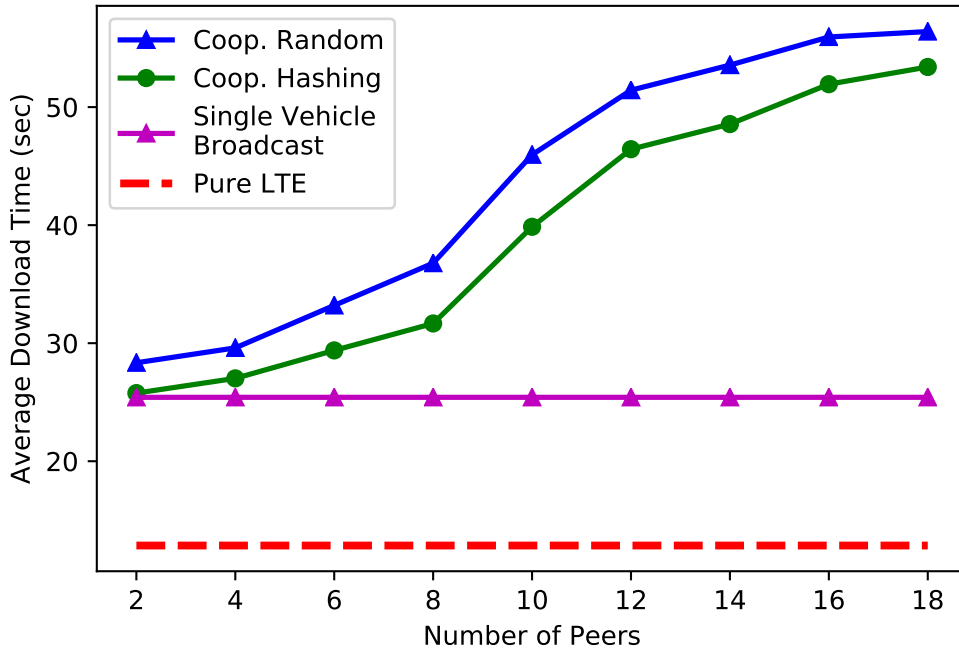
Figure 5.3: Average file download time vs. the average number of peers

irrelevant, and a node on average takes approximately twelve seconds to download a complete file. When a single node downloads and distributes the file, the download time is relatively fixed, regardless of the number of peers, however the additional hop from the eNodeB to the vehicle adds some additional delay. Downloading content with a cluster increases the download time by 53% when compared to Pure LTE. With the cooperative schemes, as the number of peers increases, so does the download time. This is the result of more nodes requiring access to the shared wireless channel. The Random scheme takes slightly longer than the Hashing scheme due to vehicles requesting the same data segments, which requires additional requests for segments that have not been received. The Hashing scheme avoids this by identifying which content each node is responsible for.

