Technologies for Safe and Efficient Transportation

A U.S. DOT UNIVERSITY TRANSPORTATION CENTER

T-SET Final Research Report

Vehicle-to-Vehicle Communications for Safer Intersections: Virtual Traffic Lights

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I. Research Project Description

Given the pace of urbanization in the whole world in the last decade, it is no secret that the traffic congestion in urban areas has steadily gotten worse and is bound to deteriorate further unless new cost-effective and scalable solutions can be found. In fact, the most major cities of the U.S. (such as NYC, Los Angeles, Chicago, etc.) commute times of 1.5 hours or more (45 min each way) is not uncommon [1]. The situation is even worse in Asia and Latin America. So, congestion problem is already an acute global problem which will get worse since the road capacity needed for increased number of vehicles in cities is far from being sufficient. In the current economic climate, it seems unlikely that a road capacity increase commensurate with the increase in the number of vehicles will occur in the foreseeable future.

Increasing the use of information technology (IT) in future vehicles can solve or mitigate many of the fundamental problems we face today in transportation such as energy efficiency, reduced carbon footprint for cars, greener environment, and several others. Note that the premise of the proposed work here lies in the technology known as vehicle-to-vehicle communications. Vehicles are assumed to be equipped with communications devices which allow them to communicate among themselves. A group of equipped vehicles thus form a vehicular ad hoc network which is a special application of wireless ad hoc networks with different constraints [2-9]. Specifically, the focus of the proposed work is on making vehicles more intelligent for increasing safety at intersections, mitigating congestion, reducing the commute time of urban workers, increasing productivity of the USA (as well as other countries), increasing the energy efficiency of cars, reducing the carbon footprint of cars, and supporting a greener environment.

Figure 1: In-vehicle traffic lights

In particular, we propose a new technology, which migrate infrastructure-based traffic lights to in-car traffic lights, as shown in Figure 1. Using the emerging vehicle-to-vehicle

(V2V) communications capability of modern cars through the DSRC standard at 5.9 GHz, it has been shown that this technology can make traffic control ubiquitous at every intersection in urban areas. Through V2V communications, the vehicles at different legs (or approaches) of an intersection can elect a leader, which can manage the traffic flow at that intersection, thus acting as a "Virtual Traffic Light". The results of our investigation have shown that this technology can reduce the commute time of urban workers between 40-60% during rush hours which seems pretty significant in terms of reducing accidents at intersections, mitigating congestion, increasing productivity, reducing carbon footprint of cars, increasing the energy-efficiency of transportation, and supporting a greener environment.

Background

In the proposed self-organized traffic control paradigm, through the advent of vehicle-to-vehicle (V2V) communications, vehicles communicate among themselves (i.e., in ad hoc manner without any the help from the existing infrastructure) to resolve conflicts at intersections and determine who should cross the intersections first (i.e., they establish the "right of way"). Without any centralized infrastructure, the proposed scheme operates in a distributed manner under the assumption that each vehicle periodically broadcasts hello messages to announce its presence, current position, and velocity to other nearby vehicles. A vehicle can therefore construct the local map and determine if there is an ensuing conflict at the intersection it is about to approach. In situations where a conflict is detected, vehicles involved in the conflict perform the following three steps as shown in Figure 2:
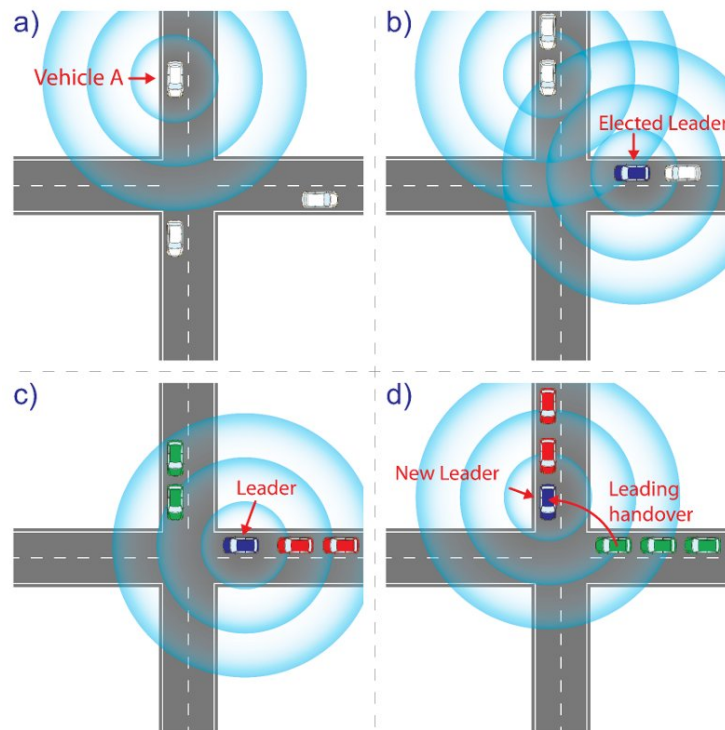

Figure 2: Principle of Operation of the proposed Virtual Traffic Lights concept

A. Leader Election process

As vehicles approach the same intersection (when, a conflict is detected), they must agree on electing one of them to act as the leader for the intersection. The elected leader will serve as temporary traffic light infrastructure and is responsible for creating and broadcasting traffic light information. Other vehicles act as passive nodes, listen to and obey the traffic light information broadcast from the leader. To avoid unnecessary leader election process, the leader is presented with red light and stops at the intersection while leading it.

B. Generation of Traffic Light information

Once a leader is elected, it determines how long each approaching direction should receive the right of way (i.e., phase layout of the traffic light). This phase layout could be pre-programmed or dynamically configured based on several parameters such as the volume of traffic in each direction, level of congestion at the intersection, priority of roads, etc. To enable a fair use of the intersection, the number of cars waiting in each road should also be taken into account. Phase preemption could also be enabled - once the VTL leader detects that the road with the green light has no additional vehicles attempting to cross the intersection, the current phase is interrupted and the green light is given to the next connecting road.

C. Leader Handover

When the green light is in the leader's lane, a new leader must be elected to maintain the virtual traffic light infrastructure. The new leader can be elected by two possible mechanisms: - i) the current leader hands over the leading task to one of the vehicles stopped before a red light at the intersection or ii) the new leader election is performed if there are no stopped vehicles under red lights.

It has been shown by extensive simulations that the aforementioned traffic control scheme (i.e., Virtual Traffic Light (VTL) system) could provide up to 60% improvement in traffic flow [2]. Such a significant improvement is due to two reasons: i) VTL can render traffic control truly ubiquitous as compared to only about 20% of intersections that are currently equipped with traffic lights; and ii) VTL reduces the dead period of intersections (i.e., unnecessary red lights when green light is given to the road with no additional traffic). Interestingly, despite a substantial improvement in traffic flow, it is also reported in [2] that the VTL system slightly increases the time a driver is exposed to red light.

It should be noted that the above virtual traffic light system operates based on the following assumptions:

- All vehicles are equipped with DSRC radios.
- All vehicles share the same digital map and positioning system device that has lane-level accuracy.
- The RF propagation problems such as obstructions due to buildings at the corners of intersections do not disrupt the necessary vehicle-to-vehicle communication for electing a leader that will serve as a virtual traffic light.
- Other communications problems due to collision of transmitted packets or beacon messages by vehicles are not severe.

In this report, we discuss the aforementioned assumptions and propose solutions that can address the situations where one or several of the aforementioned assumptions are not satisfied. This report is comprised of five main parts:

In Part 1, a large-scale simulator using open-source simulators which will comprise a mobility simulator (i.e., SUMO) integrated with a network simulator (i.e., ns-2) and assess the performance of the developed VTL solution.

Part 2 quantifies the impact of RF obstructions and communications problems at intersections on the proposed VTL scheme and propose a fault-tolerant VTL solution that can reliably detect failures, prevent adverse consequences, and is resilient to RF obstructions and communications problem

Part 3 quantifies the severity of the "partial penetration" problem and proposes practical solutions (hardware and software platforms) for addressing the problem. In addition, in this part of the report, a new method and system is also presented for the co-existence of VTL with the current infrastructure-based traffic control systems under very low penetration rates of DSRC and VTL technology. Based on the game-theoretical approach proposed, it is shown that the adoption of VTL technology can be accelerated by providing incentives to vehicles equipped with VTL technology.

Part 4 presents a development of VTL prototype to verify the feasibility of implementing VTL using hardware that is available in today's market.

Part 5 presents new algorithms and technologies that will take into account the presence of pedestrians and cyclists at intersections.

To put the results of this report into perspective, it might be helpful to recall some of the statistics published by the US Department of Transportation (DoT) regarding the safety of road transportation: every year in the USA there are about 35,000 fatalities and tens of thousands of critical injuries due to accidents. It is probably not surprising to see that more than 20% of these accidents take place at intersections (intersections with or without traffic signals). The financial and human cost of these accidents is huge and certainly a major concern.

It is interesting to note that, according to the DoT statistics, less than 1% of all the intersections in the USA are equipped with traffic lights. This is due to two major reasons:

I. The high cost of deploying traffic lights (somewhere between $ 50,000--- $ 200,000 depending on how sophisticated the intersection is)
II. The low volume of traffic at certain intersections might not warrant the high-cost of deploying traffic lights

However, it has been known by the DoT and Traffic Engineering Community (both in the government and private sectors) that an intersection equipped with traffic lights is safer than an intersection without traffic lights. Nevertheless, the aforementioned two reasons have resulted in the landscape we observe today.

These statistics point to the fact that the existing traffic control systems might be inadequate in preventing such accidents which lead to such a huge number of fatalities and injuries. Despite the fact that all vehicles in the US are equipped with seat belts and air bags, such high numbers of accidents and the resulting human loss and injuries (in addition to financial losses) call for a new way of handling traffic on the road network to make it safer. More specifically, a 3rd level of safety system (radio communications in the

form of DSRC technology) might be needed to improve the safety on the roads substantially.

It is our hope that the results of this report make a compelling case for the use of two new technologies for safer intersections:

1. Use of DSRC technology in every car and the use of V2V and V2I communications;
2. Use of Virtual Traffic Lights enabled by DSRC technology as a new traffic control paradigm (thus making traffic lights ubiquitous at every intersection as opposed to the 1% statistic mentioned above).

Part 1:
Performance assessment of the Virtual Traffic Lights

I. Executive summary

Traffic congestion in major capitals of the world is a daunting problem awaiting new solutions that are scalable and cost-efficient. In fact, the severity of this problem has increased over the last 10 years in parallel with the accelerated urbanization of the world. Given that more than 50% of the world population now lives in urban areas, it is not surprising that the number of vehicles on the roads have increased dramatically over the last decade, far exceeding the capacity of the road network in major cities. Unfortunately, the investments for increasing the road capacity have stayed relatively modest, thus exacerbating the congestion problem. It is well known that other modes of transportation could mitigate the traffic congestion problem. For example, railway transportation is a very energy-efficient mode of transportation (about 2-5 times more energy efficient than road transportation); however, the initial deployment cost of rail transportation is quite high. This partially explains why more than 80% passenger transportation uses road transportation as opposed to railway, air, or maritime in the USA and Europe. Another widely used technique to mitigate congestion is to use dynamic pricing (also called congestion pricing) during rush hours. In major cities like London, Los Angeles, Atlanta, etc. this technique has been implemented over the last decade with some success. On the other hand, congestion pricing forces urban workers either to pay for the routes in high demand, or change their routes to less favorable paths, or change their schedules for travel considerably, thus significantly affecting their lifestyles. In most cases, the socio-economic impact of congestion pricing could be quite serious, adversely affecting urban workers. Consequently, this scheme has not been adopted by several countries as the repercussions were found to be too severe.

A promising approach for mitigating congestion and reducing the commute time of urban workers was proposed recently. This new approach is known as Virtual Traffic Lights (VTL) and it leverages the presence of Dedicated Short Range Communications (DSRC) technology operating at 5.9 GHz. DSRC radios are expected to be a mandate in the next 2-3 years in the USA and possibly Europe and Japan. By leveraging the ubiquitous existence of DSRC radios, VTL scheme shows how vehicles can establish a leader at every intersection that can undertake the responsibility of traffic control at that specific intersection temporarily. This responsibility is then handed over to another cluster leader in the orthogonal direction after some time. This right of way decided by the elected leader is broadcast to all the vehicles in the same direction as well as the orthogonal direction. The man-machine interface used to inform each driver about the "right-of-way" is envisioned to be a display unit which will be on the windshield of every vehicle, thus making it convenient for each driver whether he should proceed or stop at that intersection.

In this report, performance of the proposed VTL concept is assessed in a comprehensive and systematic manner. The study and results presented in this part aim the answer the following questions/issues:

Part #1.1: What is the asymptotic benefit of VTL whereby the considered time horizon is longer and it is assumed that the drivers change their choices and habits in terms of the routes they take during rush hours after seeing that VTL scheme provide universal traffic control at every intersection?

We first analyze the immediate benefit of the VTL scheme assuming the driving habits of vehicle drivers do not change. The time horizon here is

short and it is assumed that the choices drivers make during rush hour will not change instantaneously. Then, the asymptotic benefit of VTL is reported.

The observed benefit in terms of reducing commute time of urban workers approaches 100% asymptotically, which is very significant. The reported results are verified by two different large-scale simulators, DIVERT and SUMO, thus building confidence in the validity of the trends and the numerical results.