Figure 5.4 shows that the less peers a vehicle has, the more data the vehicle will need to request over LTE in order to complete a file download. The higher number of cluster members increases the potential for a cluster to have a broader set of the desired content, which subsequently reduces the number of LTE requests. With Pure LTE, all requests occur
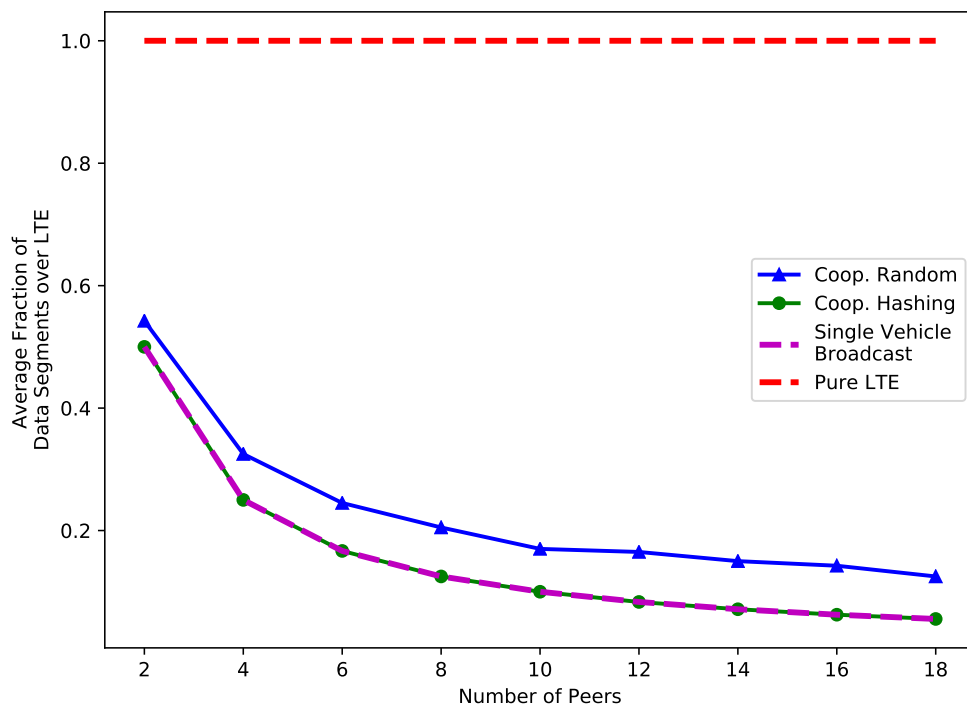
Figure 5.4: Average ratio of data request over LTE vs. average number of peer
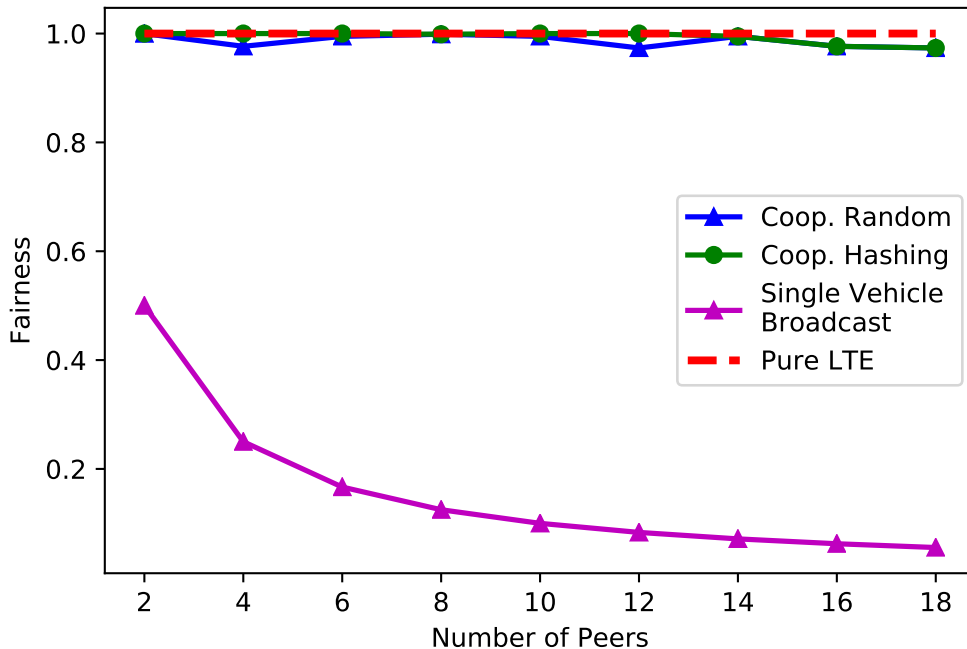
Figure 5.5: Fairness vs. average number of peer

via LTE and no cellular resources are saved. With Hashing and single vehicle broadcast, the optimal data request ratio is obtained, which is equivalent to a single file downloaded for a cluster.

Cellular resources are expensive, so ensuring that each node fairly contributes to the download process is important. We use the Jain's Fairness index to define fairness:

$$J = \frac{(\sum_{i=1}^{n} c_i)^2}{n \cdot \sum_{i=1}^{n} c_i^2} \tag{5.1}$$

Figure 5.5 shows the fairness achieved by the various schemes. Pure LTE is fair because there is no cooperation at all, so each interested node uses the same amount of resources to collect a file. The cooperative schemes provide a high degree of fairness due to the participation of cluster members in the download process. However, the single vehicle broadcast scheme has low fairness that decreases as the number of peers increases. This is a result of one node sharing the entire file while other vehicles receive it from the downloading vehicle.

5.4   Conclusion

In this chapter, we proposed a protocol for vehicular heterogeneous networks to offload traffic in the cellular network and enable cooperative downloading among vehicles. We proposed using consistent hashing to provide vehicles the ability to request content from the Internet with minimal communication overhead. We evaluated our protocol against random selection of content and LTE only. Our experimental results showed that in regards to download times, our protocol does not out perform LTE, but it can significantly reduce the cellular resources utilized in the cellular network.

CHAPTER 6

Conclusion

In this dissertation we presented vehicular applications and protocols that improve traffic efficiency and safety. These protocols rely on data that can be generated and shared locally or data that is necessary to retrieve from a backend server. In a vehicular environment, requesting content from a backend server will require accessing infrastructure that is connected to the Internet, which will likely be cellular infrastructure. We proposed a scheme to efficiently access cellular resources and share content locally between vehicles.

For vehicular safety we proposed an application that classifies the risk of accidents based on historical data, and provides commuters with the ability to factor route safety into navigation decisions. To improve traffic efficiency, we addressed the shock wave phenomenon, and proposed a scheme to redistribute traffic entering a shock wave point to mitigate the impact of shock waves.

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