Part #1.2: How does the substantial benefit in terms of commute time provided by the VTL get distributed to urban workers during rush hours?

While the benefit of the VTL scheme is pervasive as it applies to any type of road topology in urban areas, it is clear that the congestion phenomenon is exacerbated during rush hours (both in the morning and evening rush hours). It is therefore of paramount importance to understand and quantify the potential reduction in commute time or urban workers during rush hours. Ultimately, this is what commuters care about. The time spent by millions of commuters every day in traveling to and from work is not only wasted and unproductive time but also a very stressful experience and it has long-term adverse effects on the psychological and physical health of urban workers.

Part #1.3: What are the advantages and disadvantages of the VTL scheme as compared to other pervasive solutions proposed to address traffic congestion problem?

In this report, we argue that VTL approach is more efficient in alleviating traffic congestion problem as compared to the widely used dynamic congestion-pricing scheme. As will be shown in this report, with the VTL scheme, urban workers will experience less traffic congestion and significantly less time commute time. More importantly, as compared to the congestion-pricing scheme which is effective only in some scenarios with specific vehicle density, benefits of VTL scheme can be obtained in any scenarios.

Part #1.4: How can the proposed VTL scheme facilitate and handle vehicles with different priorities such as emergency vehicles, transit buses, etc.?

Based on the same self-organizing principle, in this report, we propose a self-organized traffic control paradigm that aims to facilitate and expedite the motion of emergency vehicles through traffic in urban areas in the case of an accident or emergency situation. The proposed traffic control scheme could possibly be easily extended to address the priority management of other transportation systems (e.g., transit buses, light rails, etc.) Similar to the VTL scheme, the proposed priority intersection control scheme has a negligible impact on the flow of normal traffic.

<u>**Part #1.1**</u>

System Model and Preliminaries

Figure 1.1.1 depicts the new simulation scenario as a proof-of concept example. The objective is to reproduce what typically happens in a real city, where most of the vehicles enter from a main "source area" (this is typically where most of the urban workers and professionals are during the work day), and move towards a common destination, which in the morning rush-hour period, for example, should correspond to a "business area", and during the afternoon rush-hour period should correspond to the residential area where urban workers live. However, observe that Figure 1.1.1 (a) depicts a generic and ideal scenario whereby all routes are equally likely to be used. Figure 1.1.1 (b) shows a more realistic scenario where certain routes (three shown here) are preferred because they might have more lanes or could have more intersections which make it easier to travel during rush hours.
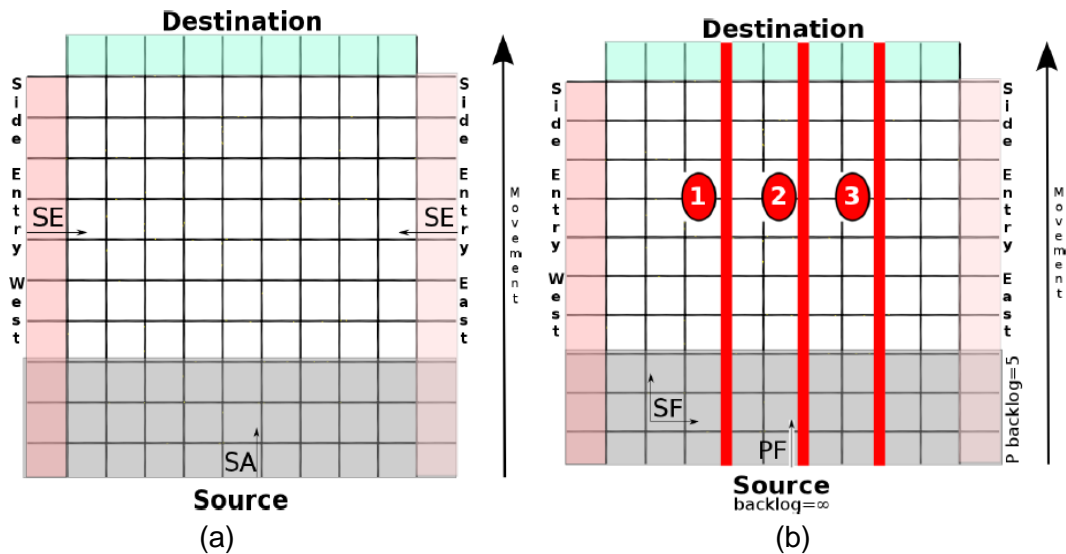

(a)   (b)

Figure 1.1.1: Figure 1.1.1(a) shows the generic system model used in the simulations. In this 16x16 MG scenario the bottom part presents the source area (SA) while the top part represents the destination area. Figure 1.1.1 (b) shows a more realistic scenario which shows that the source traffic is drained by three main routes, shown in red color.

In the scenario depicted in Figure 1.1.1 (b), vehicles only leave the source area to the destination via one of the three "main pipes" (i.e., primary roads) and no vehicles can enter these three roads outside the source area. These vehicles may start from the primary roads (PF) in the bottom part of the source area or from one of the road segments inside the source area (SF). Table 1.1.1 shows the values used as frequency, for each kind of route, according to the nomenclature used in Figure 1.1.1 (b).

Table 1.1.1: Simulation setting of MG 16x16 scenario and route frequency for routes starting in the bottom entry of the "primary roads" (PF), and routes starting from anywhere else (SF).

MG 16x16 Setup	
Parameter	Value
Length of a block	125 m
Number of streets	32
Number of lanes in each direction	1
Junction size	2.5 m
Green split	20 s
Yellow split	5 s
Cycle duration	45 s
Number of vehicles	2000-30,000
Route Frequency	
PF	1
SF	PF/5

Main findings

In this section, we present the results of our large-scale simulation. Figure 1.1.2(top) shows the percentage benefit of the VTL scheme over TL scheme for the scenario shown in Figure 1.1.1(b). Namely, a 16x16 Manhattan Grid topology is considered with a source and destination area as depicted in Figure 1.1.1. It is also assumed that most of the rush hour traffic uses 3 major paths (or "pipes") due to several possible reasons (capacity, presence of traffic lights, etc.). While the percentage of intersections equipped with traffic lights is between 15-25% in most cities, in this study with DIVERT simulator, a more futuristic viewpoint is taken and higher percentage of intersections are assumed to be equipped with traffic lights.

Observe from Figure 1.1.2(top) that the percentage benefit of VTL over TL peaks when the number of commuters is around 5,000 and is about 70%. As the number of commuters increases to 25,000 vehicles, the percentage benefit in reducing the average commute time of urban workers reduces to about 45% which is still very significant. From the large-scale simulations it can be observed that the road capacity of the 16x16 MG gets saturated much faster with the regular traffic lights (TL) scheme compared to the VTL scheme which, in turn, reduces the flow rate of TL, thus increasing the average commute time. The VTL scheme, however, delays the saturation phenomenon of the road capacity considerably and full saturation occurs at much higher numbers of commuters. It is interesting to note that the percentage benefit of VTL in reducing the average commute time stabilizes after a certain number of commuters (25,000 in Figure 1.1.2(top)) to about 45%. This benefit does not seem to be too sensitive to the percentage of intersections equipped with traffic lights.

Figure 1.1.2(bottom) depicts the future benefits of the VTL scheme in terms of reducing the average commute time of urban workers. It is assumed that because of the inherent benefits of the VTL scheme, in the 16x16 MG scenario, people will start using all the

other paths as well in addition to the 3 paths (or "pipes") which was assumed in Figure 1.1.2(top). Of course, this may not happen overnight but it will happen over time in an asymptotic manner. The difference in the percentage benefit between Figure 1.1.2 (bottom) which represents the asymptotic benefits of VTL scheme and Figure 1.1.2 (top) which corresponds to the immediate benefits of VTL is quite striking. Observe that the peak benefit occurs for a larger number of commuters (as opposed to 5,000 commuters in Figure 1.1.2 (top)). This confirms the intuition that, over time the unused paths between source and destination will start getting used by the commuters, thus increasing the capacity of the network substantially. Observe that the percentage benefit in terms of reducing the average commute time is about 90% even for 60,000 commuters which is amazing.
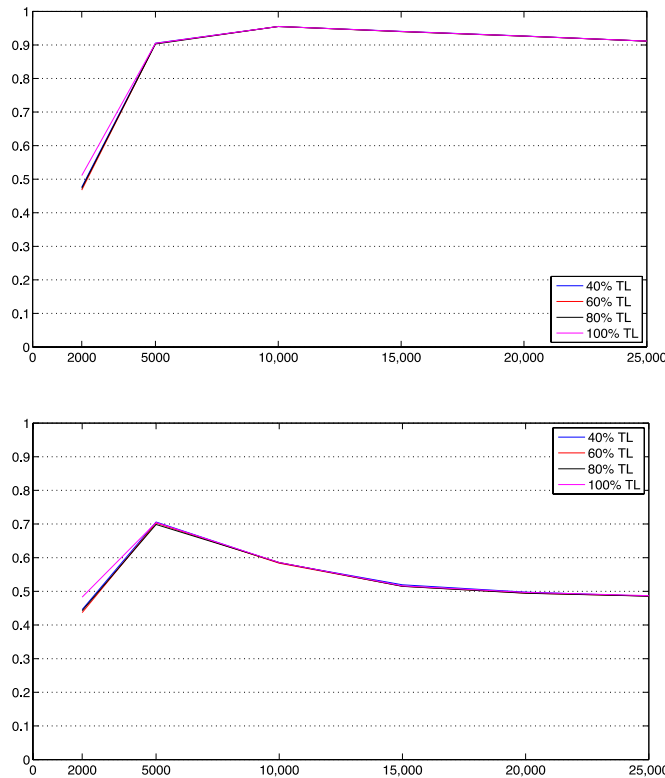

Figure 1.1.2: The Future of VTL

To put the results reported in this report into perspective, it might be important to take a look at the average daily commute time of urban workers in different capitals or major cities. This is shown in Table 1.1.2.

The key results reported in this report show the asymptotic benefits of the Virtual Traffic Lights scheme over the current traffic management scheme (the TL scheme). This asymptotic benefit approaches 100% which shows the potential of the VTL scheme as people start using other routes also over time, as they offer a faster alternative to reaching their destination. .

Ultimately, it is important to understand that the numerical results presented in this report on the future benefits of VTL point to a fundamental property of the VTL scheme: Virtual

Traffic Lights will asymptotically lead to "unclogging of the pipes"" by *dynamic load balancing*.

Table 1.1.2: Daily commute time of urban workers in different capitals or major cities

Mexico city	3 hours
Sao Paulo	2-3 hours
Moscow	> 3 hours
Bangkok	2 hours
Beijing	104 min
London	100 min
Toronto	80 min
New York City	68 min
Los Angeles	56 min
Barcelona	48 min

Conclusions

Average commute times of urban workers in most major cities of the world have gotten steadily worse over the last 5 years. This acute problem needs scalable and cost-efficient solutions. It is shown in this report that a promising new scheme known as Virtual Traffic Lights can reduce average commute times during rush hours by more than 35% and this benefit might approach 80-90% as people opt for alternative routes that they do not use currently. This asymptotic benefit stems from the ubiquitous traffic control enabled by this new scheme.

Acknowledgment

Part #1.2

Based on similar settings, in this part, we analyze the benefit of the Virtual Traffic Lights in a more detailed fashion. To be specific, we focus on the reduction of commute time and how such benefit is distributed to individual commuters.

Key findings

Figure 1.2.1 shows the simulation results obtained using the DIVERT simulator for the 10x10 MG scenario where the commuters prefer the 3 routes (or pipes) going from the source area to the destination. Figure 1.2.1(a) shows the probability distribution of the average commute time of 15,000 commuters during the rush hour for the VTL and the regular traffic lights (TL) scheme. The mean commute time of VTL is 3154.6s whereas the mean commute time for TL is 6838.3s. This corresponds to a 53.87% benefit for VTL with respect to TL. When the number of commuters is 30,000 similar benefits are observed: the average commute time of VTL is 10683.3s whereas the average commute time of TL is 18183.2s (see Figure 1.2.1(a)). This corresponds to a 41.25% benefit when one uses VTL which is quite significant.

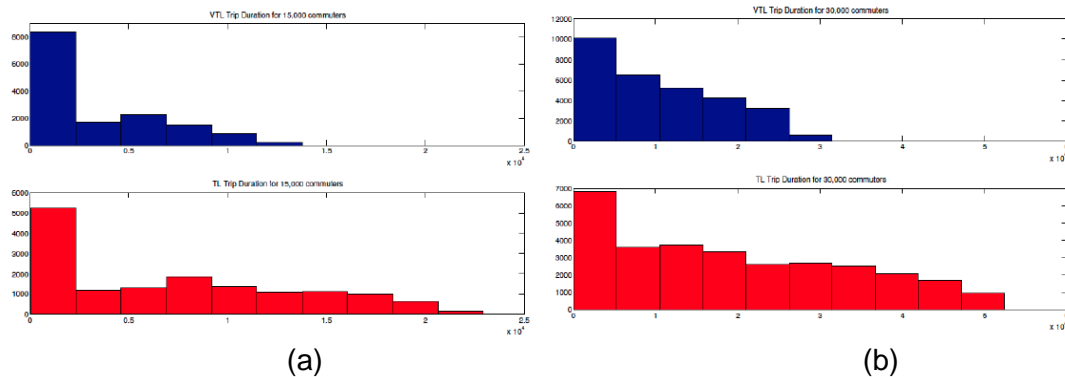(a)   (b)

Figure 1.2.1(a): probability density functions (pdf's) of travel time or commute time for 15,000 commuters. The mean of the pdf's of VTL and TL are 3154.55s and 6383.27s, respectively. The variance of the pdf's of VTL and TL are 5.6510×10^6 s^2 and 1.2166×10^7 s^2, respectively. Figure 1.2.1(b): pdf of travel time or commute time for 15,000 commuters. The mean of the pdf's of VTL and TL are 10683.3s and 18183.2s, respectively. The variance of the pdf's of VTL and TL are 9.8275×10^7 s^2 and 2.4939×10^8 s^2, respectively.

It is also important to look at the second-order statistics of the average commute time. More specifically, Figure 1.2.1(a) shows that the variance of commute time reduces from 1.2166×10^6 s^2 to 5.6510×10^6 s^2 when the number of commuters is 15,000. This corresponds to a 78.47% reduction in the variance which is quite significant. When the number of commuters is 30,000 (see Figure 1.2.1(b)), the variance of commute time is reduced from 2.4939×10^8 s^2 to 9.8275×10^7 s^2 which corresponds to a 60.59% improvement with VTL.

It should also be mentioned that the focus of the work presented is on quantifying the <u>relative benefit</u> of VTL over TL scheme as opposed to computing the absolute values of average commute times. Clearly, the average commute times of urban workers are very different in different cities due to the size of the network area, number of commuters, the social behavior of urban workers, the percentage of intersections equipped with traffic lights.

Based on the specific data pertaining to Pittsburgh and Porto, the scenario considered in Figure 1.1.1 utilized only 3 routes (or "pipes") between the source and the destination. In different cities, this number could be more than 3 routes. Again, extensive simulations conducted with both DIVERT and SUMO have shown that the relative benefit of VTL and TL will not change significantly if the number of routes is more than 3.

Finally, several caveats should be mentioned to avoid possible misconceptions and pitfalls: the benefit of VTL in terms of reducing average commute time does not imply that all commuters get the same percentage benefit. Commuters whose commute involve crossing a lot of intersections between home and work will be the greatest beneficiaries. On the other hand, those commuters who spend a major portion of their commute on a highway and only a small portion of their commute within the city will clearly benefit for less than the former category of commuters. While the commuters in the former category might enjoy a benefit of 60% reduction in their commute time, the commuters in the second category might enjoy a benefit which might be only 10%. If the numbers of commuters in the two categories are equal, then the average benefit for the whole commuter population will be 35%.

Conclusions

Recent studies have shown that commute times of urban workers in major cities such as Mexico City, Sao Paulo, Bangkok, Beijing, Moscow, London, and Toronto have gotten worse in the last 5 years. Longer commute times have major implications on the health of urban workers (psychologically, mentally, physically, and socially). Longer commute times decrease social interaction, and increase stress, blood pressure, and obesity (thus making people overweight) which, in turn, might cause or contribute to heart disease, diabetes, and some cancers. It is thus clear that the repercussions of longer commute times go far beyond the productivity lost and, in fact, is directly related to the health of urban workers.

In this report, it is shown that a new scheme known as Virtual Traffic Lights can reduce the average commute time of urban workers during rush hours substantially. More specifically, results show that more than 30% reduction in average commute time during rush hours can be achieved by using the Virtual Traffic Lights scheme for traffic control. Much work remains to be done for successful implementation of the VTL scheme (both in terms of technology and the required legislation). The benefits outlined and quantified in this report, however, make a compelling case for this new approach which is scalable and cost-efficient.

Acknowledgment

Part 1.3

Study in this part focuses on the comparison between the proposed VTL scheme and existing and pervasive solutions that have been already proposed and implemented to resolve the urban congestion problem. To be specific, the most pervasive congestion pricing solution in which commuters pay directly for use of a particular roadway during a particular time of day is chosen in this study.
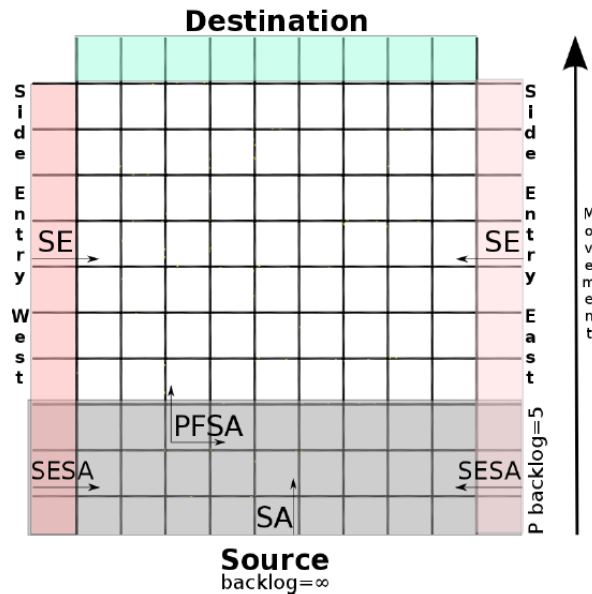
System Model and Parameters

Figure 1.3.1 shows the generic system model used in the simulations. In this 10x10 MG scenario the bottom part presents the source area (SA) while the top part represents the destination area. The source area could be the downtown area in a city where most workers go to for work in the morning and they leave this area in the afternoon rush hours to go to their homes. In the source area, vehicles may enter from the bottom of part of the source area (SA), from one of the road segments within the source area (PFSA), side entry within the source area (SESA), or from the side entry outside the source area (SE).

Figure 1.3.1 depicts the new simulation scenario used for this part of our studies. The objective is to reproduce what typically happens in a real city, where most of the vehicles enter from a main "source area" (this is typically where most of the urban workers and professionals are during the work day), and move towards a common destination, which in the morning rush-hour period, for example, should correspond to a "business area", and during the afternoon rush-hour period should correspond to the residential area where urban workers live. Vehicles/Drivers are then commuters. The simulation model thus follows the practical scenarios as much as possible in an effort to mimic reality. Taking this into consideration, it is only logical to assign different frequencies to each route, considering its entry point, e.g. routes starting in the "source area" (SA in Figure 1.3.1) have a greater frequency than routes starting outside (SE in Figure 1.3.1). In addition, vehicles may also start from one of the road segments within the source area (PFSA) or from the side entry inside the source area (SESA).

In addition, only 16% of the intersections in the scenario depicted in Figure 1.3.1 are

governed by traffic lights. Given that the density of vehicles is much higher in the source area, the traffic lights are randomly placed over the map with 10% of traffic lights in the source area and the remaining 6% over the rest of the map. This assumption mimics what happens in real urban cities such as Porto, Portugal where only 16% of intersections in downtown Porto are equipped with traffic lights. Pre-timed traffic lights are assumed for all equipped intersections with 50-second duration and 50/50 green split whereas stop signs are used for all of the non-equipped intersections.
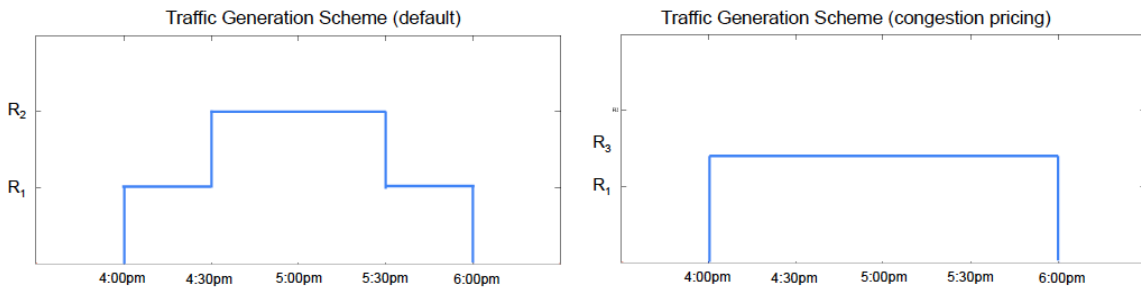

Figure 1.3.2: Step function representing our new traffic generation scheme (left) and constant function representing the traffic generation scheme when the congestion pricing scheme is implemented (right).

It is known that the traffic behavior in the rush-hour period is not constant: there is a first wave of commuters that try to enter/leave the city sooner to avoid traffic jams; this is then followed by the period when most commuters enter/leave, that is, when the traffic generation is higher; and finally another wave with the remaining vehicles. To represent this behavior, one can define a step-function which associates different traffic generation rates to different time slots during the 2 hours of the rush hour. Figure 1.3.2(left) represents our "traffic generation scheme", where the different rates are indicated as R_1 and R_2. Considering again the function in Figure 1.3.2(left), one can see that the area under the Traffic Generation Rate gives the total number of commuter vehicles.

To simulate the effect of dynamic congestion pricing, we assume that in an ideal implementation (i.e., congestion is correctly priced during the peak hours between 4:30pm and 5:30pm), the dynamic congestion pricing will smooth out the traffic generation rate from the step function (shown in Figure 1.3.2(left)) to the constant function (shown in Figure 1.3.2(right)). Note that to compare performance of the congestion pricing and VTL schemes, the total number of vehicles generated within 2 hours in both scenarios is kept constant (i.e., the area under the the two plots is identical). As a result, the rate R_3 at which vehicles are generated in Figure 1.3.2 can be expressed as follows:

$$R_3 = 1.5 \, R_1$$

Results

Figure 1.3.3 shows the simulation results obtained using the SUMO simulator [10] for the 10x10 MG scenario depicted in Figure 1.1.1. The results are presented as a percentage

benefit in terms of trip duration when the traffic light (TL) scheme is used with the step function traffic generation rate (see Figure 1.3.2(left)). Observe from the figure that while the dynamic pricing scheme provides up to 65% improvement in terms of commute time, the benefits can only be gained when the number of commuters is at least 7,000 and less than 20,000. It is interesting to note that when the number of commuters is more than 20,000, the dynamic congestion pricing scheme may lead to a slight increase in commute time.
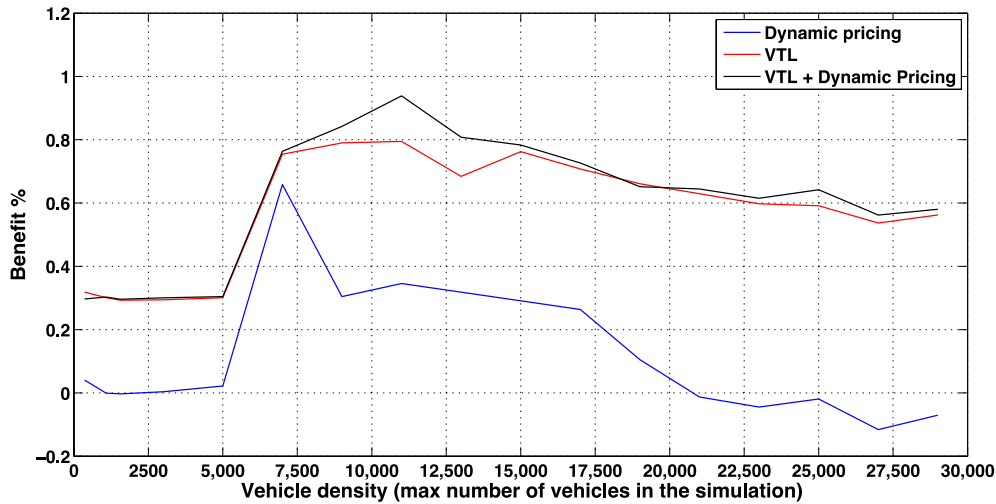

Figure 1.3.3: Percentage benefit in terms of trip duration when dynamic congestion pricing and/or VTL schemes are implemented when the TL scheme with step function traffic generation rate is used as a benchmark scheme.

In contrast to the dynamic congestion pricing scheme, the VTL scheme provides substantial improvement in terms of commute time regardless of the number of commuters and the improvement is far superior to that provided by the pricing scheme (i.e., 36% versus 80% for a scenario with 11,000 commuters).

Massive rural-to-urban migration during the past several decades causes a rapid increase in population in urban cities and is expected to continue in the next decades. There is no doubt that this phenomenon will continue to have an adverse effect on the commute time of urban workers especially in the current tough economic conditions which leave little hope for adequate investment to increase the capacity of road networks to meet the increased demand. Recent studies show that even when solutions such as road-use fee, congestion pricing have been implemented to alleviate traffic congestion, commute times of urban workers in major cities such as Mexico City, Sao Paulo, Bangkok, Beijing, Moscow, London, and Toronto have gotten worse and this problem is bound to deteriorate as the number of cars on the road is expected to double within the next decade.

In this part, it is shown that a new scheme known as Virtual Traffic Lights can be used together or as an alternative to congestion pricing scheme in addressing the severe traffic congestion issue in urban areas. More specifically, results have shown that the VTL scheme can outperform the congestion pricing scheme as it can reduce the commute time by up to 80% whereas the congestion pricing scheme can provide only up to 65% reduction in commute time. Furthermore, it is also shown that benefits of the

congestion pricing scheme is limited (i.e., benefits are observed only in a moderately-dense scenario) while the VTL scheme can provide substantial improvement in terms of commute time in all scenarios regardless of vehicle density. While much work remains to be done for successful implementation of the VTL scheme (both in terms of technology and the required legislation), the benefits outlined and quantified in this report, however, make a compelling case for this new approach which is scalable and cost-efficient.

Part #1.4

Inspired by social insect colonies such as ants, bees, and termites, in this part, we propose a self-organizing network solution to one of the major problems in emergency response management [2]; i.e., facilitating and expediting the motion of emergency vehicles through traffic and/or congestion in urban areas. The proposed scheme is an important new extension of the VTL system described in previous sections. By detecting the presence of an emergency vehicle (EV), the proposed scheme, namely Virtual Traffic Light with Priority Intersection Control (VTL-PIC), assigns priority (e.g., gives right of way) to the road on which the EV travels. To enable the priority scheme, two additional mechanisms (i.e., local rules) are designed and added to the original VTL scheme.

1) Detection of an emergency vehicle when it approaches and leaves an intersection

It is clear that detection of an emergency vehicle is a critical component of the proposed VTL-PIC scheme. In our proposed solution, upon approaching an intersection, the EV periodically broadcasts a PIC request message to announce its presence and demand for priority until it receives a PIC grant message from a vehicle that is leading the intersection (i.e., the intersection leader). Note that in addition to the PIC request message, the intersection leader can detect the presence of the EV when it receives hello message generated by the EV.

Besides PIC request messages, the EV is also required to inform the intersection leader upon leaving the intersection so that the intersection could now resume its normal operation for normal traffic management. A PIC clear message is used to handle such detection. When the EV crosses the conflict point (intersection), it periodically broadcasts a PIC clear message for a certain period of time. In the case when PIC clear messages are lost, the intersection leader can also detect the departure of the EV when it does not receive hello messages from the EV for a certain period of time.

2) Priority assignment scheme

Once the presence of an EV is detected, phase layout configuration of the traffic signals of the intersection needs to be re-computed and broadcast to vehicles involved in the conflict at that intersection. While there are a number of algorithms that could be used for priority assignment, a simple scheme (i.e., the road on which the EV is traveling always gets the green signal) is used in our protocol to illustrate how priority intersection control could be used in conjunction with the VTL system.

Principle of operation

 Figures 1.4.1 and 1.4.2 depict the flow diagrams of an EV and a non-EV vehicle upon approaching an intersection, respectively.

Upon approaching an intersection, an emergency vehicle determines if there is already a VTL set up for the intersection by passively listening to the VTL message broadcasted by the leader. In the case when no VTL exists and no conflict is detected at the intersection, the EV can pass through the intersection with no additional communication. In the case where a conflict is detected or a VTL is already set up, the EV announces its presence and requests priority for right-of-way at the intersection by sending a PIC

request message to the intersection leader.

Note that in the case where the leader has not been elected, the closest vehicle to the intersection that travels in the orthogonal direction to that of the EV is automatically chosen as the leader (see Figure 1.4.2). The PIC request is periodically transmitted until the EV receives a PIC grant message sent from the leader to acknowledge the presence and granted priority to the EV. In the unlikely case where the EV reaches the intersection and has not received a PIC grant message, the EV resorts back to the conventional procedure; i.e., slows down and watches for other vehicles as it crosses the intersection. As soon as the EV leaves the intersection, it broadcasts a PIC clear message to the leader to release the intersection for normal traffic use.
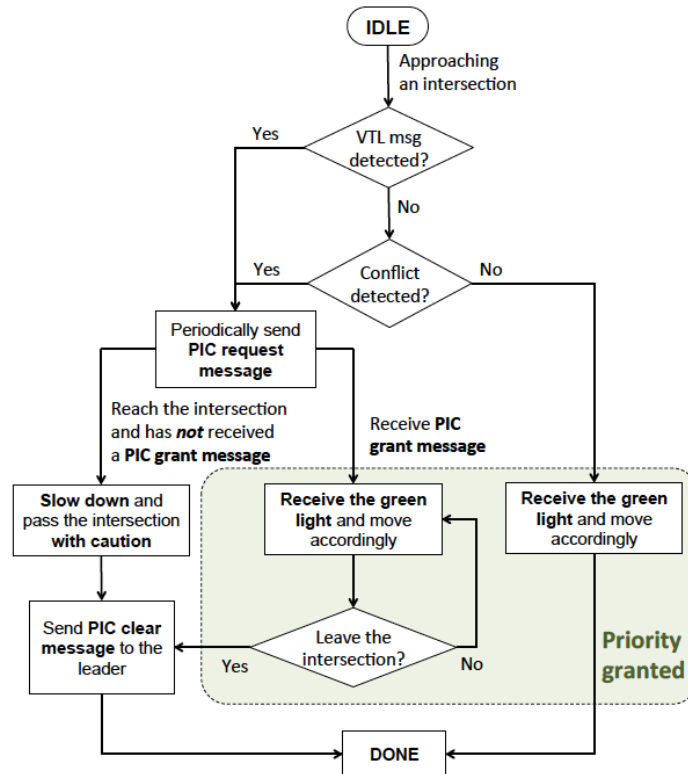

Figure 1.4.1. Flow diagram describing the principle of operation of an emergency vehicle when it approaches an intersection.

Flow diagram of the algorithm used for non-EV vehicles are shown in Figure 1.4.2. When the leader vehicle receives a PIC request message (or a hello message) sent from the approaching EV, the leader determines if it should continue to lead the intersection. In other words, in the case when the leader is traveling in front of the EV and blocking the EV's movement, the leader hands its leading task over to other vehicles. Otherwise, the leader that does not block the movement of the EV continues to lead the intersection, replies to a PIC request message with a PIC grant message. To permit the EV to pass through the intersection, the leader re-computes phase layout of the traffic signals and communicate the new configuration to all vehicles in the intersection. Once the leader detects that the EV leaves the intersection (either through the reception of a PIC clear message or several omissions of hello messages from the EV), the leader re-computes the traffic signal configuration to allow normal traffic management. Upon receiving a PIC request message from an EV, other non-EV vehicles that do not assume the leading task could become the leader in one of the

following two circumstances:

- If there is no VTL currently setup for the intersection, the vehicle elects itself as the intersection leader if it is the closest non-EV vehicle to the intersection.
- If a VTL has been setup for the intersection and the vehicle receives a handover message from the current leader, it assumes the leading task and becomes the new leader.
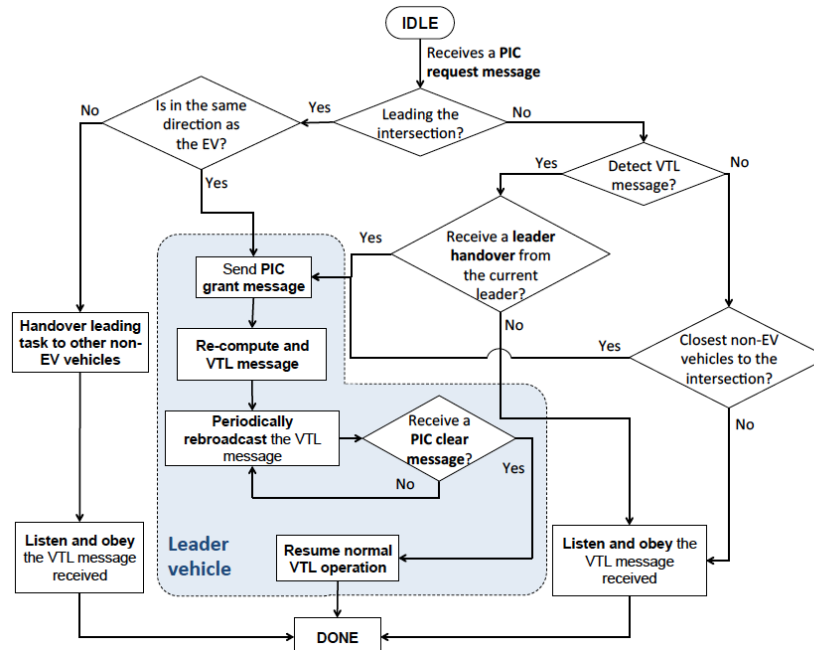

Figure 1.4.2. Flow diagram describing the principle of operation of a non-EV vehicle.

A vehicle that assumes the leading task (or leading role) because of one of the above scenarios needs to transmit a PIC grant message to the EV, computes the corresponding phase layout of traffic signals and broadcasts the traffic light message to all vehicles. Similar to the VTL scheme, other vehicles remain as passive nodes (i.e., they listen and obey to the traffic light message they receive).

Priority assignment scheme
In the proposed VTL-PIC scheme, an intersection leader always gives right of way (i.e., green light) to the road on which an EV is traveling. "Always-green" configuration continues until the EV has left the intersection and normal operation of the VTL-PIC is then resumed.

It is an interesting subject for future study to determine the optimal priority scheme for priority vehicles. It is also possible to extend the priority scheme concept to other types of vehicles such as transit buses, rails, etc. Although the latter does not necessarily correspond to emergency management, it could substantially improve the public transit efficiency [13].

Simulation setting

In order to evaluate the proposed VTL-PIC protocol, we resort to SUMO traffic mobility

simulator, an open-source microscopic simulator developed by the Institute of Transportation Systems at the German Aerospace Center [14]. A 10 X 10 Manhattan grid network topology is assumed in the simulations with 125-meter block length. Traffic generation pattern used in the simulations is depicted in Figure 1.4.3 where the traffic generation rate (e.g., R1 and R2 [veh/hr]) varies based on one of the varying parameters, number of total vehicles injected into the simulations, N. The step function shown in Figure 1.4.3 is used to capture the traffic behavior during the rush-hour period; there is a first wave of commuters that try to enter/leave the city sooner to avoid traffic jams and is then followed by the period when most commuters enter/leave; and finally another wave with the remaining vehicles [11].

Hence, relationship between these three parameters is shown below:

$$R_1 = \frac{N}{3}, \qquad R_2 = 2R_1 = \frac{2N}{3}$$

One emergency vehicle is artificially added into the simulation at t = 5400 seconds (i.e., after 90 minutes since the simulation starts). The emergency vehicle starts from the center of the source area to its destination in the top-right of the network. Note that for a dense scenario, we observe a large backlog time (i.e., time elapsed from the time a vehicle is generated to the time it is inserted into the network). Three different traffic control schemes are implemented and evaluated: i) baseline scheme where only physical traffic lights are used at intersections and an emergency vehicle does not receive any priority at intersections[1], ii) VTL scheme where the virtual traffic light is used as the traffic control mechanism at intersections; however, it does not give priority to the emergency vehicle, and iii) VTL-PIC scheme where both VTL and priority scheme are implemented.
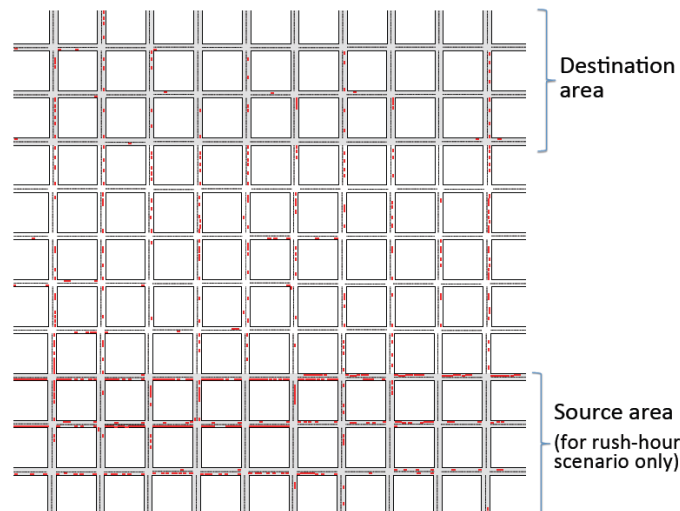

Figure 1.4.3. A 10 X 10 Manhattan grid topology with 125-meter block length is used in the simulations. The bottom 3 X 10 area is the source area where vehicles are injected into the network. Small red dots represent vehicles.

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[1] An emergency vehicle is treated as a normal vehicle. This assumption is valid in a heavily congested urban scenario; vehicles could not move to the side to give way to the emergency vehicle.
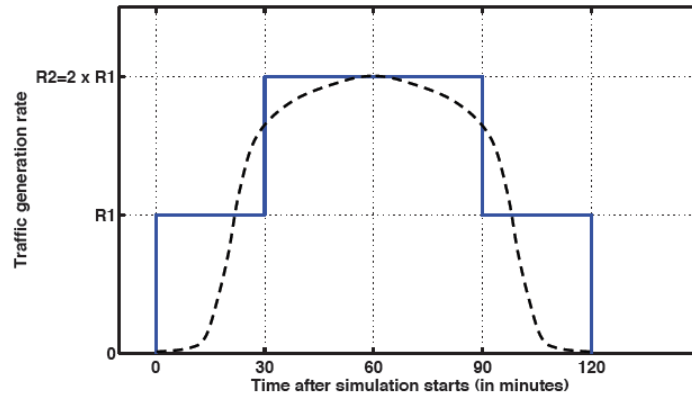
Figure 1.4.4. Traffic generation pattern used in the simulations. While the dotted line shows the realistic traffic generation rate, the staircase in blue color shows the approximation used in the simulations.

Results

Figures 1.4.5 and 1.4.6 show the simulation results in terms of travel time of the EV and non-EV vehicles as a function of total number of vehicles generated, respectively. Observe that travel time of both types of vehicles decreases when the VTL system is in place and the proposed VTL-PIC protocol further decreases the travel time of the EV vehicle. It is worth pointing out that despite emergency vehicle priority, VTL-PIC has little or no effect on the travel time of non-EV vehicles (see Figure 1.4.6).
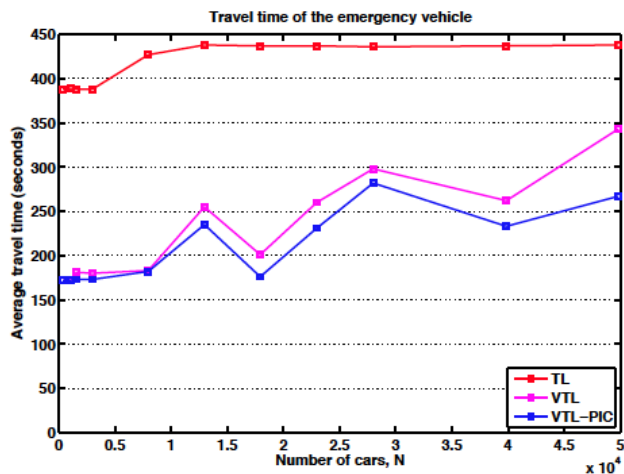

Figure 1.4.5. Average travel time of the emergency vehicle which is inserted into the network at t = 90 minutes during rush hour.
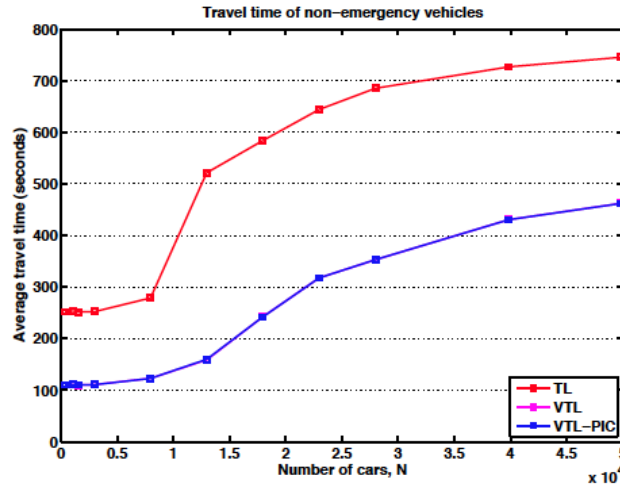
Figure 1.4.6. Average travel time of non-EV vehicles in the rush hour scenario. Observe that there is negligible difference between the non-EV travel time when VTL and VTL-PIC schemes are used.

Related Work

Several approaches have been proposed for priority management at intersections for emergency, municipal, and mass transit buses. These approaches are usually known as Emergency Vehicle Preemption (EVP) systems. While theses systems have been shown through empirical studies to reduce response time for emergency vehicles (EV), all of the proposed schemes rely on some kind of infrastructure and require additional costly equipment to be installed at poles, signal arms, and/or centralized traffic control center; hence, coverage and benefits of such systems are fundamentally limited by the number of equipped intersections.

A. Centralized Control system

Centralized control system is the most basic system where EVP mechanism could be implemented in the most straightforward manner. Examples of such systems include Global Traffic Technologies (GTT)'s OpticomTM Central Management Software [18] and GERTRUDE [19]. In GTT's commercial product, arrival of the emergency vehicles to an intersection is recognized by the traffic signal controller through light, sound, or radio waves depending on the technology used at a particular intersection. Once detected, the centralized urban traffic control software decides if signal preemption is warranted and if necessary, interrupts the normal green-yellow-and-red cycle to change the light to green for the emergency vehicle.

B. Intersection-based system

Another alternative for implementing an EVP is to allow local intersections to make a preemption decision. This system therefore could operate without backbone network connecting all intersections to a central control center; hence, a more scalable solution than the centralized system. Similar to the above approach, as an emergency vehicle approaches a traffic signal, a light-, radio-, or sound-based detection mechanism triggers the traffic signal controller, which is installed at the signal pole and/or arm, to adjust the traffic light pattern. EMTRAC systems [20] and E-ViEWs Safety Systems [24] are the two most prevalent solutions and have been implemented in the States of California, Texas,

Virginia in the USA and Ontario and Quebec in Canada [21-23].

The same system can also be extended to mitigate disaster evacuation, especially in a situation where police-assisted traffic controls are not feasible [23]. However, the emergency vehicles and the intersection are required to be equipped with the specialized equipment at installation cost of $3,000 per vehicle, and $10,000 per intersection. In addition, other proposed solutions such as Peek's UTOPIA network management and control [25], MOBILE [26], and Novax's BUS PLUS Traffic Signal Priority System [13] are based on a similar idea.

Conclusion

We have proposed a self-organized traffic control scheme that helps facilitate emergency response operations (i.e., facilitate and expedite the movement of emergency vehicles through traffic in urban areas). In the proposed VTL-PIC scheme, vehicles communicate among themselves to resolve potential conflicts at intersections and determine a priority scheme according to which roads (or approaches) are given the right of way. Local rules at intersections corresponding to the detection of the presence (and absence) of an emergency vehicle as well as the priority scheme that assigns priority to the emergency vehicles are designed and incorporated into the VTL-PIC scheme. Results also show that the proposed VTL-PIC protocol has a negligible negative impact on the travel time of non-emergency vehicles. For bigger or denser cities, the reduction in travel time of emergency vehicles will be even larger.

It is worth noting that in addition to improving emergency traffic efficiency, the VTL-PIC scheme makes intersections much safer for the emergency vehicles as it always displays green and red lights to the emergency vehicles and non-emergency vehicles in the opposing direction, respectively. The priority intersection control scheme presented here could possibly be extended to handle other priority vehicles such as transit buses, rails, etc. Further research is needed to explore such important extensions.

**Part 2.1:
Effect of RF Obstruction to the VTL system**

I. Executive Summary

Motivated by the idea to reduce deployment costs and to dynamically regulate vehicular traffic flows at intersections, inter-vehicle communications based virtual traffic lights are envisioned to replace traditional infrastructure based traffic lights. According to recent studies, virtual traffic lights are expected to increase traffic flow by up to 60 %. Yet, those studies were based on the assumption of a perfectly reliable communication, i.e., notification messages which signal a traffic light were always received by vehicles located within a certain distance to the sender. Hence, effects such as signal fading or non-line-of-sight conditions due to buildings were neglected. Such effects, however, can have a negative impact on the dissemination of the notification messages. This poster report therefore studies whether these effects lead to significantly larger dissemination delays or not, and whether this increase is crucial for the feasibility of virtual traffic lights. According to the results of this study, the delay is not significantly larger, and virtual traffic lights seem to be feasible under such challenging conditions.

II. Introduction

Various inter-vehicle communications based traffic telematics applications are envisioned to improve the safety level and the efficiency of road traffic. While active safety applications aim to warn drivers of imminent dangers within their close vicinity, traffic efficiency applications intend to improve the traffic flow on a much larger scale; hence efficiency applications tolerate significantly larger information dissemination delays than safety applications. In most of the envisioned applications, there is a clear relationship between the objective of the application and its requirements. However, there is one example which on the one hand aims to improve traffic efficiency, but on the other hand suffers from the same time-critical requirements as safety applications: dynamic intersection traffic management based on virtual traffic lights (VTL). Instead of regulating road traffic using traditional traffic lights with a fixed signaling schedule, virtual traffic lights are implemented in a distributed manner by vehicles themselves, and allow to self-adapt the signaling schedule with respect to the current traffic volume. While the introduction of virtual traffic lights reduces the cost of intersection management since no dedicated infrastructure has to be deployed, their usage may add a new safety risk if a robust and reliable operation is not guaranteed. For instance, if vehicles do not agree on one traffic signaling schedule, or if individual vehicles do not receive red light notifications early enough, conflicting and possibly dangerous driving maneuvers may be the consequence. Hence, VTL should only be implemented if a controlled and reliable operation can be ensured.

Recently, authors of [1] and [2] presented a decentralized approach to virtual traffic lights. In their two-step approach, vehicles first have to agree on a virtual traffic light leader whenever they approach an intersection. This leader then adopts the role of a temporary virtual infrastructure, and broadcasts the traffic light schedule to neighboring vehicles.

Eventually, this leader hands over the leadership to another vehicle and passes the intersection once it receives a green light notification. According to the results presented by the authors, this approach is able to increase traffic flow in urban areas by up to 60% in comparison to traditional intersection management. However, their evaluation is based on optimistic and ideal assumptions, i.e., they neglected the existence of radio obstacles, and considered a perfect communications system based on which every

broadcast message is received by every vehicle within a certain distance. Apparently, the assumptions made in [2] are not realistic. For instance, as measurement campaigns have shown, e.g., in [27-31], non-line-of-sight (NLOS) conditions do exist at most intersections in urban or suburban environments. Hence, a perfect and reliable delivery of messages "around the corner" cannot always be assumed. Further, concurrent packet transmissions by multiple vehicles might further reduce the communication performance due to resulting packet collisions.

As a consequence, one cannot rely on the successful reception of every single message, which can lead to the situation that either the election process does not succeed in time, or traffic signaling messages are not received in time. In this poster report we therefore study the feasibility of a virtual traffic light application under NLOS conditions, i.e., in urban and suburban environments. In particular, we provide an answer to the question whether NLOS conditions and signal fading prohibit a timely election of the virtual traffic light leader.

III. Background

In this section we first briefly describe the general concept of VTL as presented by Ferreira et al. (refer to the original paper in [2] for more details). Then, we discuss the impact of realistic communication effects such as radio obstacles and signal fading.

General Concept
According to [2], the overall process of VTL is divided into two phases: Election of a VTL Leader and Handover of VTL Leadership. In order to support the VTL application, in particular the first stage, all vehicles are assumed to periodically broadcast Content Awareness Messages (CAM). Such messages contain at least the own position and driving direction, such that each vehicle is able to establish mutual awareness. Further, the own VTL status is included.

For the election of a VTL leader possible candidates (denoted as cluster leaders) are determined for each road segment that leads towards the intersection. The cluster leader is defined as the vehicle which is closest to the intersection (in comparison to all other vehicles in the same cluster). Each cluster leader is a candidate for the VTL leader role and follows the same rules to decide whether it is going to be the VTL leader or not. Namely, a cluster leader ensures that at least one more conflicting vehicle is approaching the intersection and checks that the conflicting cluster leader is closer to the intersection, so that the vehicles that are already closer to the intersection get a green light in order to avoid hard braking or a possible accident. If above conditions are fulfilled for one of the candidates, it adopts the VTL leader role, and takes control. During the control period, the VTL leader schedules the flow of all other clusters, and changes the traffic light signals if no vehicles remain to be scheduled, or if the time slice has expired. In the latter case, VTL leader needs to handover its VTL leadership.

During the handover the current VTL leader selects a new leader out of the existing cluster leaders. Shortly before handing over the control, the current VTL leader assigns a green signal to its own cluster to continue his travel, and a red signal to the cluster of the new VTL leader.

Impact of Realistic Communication Effects

As already stated, fading channel and radio obstacles may influence the performance and feasibility of a virtual traffic light system. While it is usually not safety-critical if vehicles in a cluster initially disagree on the current cluster leader, it is critical if VTL leadership is adopted too late or not at all as vehicles would be unable to react accordingly. In the following we will thus only focus on the VTL leader election itself, as the corresponding communication conditions are generally worse, compared to handovers or traffic light signal distribution (where occasionally even line-of-sight can be assumed).

IV. Evaluation

As the focus of this work is not the evaluation of large scale traffic efficiency improvements by VTL, but instead to investigate whether VTL is feasible under NLOS conditions, we limit the scope of the evaluation to a scenario with only one intersection. An analytical approach is used to assess worst-case conditions, whereby a simulation based evaluation, with a more realistic modeling of protocol and driver behavior, allowed us to stress different aspects of VTL. For our scenario we took a typical representative city intersections. It consists of a regular, single lane, 4-way intersection with an inter-building distance of 22 m. Radio propagation was modeled using the VirtualSource11p NLOS communication model [27]. Note that the difference between the urban and suburban1 configuration for the radio propagation model is an additional path loss of 2.94 dB with suburban settings. The evaluation itself is based on the following metrics:

- VTL leader election distance [m]: the distance at which the coordination of the VTL protocol is finished and a vehicle declares itself as the VTL leader. Consequently, it is a lower bound distance of when a driver is signalized to stop.
- Required deceleration [m/s^2]: This metric can be directly deduced from the distance at which a driver is signalized to stop and the vehicle's speed. It indicates the minimum deceleration value a driver has to achieve on average in order to be able to stop before the intersection. It can be viewed as one indicator of the safety state a driver is in.
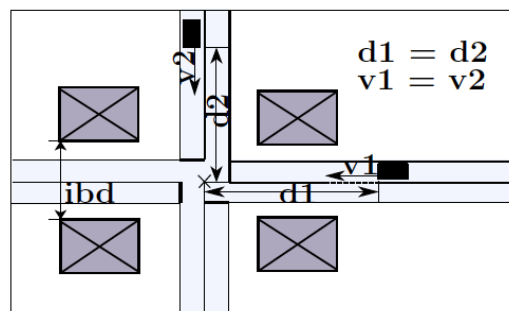
Results

Figure 2.1.1: The worst-case scenario layout. Speed and distance to the intersection crossing of both vehicles are exactly the same. Inter-building distance (ibd) is equal to 22 m.

In the following, we present an analytical evaluation of the worst-case scenario. This scenario consists of two vehicles on perpendicular roads that are simultaneously approaching an empty intersection, as depicted in Figure 2.1.1. In this setup no VTL leader is already existent and the communication conditions are worst due to both vehicles being equally far away from the intersection. Since both vehicles are

respectively their own cluster leaders, a vehicle becomes aware of its status as being the designated VTL leader the first time a CAM message from another vehicle is received. Figure 2.2.2 depicts the probability that at a certain distance to the intersection at least one CAM message was received. We are hereby considering packet generation rates of 4 Hz and 10 Hz (corresponding to beacon messages every 250 ms and 100 ms, respectively), as well as urban and suburban communication conditions. It can be clearly seen, that under the condition of synchronously approaching vehicles i) no communication at distances of more than 90 meters from the intersection is reasonable; and that ii) at a distance of 40 meters there is a high probability that a vehicle is aware of its status as being the VTL leader.
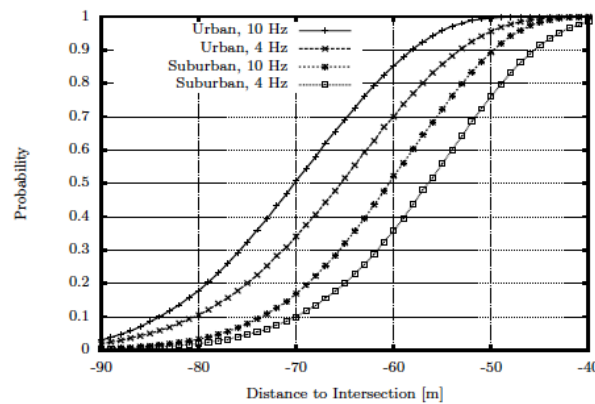

Figure 2.1.2: Probability of receiving at least one message from a vehicle on a perpendicular road, equally far away from the intersection, until distance x

The distance at which a vehicle becomes aware of its status as VTL leader is equivalent to the distance at which the corresponding driver is signalized to stop. Hence, one can calculate the required deceleration of the driver in order to be able to stop before the intersection. The required deceleration of the VTL leader is the maximum over all vehicles, since it is the closest vehicle to the intersection. In Figure 2.1.3 we plot the resulting required deceleration for various communication settings. As can be seen, the required deceleration decreases rapidly for every setting and even in worst case considered communication conditions reaches zero with non critical values and does not exceed -3 m/s^2. The analytical assessment is affirmed by our simulation results, with better overall results. Due to space restrictions, however, we are only able to briefly outline some simulation-based results.

- The probability of a vehicle being aware of its status as designated VTL leader at a certain distance is in general higher. This is due to the fact that, contrary to the analytical worst-case assumption, cluster leaders are in general not simultaneously approaching an intersection. As an example: The probability of being aware of the VTL leader status is increased from about 52 %(Urban, 4 Hz) at a distance of 65 meters (see Figure 2.1.2) to 89% over all simulated scenarios.

- On average, 16 out of 100 simulated vehicles become a VTL leader, whereby only 6 "regular" leader elections take place and 10 handovers are performed. Handovers are in general less critical than regular elections, since i) the old VTL leader is in close vicinity to the intersection and ii) even line-of-sight conditions can be assumed for several seconds while the old VTL leader is at the center of
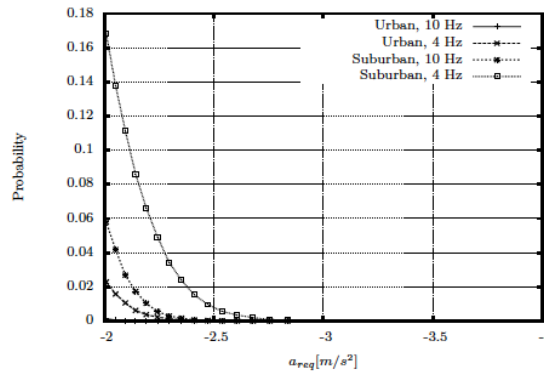
the intersection.

Figure 2.1.3: Minimum required deceleration values the designated VTL leader has to achieve in order to be able to stop in front of the intersection

V. Summary

In this report we investigated the feasibility of virtual traffic lights in a basic intersection scenario that exhibits NLOS conditions. While previous studies have shown that the VTL concept works and is feasible in a "perfect world", NLOS channel conditions, as they exist in the "real world", may lead to a different outcome of the assessment.

According to the results shown in this report, the expected impact of NLOS conditions on the performance of VTL can be confirmed. However, the results indicate that this impact is not significant and that NLOS conditions do not prohibit a timely detection and the possibility to take appropriate actions. In particular, the results show that the traffic flow regulation starts early enough so that all vehicles become aware of the current traffic signal schedule in time. Hence, each vehicle is able to react and adhere to the instructions given by the VTL leader. While these results show the feasibility of Virtual Traffic Lights under NLOS channel conditions, further research is needed to cover all the possible scenarios and other sources of impairment.

Part 2.2:
Fault-Tolerant VTL system

I. Executive Summary

Virtual Traffic Light (VTL) systems are envisioned to enable efficient intersection management in the absence of physical traffic lights. By using the onboard communication devices, VTL systems mimic the functionality of traditional traffic lights through the concepts of cluster and intersection leader election and handover. For VTL systems to be safe intersection mediators, procedures need to be implemented that ensure safe behavior in case of faults. In this report, we explore fault-tolerance and fail-safety (FSFT) concerns in Virtual Traffic Light (VTL) systems. We develop a methodology for FSFT design in VTL systems, as well as several fault-handling procedures. Specifically, we analyze the behavior of VTL under: 1) varying and detrimental propagation characteristics; 2) vehicle location uncertainty; and 3) leader contention, disappearance, and failure to handover. We thoroughly validate the proposed FSFT procedures by implementing the procedures and the VTL algorithm in a realistic network and traffic simulator. Our results show that the VTL algorithm is inherently resilient to location uncertainties. We also show that safe VTL operation is possible in case of poor propagation conditions, and that unacknowledged leader handovers can be handled elegantly.

II. Introduction

Virtual Traffic Lights (VTL) is a biologically-inspired solution for reducing traffic in a decentralized manner. It was shown in that VTLs can reduce travel times by as much as 60% under ideal conditions. Additionally, the work in showed that safe VTL operation is feasible in non-line-of-sight environments, with gradual degradation under deteriorating propagation characteristics. However, less work has been done to study other possible failure modes, how to detect them, and how to ensure that the system remains safe when they occur. It is these considerations that we aim to explore. VTL systems have the potential to significantly increase traffic flow rates, especially at high vehicle densities.

However, they can only be adopted if intersections reliant on VTL can be made at least as safe as regular ones. If a VTL intersection can be shown to be even safer than a standard intersection, then adoption of the VTL system would be even more logical.

In order to be as safe as regular intersections, a realizable VTL system must be both fail-safe and fault-tolerant. That is, it must be able to detect any fault conditions and, when necessary, default to a "safe" operating state (e.g., presenting a blinking red light to all drivers at the intersection). In most situations, it should be able to solve a detected fault in an efficient and natural manner. For example, operating in a low-range wireless network environment presents unique challenges to the design of a VTL system. Connectivity could fail if the wireless link is unavailable; therefore a VTL system must be able to detect this and similar conditions (e.g., radio failures, vehicle location inaccuracies, malicious behavior, etc.). In addition, VTL-equipped intersections must be able to provide priority access to emergency vehicles. They could also provide safety functionality that non-equipped intersections cannot, such as giving priority to vehicles that cannot stop (e.g., due to icy road or a brake failure).

The focus of this report is twofold: 1) evaluating how various faults affect the performance of the VTL systems; and 2) designing and evaluating fault-tolerant procedures that ensure a safe operation of VTL systems. First, we identify possible faults and the inputs that can be used to detect them. Next, we implement the VTL

protocol in a realistic simulation environment and evaluate its performance in the presence of faults (e.g., detrimental propagation, location uncertainty, leader selection contention, etc.).

We design robust and computationally manageable fault-tolerant procedures that implement the conditions for transitioning between different states of the VTL system, including fail-safe states. If certain inputs are received, the procedure either attempts to recover to the normal state or transition to the fail-safe state if no normal state can be reached. We show that, by implementing the proposed procedures, the VTL system can reliably detect failures and prevent adverse consequences. We also explored the impact of safety considerations on the performance of VTL in terms of vehicle throughput and travel times. The results showed that safe functioning of the VTL systems can be achieved while incurring only a low cost in terms of efficiency.

In this work, we are not considering negligent drivers. No amount of built-in fault-tolerance will provide desired safety if drivers ignore the traffic lights, whether the lights are physical or virtual. Furthermore, our focus is not on security concerns due to malicious drivers. Rather, we focus on ensuring the safety of the VTL system in case of non-malicious faults (i.e., faults not due to human misbehavior).

III. Virtual Traffic Light Overview

Before describing the potential faults in a VTL system, we take a closer look at how the system is intended to function under nominal conditions. Figure 2.2.1 shows the state machine diagram for a VTL-enabled vehicle. The abbreviations in the subsequent text can be found in Table 2.2.1.

CL	Cluster Leader
CT	Communication Threshhold
ET	Election Threshhold

TABLE 2.2.1: Some abbreviations used to describe the states.

Below we briefly describe possible actions in each of the states shown in Fig. 2.2.1 (note that each vehicle is initialized in the Slave state).
- Slave
    - Passively listen to VTL state
    - If in front of cluster, transition to CL Before CT or CL Leader Init states
- CL Before CT (Communication Threshold)
    - Continue until within VTL intersection range, then transition to CL Leader Init
- CL Leader Init
    - Perform leader election amongst other Cluster Leaders
    - If elected VTL Leader, transition to VTL Leader.
    - Otherwise, transition to CL Passive
- CL Passive
    - Continue through intersection, then transition to Finished
    - If selected by the VTL Leader for the handover, transition to VTL Leader
- VTL Leader

- o Give own lane red light, and other appropriate lanes a green light
- o After specified time interval or when there are no conflicting cars, transition to VTL Leader Handover
- VTL Leader Handover
  - o Broadcast next VTL Leader's identity
  - o When new VTL Leader acknowledges handover, transition to CL Passive
- Finished
  - o Have no more influence on or effects from this intersection
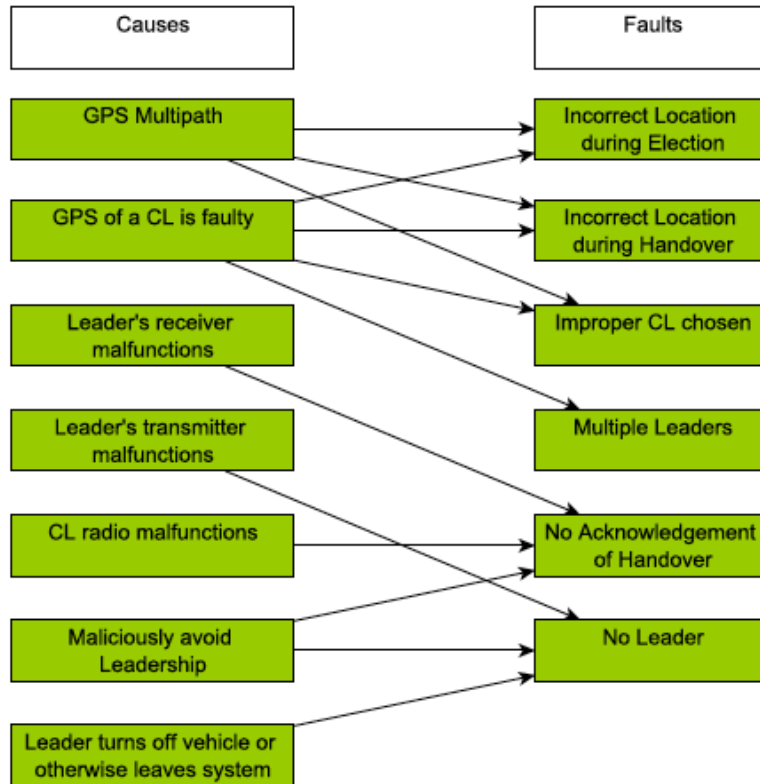 - o If necessary, begin process for next intersection

Figure 2.2.1. The left column shows possible causes that can cause failures in the right column.

IV. Fault Analysis

Approach to Fault-Tolerant Design

Attempting to enumerate every possible scenario which could arise in a faulty VTL would be infeasible. Instead, we distinguish the causes of faulty behavior and the effects of those causes (i.e., the actual faults). As shown in [2], a fault can be caused by different events. We group similar faults and look at the effect they have on the system. Since the strategies for making VTL systems failsafe and fault-tolerant rely on how the faults affect the system, and not what caused them. To that end, we identify the most common and the most destructive faults in the system, and we examine them. Figure 2.2.1 shows that there are many possible causes of a single failure. Below we discuss in more detail each of the failures and how it is handled.
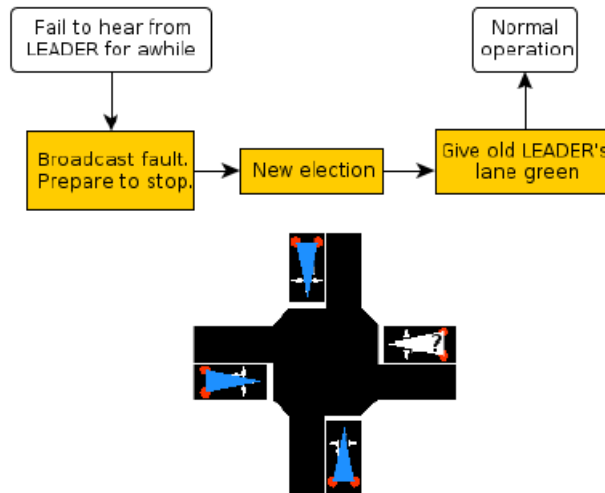
Fig. 2.2.2. Handling VTL Leader disappearance.

Leader Disappearance

Most of the faults are related to the VTL Leader. The first of these is a situation in which there is an established VTL Leader, but that vehicle is removed from the system for some reason (e.g., vehicle leaves the system or its radio malfunctions). We can see a diagram for resolving this situation in Figure 2.2.2.

Vehicles will passively determine if the VTL Leader has disappeared. The vehicle which first notices the disappearance of the leader (e.g., due to a lack of periodic VTL messages) alerts other vehicles. This ensures that all vehicles become aware of the potential fault, and are prepared to stop if necessary. This may require temporarily setting all lights to yellow or red. The Cluster Leaders then begin a new leader election process, which would imply them re-entering the CL Leader Init state.

After a new Leader is elected, it gives the right-of-way to the old leader's lane (since it may be malfunctioning, we don't want other vehicles proceeding.) After a preset amount of time, the VTL continues normally under the new Leader. If the old leader's lane fails to clear (based on the movements of any other cars in that lane) then the system enters the fail-safe state.

Location Uncertainty during Leader Election

During the normal leader election process, uncertainty in the Cluster Leaders' location information can be a problem. This is because the CLs' distance from the intersection is important when determining who is best suited to be the Leader, both for safety and efficiency. A location inaccuracy can be noticed by any sudden jumps in location, or any significant differences between the current GPS measurements and the estimated position based on previous GPS and speedometer measurements. If the GPS seems to be inaccurate, the estimated location based on the other instruments could be used to detect the anomaly.
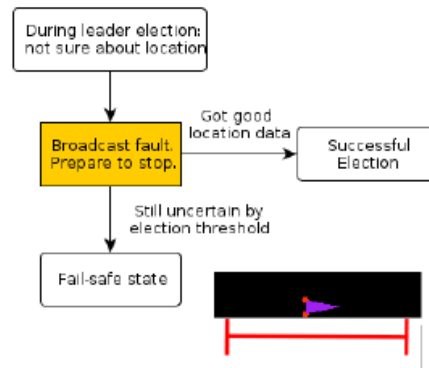
Figure 2.2.3: The finite state machine for a fault in which some Cluster Leader location information is uncertain during the leader election phase.

Figure 2.2.3 shows a resolution scheme for this situation. First, when a CL notices the location variance, it should alert the other CLs. Similarly to the "Disappearing Leader" fault, all vehicles should be prepared to stop, which could involve changing the VTL lights accordingly. If at least one CL has accurate location information on the other CLs, then the election can proceed normally under that CL's direction. However, if the uncertainty remains, then as the vehicles approach the intersection they will all begin to slow down. With smaller inter-vehicle distances and lower velocities, location information should be completely resolved and the election process can resume normally. If, however, the uncertainty remains, then a failsafe state must be entered.

V. Simulation

We use simulations to evaluate the fail-safe and fault-tolerant procedures described in previous section in terms of preventing dangerous situations. We also determine the added delay the fault-tolerant VTL incurs when compared to VTL. For this purpose, we implement the VTL system and the fault-tolerant procedures in the OVNIS Platform, which integrates the SUMO traffic simulator and ns3 network simulator. The bulk of the logic of fault-tolerant procedures has been implemented in the VTL Vehicle and VTL Packets class. The details on the methods and fields in the VTL Vehicle and VTL Packets class are shown in Appendices A and B, respectively.

Standard	802.11p
Maximum communication range	100 m
Constant speed propagation delay	c
Receiver sensitivity	-96.0 dBm
CCA threshold	-99.0 dBm
Tx Gain	0 dB
Rx Gain	0 dB
Nominal Tx Power	16.02 dBm
Log-distance path loss:	
PL_0	47 dB
d_0	1 m
Path loss exponent	3
Nakagami fading:	
Shape parameter	1.5 or 0.75 (depending on distance)

TABLE 2.2.2: Network simulator parameters

Our simulation uses the well-known ns3 model YANS to simulate the 802.11p network. Log-distance path loss with Nakagami fading was chosen as a good approximation for

urban environments. Numerical values for the network simulator parameters are given in Table 2.2.2. For each scenario and parameter value, a single 2000 second simulation was performed. The mobility model parameters are based on SUMO defaults (car following and deceleration) with reasonable speed limits for each scenario, and are shown in Table 2.2.3.

Car-following model	SUMOKrauß
Cross intersection:	
Speed	35 mph
Maximum deceleration	5 m/s^2
4x4, 125 m Manhattan grid:	
Speed	25 mph
Maximum deceleration	4.5 m/s^2

TABLE 2.2.3: Mobility model parameters

VI. Results

When running tests in the simulation for the faults and fault-tolerance procedures, we seek to determine the effects on both the safety and the efficiency of the system. To evaluate the safety, we measure the required deceleration of vehicles in the system. A higher deceleration implies that the system is less safe. According to the US Department of Transportation, vehicles designed to hold less than 10 passengers must be able to decelerate at a rate of 6.4m/s^2. For all vehicles, the deceleration must be at least 4.26 m/s^2. Any situation where the maximum required deceleration is higher than these thresholds is unacceptable from a safety perspective. To evaluate the efficiency, we measure the average time for a vehicle to travel from its source to the destination. A lower average time implies that the system is more efficient. The bounds (red) were calculated assuming a normal distribution. That is, the bound is calculated as the sample mean (blue) plus or minus twice the sample standard deviation.
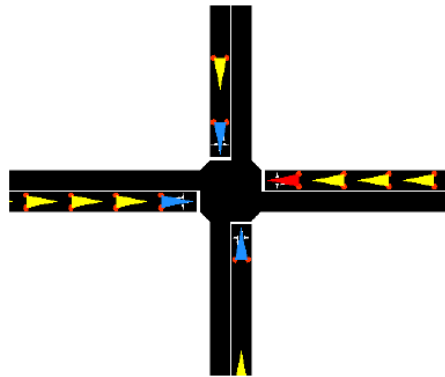

Figure 2.2.4: A screen shot from our simulation. The leader is red, cluster leaders blue, and the yellow cars are slaves.

GPS Inaccuracies

Our inducement of GPS inaccuracies is based on the following assumptions. First, we assume that the vehicle is equipped with a map-assisted GPS device. This is a reasonable assumption, given that we are assuming that vehicles are equipped with both VTL and GPS devices in the first place. The important effect of this assumption is

that location errors occur only along roads and not across different roads. In other words, we assume that the GPS can detect and report when a vehicle "jumps" from one road to another. Furthermore, we assume that GPS errors are zero mean Gaussian random variables independent of each other.
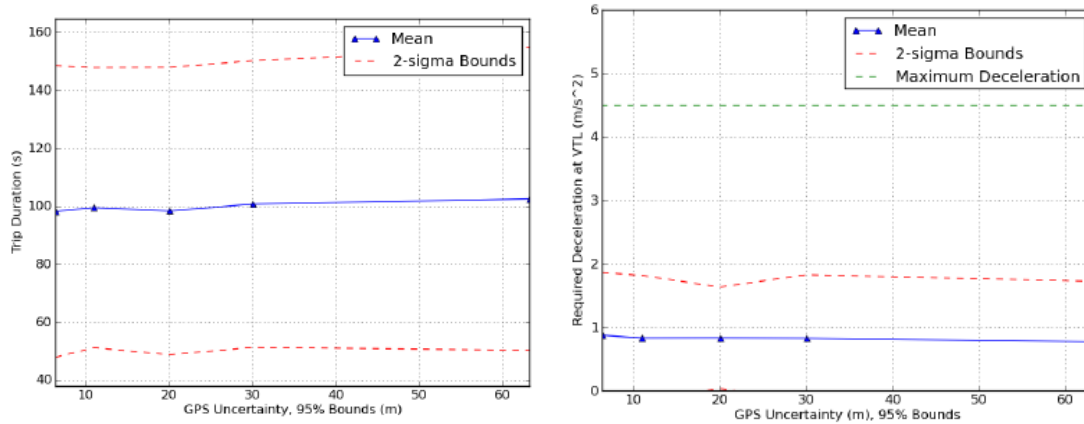

Figure 2.2.5: Average trip duration (left) and safety of the system (right) in the presence of GPS inaccuracy: single intersection scenario. No additional fault tolerance procedures.

In Figures 2.2.5, we see the results with respect to different GPS error variance in a single intersection simulation. These results are without the proposed fault-tolerant procedures for handling GPS errors, yet we see that the GPS inaccuracies have no effect on either the overall efficiency or the safety. This implies that the VTL algorithm itself is already resilient to faulty GPS systems and requires no extra fault tolerance procedures, at least for good propagation conditions. The reasons for such good performance are quite informative. Regular traffic lights have little or no knowledge about the locations and positions of vehicles; safety is ensured by the design of the traffic signal program's timing. In VTL systems, a valid phase and timing are chosen as soon as vehicles detect that there is a conflict. Hence safety is not much affected by GPS inaccuracies; it is determined almost entirely by propagation characteristics. Efficiency depends mostly on making good choices on which flow to let go, based on the size of clusters. This does not depend on GPS information; Cluster Leaders just count the number of vehicles in their lane (which is assumed to be known with reasonable accuracy). This results in GPS inaccuracies not affecting the efficiency.
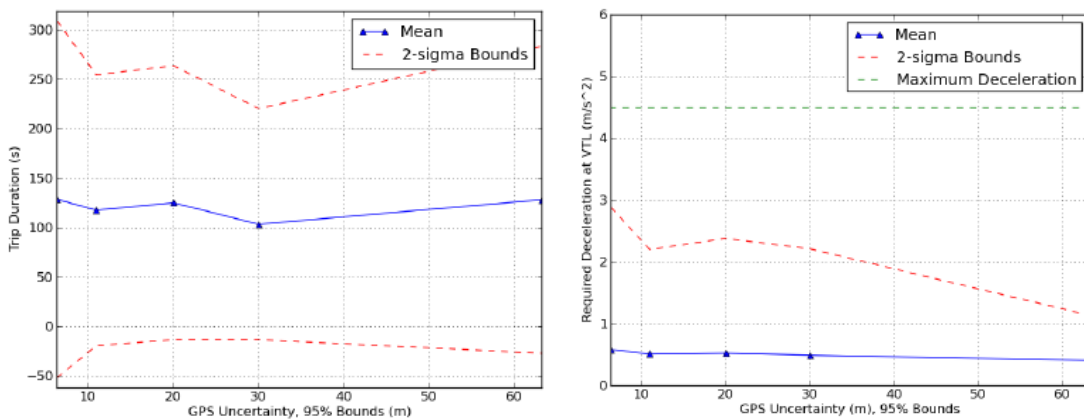
Figure 2.2.6: Average trip duration (left) and safety of the system in the presence of GPS inaccuracy: multiple intersection scenario. No additional fault-tolerance procedures.

In Figures 2.2.6, we see the results for the larger, Manhattan-style road layout. We see that the results from the single intersection also hold for this scenario, i.e., the VTL algorithm is robust to GPS inaccuracies.

Propagation Limitations

While not necessarily a direct "fault," it is important to determine how robust the VTL is when the effective transmission range reduces. In Figures 2.2.7, we see the results of limiting the distance at which vehicles can communicate. Figure 2.2.7 shows that the required deceleration decreases linearly while the bounds converge with increased transmission distance, since vehicles are aware of the need to stop sooner. The results reported in [32] showed that the minimum effective communication range, even in case of non-line-of-sight communication, is at least 40 m. We see that near the expected minimum communication distance (40 m), some vehicles within the two standard deviation bounds must decelerate faster than their allowed deceleration. We note, though, that this can occur at all times in a normal traffic light. Since standard traffic lights make no distinction on changing the phase even if a car is almost entering the intersection, this can result in many vehicles entering the intersection during a yellow light, sometimes still in the intersection when they have a red light. So this safety concern is not newly introduced by the VTL system. Therefore, the deteriorating deceleration results for distances below than 40 m are not a reason for considerable concern. Figure 2.2.7 shows that the efficiency remains mostly constant as the effective communication distance varies.

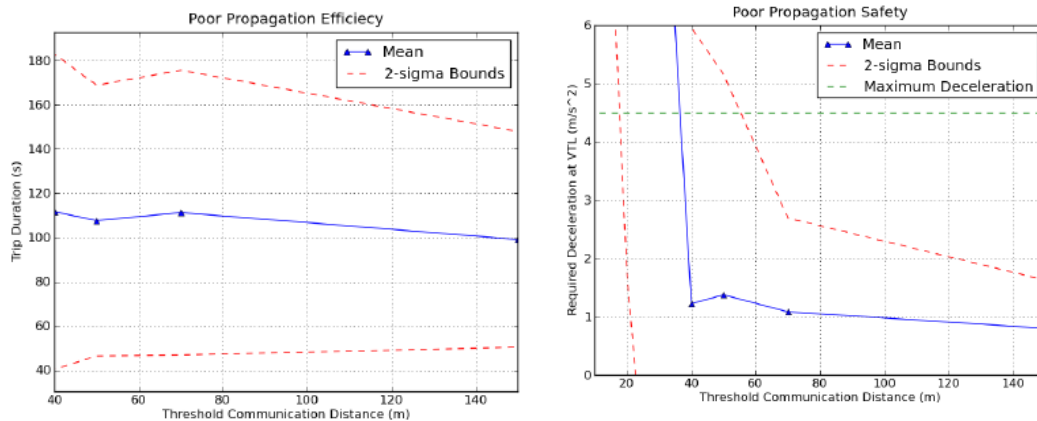Figure 2.2.7: The efficiency (left) and safety (right) of the system with varying communication distances on a single intersection.

VII. Conclusion and Future Work

In this report, we examined the Virtual Traffic Light system with respect to faults that may occur in a real-world scenario. We formalized the VTL algorithm and the faults that could occur. We then implemented some of the most prominent faults (failed handover, VTL

Leader and Cluster Leader contention, and GPS uncertainty) in a realistic simulation environment.

We found that for some faults, such as GPS inaccuracies, the basic VTL algorithm is robust enough such that the errors do not affect the efficiency or safety of the system. For other faults, such as the VTL Leader handover process failure, our proposed fault-tolerant procedures are enough to ensure that the safety and efficiency remain mostly unchanged even with unrealistically high number of failures.

Lastly, we see that under certain conditions, some faults may be less safe than desirable, although these are unlikely to be more dangerous than a normal traffic light. We found very poor propagation in a single intersection to be one of these less safe situations, given the settings of our simulations. In other situations, such as in a downtown grid of roads, the VTL is robust against these faults, and shows potential to be more safe than a normal intersection. Although we tested what we believe to be the most common and important faults, in the future we wish to implement and evaluate more faults and fault-handling protocols. We also plan to implement the system using a more realistic propagation model (e.g. one that accounts for road geometry explicitly) and a more realistic GPS error model (possibly based on experimental data). We also plan to test the VTL system when all faults and the handling procedures are present instead of looking at the effects of each fault individually. This will be especially important for validating our finding that the VTL algorithm is inherently robust against location   uncertainty.

**Part 3.1:
Solution to the Partial Penetration Problem**

I. Executive Summary

Deploying Roadside Units (RSUs) for increasing the connectivity of vehicular ad hoc networks is deemed necessary for coping with the partial penetration of Dedicated Short Range Communications (DSRC) radios into the market at the initial stages of DSRC deployment. Several factors including cost, complexity, existing systems, and lack of cooperation between government and private sectors have impeded the deployment of RSUs. In this report, we propose to solve this formidable problem by using a biologically inspired self-organizing network approach whereby certain vehicles serve as RSUs. The proposed solution is based on designing local rules and the corresponding algorithms that implement such local rules. Results show that the proposed approach can increase the message reachability and connectivity substantially [33].

II. Introduction

Successful deployment of vehicular ad hoc networks (VANETs) where information (such as traffic, road information or safety messages) is sent, forwarded, and received by vehicles depends on the adoption of the new wireless technology, namely the Dedicated Short Range Communications (DSRC) technology. Since it is anticipated that the DSRC technology might be a mandate for modern vehicles effective 2017, with high probability, vehicle-to-infrastructure (V2I) communications-based networks will be the first type of vehicular ad hoc networks (VANETs)[2] that might be implemented and, as such, they could accelerate the adoption of the DSRC technology.

Besides V2I applications (e.g., Internet Access), additional infrastructure can also be used to improve connectivity of vehicle-to-vehicle (V2V) networks. In addition to growing demand for V2X traffic[3] and the fact that V2V applications are confined to a particular geographical area, installing special Roadside Units (RSUs) has emerged as an attractive solution (especially to the Department of Transportation) for providing infrastructure support as RSUs limit information to be disseminated within a confined area, thus resulting in smaller message delay, better information security, and possibly lower communications cost.

While RSUs seem to be a very promising solution for improving V2V communications, the cost of manufacturing, installing, and maintaining these units seem to be prohibitive for the large-scale deployment of RSUs. For example, a simplistic form of RSU (such as Roadway Probe Beacons) requires $13,000-15,000 per unit capital cost and up to $2,400 per unit per year[4] for operation and maintenance [34]. In addition to cost, effectiveness and utilization rate of RSUs may also depend on the number of DSRC-equipped vehicles that are present in a given area. As an example, consider an accident notification message; RSUs will be utilized only for vehicles within a small region that is relevant to the notification message, typically a 4 square miles area around the accident scene.

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[2] VANETs could be based on vehicle-to-infrastructure (V2I) and/or vehicle-to-vehicle (V2V) communications.

[3] V2X is an abbreviation used for both V2I and V2V communications.

[4] The price quote includes the cost of both roadside equipment and roadside wireless communications.

In this report, based on a new biologically-inspired networking paradigm, we propose to leverage the initially available DSRC-equipped vehicles to be used as temporary RSUs. Vehicles that act as temporary RSUs can make brief stops during which they act as a communication bridge for other vehicles in the network [35,36]. We envision that using vehicles as RSUs could improve not only the message reachability and network connectivity but also accelerate the adoption of DSRC technology in addition to avoiding the cost of deploying Roadside Units.

III. PROBLEM STATEMENT

The U.S. Department of Transportation (DoT) was expected to have a nationwide deployment of the roadside infrastructure in 2008 [37]. This plan, however, did not materialize and, to date, very few RSUs have been deployed. Major reasons that prevented the success of the plan can be summarized as follows:

A. Justifying the benefits that RSUs provide is difficult

Determining the value of such a radical proposition in uncertain future markets has proven to be nontrivial and fairly complicated. Even though the benefits of V2V and V2I systems in terms of safety, traffic efficiency, and environment are clear and have been reported in [38], the full benefits of the DSRC technology cannot be realized unless the technology is widely adopted by the market. Such economic justification becomes more difficult when there are other traffic information infrastructures such as Dynamic Message Sign (DMS) and 5-1-1 System which are already in place [39]. These existing systems provide both safety and traffic efficiency benefits (i.e., roadside assistance help alert drivers of slow vehicles ahead and/or upcoming work zone while a transportation and traffic information telephone hotline allows travelers to choose the most efficient mode and route to their final destination). Proven effectiveness, high user satisfaction [39], existing widespread deployment, and already-invested capital[5] into the existing systems have further impeded the nationwide deployment of RSUs.

B. Global cooperation and partnership with private sector

The deployment of roadside infrastructure (i.e., through the DoT's VII program) requires major collaboration and coalition of public and private sectors (such as US DOT, state and city authorities, auto companies, and other profit and non-profit organizations). However, the willingness of public- and private-sectors to cooperate in this effort is a major issue as privacy, ownership, funding, and use are all major concerns. Until now, this cooperation which is a prerequisite for the success of roadside infrastructure deployment, as reported in [40], has remained largely unconsummated.

C. Funding approaches

One of the most important stumbling blocks in the infrastructure deployment is funding. The DoT long-term deployment plan which envisioned 200,000-250,000 roadside units to be installed [37] potentially requires billions of dollars of investment. Current uncertain economic climate as well as the previously mentioned difficulties in justifying the benefits of this new technology and lack of a healthy cooperation between different organizations have crippled the initiative required for financing the deployment program.

It is interesting to note that most of the above reasons are non-technical in nature. Social, economic, and political issues are major obstacles that have impeded the extensive deployment of RSUs. Since major collaborative efforts are necessary to

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[5] Deployment cost of 5-1-1 system ranges from $133,000 to $1,028,000 [6].

resolve these issues, in this report, we propose an alternative approach to roadside infrastructure by leveraging the use of existing DSRC-equipped vehicles to provide RSU functionality. This approach employs a powerful self-organizing network paradigm and draws its inspiration from social insect colonies such as ants, bees, birds, and fish. Such an approach was formulated for the first time in [1] where it was suggested that several fundamental transportation problems can be solved by carefully studying the behavior of self-organizing biological systems and applying the underlying principles of their successful operation to transportation problems. In [1], as an example of this approach, it was shown that vehicular traffic at intersections in urban areas can be managed by a new technology known as "Virtual Traffic Lights" via the cooperation of vehicles at that intersection through vehicle-to-vehicle communications and without the need for infrastructure-based traffic control. In this report, we show that another acute transportation problem (namely, the deployment of RSUs) can also be solved by using the same powerful approach.

IV. PROPOSED SOLUTION: CARS AS RSUS

Inspired by social insect colonies such as ants, bees, and termites, we propose a self-organizing network solution that leverages the existing DSRC-equipped vehicles to be used as temporary RSUs. As a temporary RSU, a vehicle can make a brief stop and take on or assume the tasks of a conventional RSU - relaying messages to nearby vehicles and acting as a communication bridge for other vehicles in the network. The proposed solution consists of 2 main components, each of which addresses the following key questions:

1) Which vehicles should act as temporary RSUs? How can a vehicle determine, in an independent and distributed manner, whether or not it should temporarily serve as an RSU?

2) What are the tasks of temporary RSUs? What does a vehicle have to do while serving as a temporary RSU? How long should it continue to serve as an RSU?

In order to answer the above questions, one needs to have a target application. Different applications may require different algorithms/solutions to the aforementioned questions. To demonstrate the feasibility of the proposed concept, a specific safety application, namely a Post Crash Notification (PCN) application, is used in this report as an illustrative example to show how the proposed "poor man's solution", with zero infrastructure support, can help improve the network connectivity. The main purpose of the PCN application is to disseminate a safety message (i.e., information about the incident - time, location, etc. - which may be issued by a vehicle involved in the accident or a police car) to all vehicles within a region of interest (ROI) and the message should be disseminated to these vehicles within a short amount of time. The following subsection describes in detail how the proposed solution can be implemented.

A. Distributed algorithm for selecting a temporary RSU
Figure 3.1.1(a) presents a simple example that provides important insights into how the RSU-selection algorithm should be designed. A flow diagram of the proposed algorithm is shown in Figure 3.1.2.

Consider an example of a network as shown in Figure 3.1.1(a); black, green, and blue squares and red circle represent vehicles whereas arrows represent movement direction of vehicles. Assume, with no loss of generality, that an accident takes place at the center

of this network and the Vehicle Src involved in the accident sends out a post crash notification message (i.e., a safety message) to other vehicles in the network. After the first broadcast from Src, all vehicles in the gray-shaded region (i.e., the coverage polygon) receive the message and are informed about the accident. Note that the coverage polygon is the polygon that contains all vehicles that are informed via spatial relays from Src or other informed vehicles. In other words, the polygon contains all vehicles that could be reached from Src either via direct transmission or via multi-hop forwarding. Based on the definition of the coverage polygon, the following observations can be made:

Observation 1: Good candidates for temporary RSUs are vehicles that are positioned at the boundary of the coverage polygon.

By definition, vehicles that are on the boundary of the network polygon have both informed and *uninformed* vehicles in their vicinity[6]. These vehicles are therefore highly likely to meet with other uninformed vehicles before other non-boundary and informed vehicles meet uninformed ones. The non-boundary and informed vehicles, on the other hand, are mostly surrounded by informed vehicles; hence there is no additional benefit in having these vehicles serve as temporary RSUs. Figure 46(a) provides a simple example - coverage polygon is shaded in gray color, and blue and green rectangles represent boundary and non-boundary vehicles, respectively.

Observation 2: Only boundary vehicles that travel toward the accident should serve as temporary RSUs.

In addition to the position of vehicles, movement directions of these vehicles should also be considered as well. In this report, based on the mobility pattern assumed, we propose that only boundary vehicles that travel toward the accident should stop and serve as temporary RSUs. By having these vehicles stop at their current locations for a brief period of time (and not continue to travel toward the accident scene), the subsequent rebroadcasts from these vehicles could possibly reach other uninformed vehicles when they arrive into the RSUs' neighborhood. It should be noted that the boundary vehicles that travel in the outward direction from the scene of accident do not stop; message can be disseminated quickly through spatial relays of these vehicles that store, carry, and later forward (SCF) the message to vehicles that are in a region these vehicles travel toward (i.e., this region that outside the coverage polygon. In Figure 3.1.1(a), only vehicle C (not vehicles B, E, F, G or I) will act as a temporary RSU. In the remainder of this report, we will refer to rebroadcast from temporary RSUs (e.g., Vehicle C) as RSU rebroadcasts and rebroadcasts from other vehicles as SCF rebroadcasts.

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[6] Vicinity in this case implies nearby region and is not equivalent to the term neighborhood.
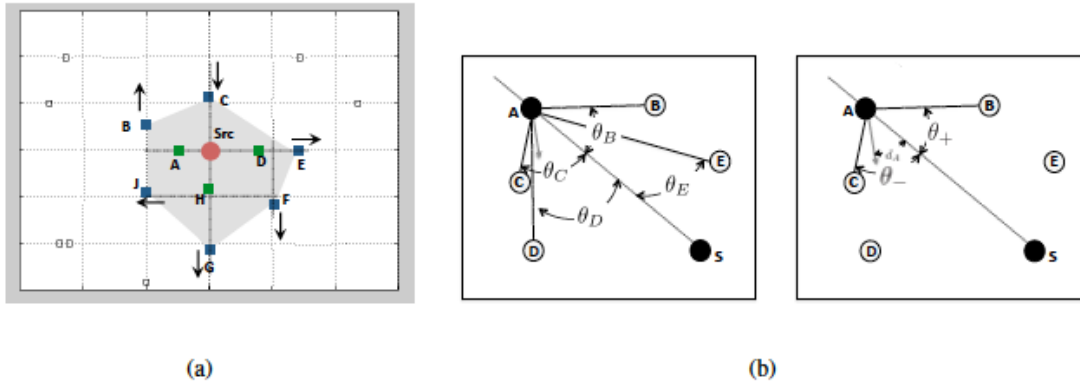
(a)

(b)

Figure 3.1.1: (a) Boundary of the network coverage polygon. Assume that the message is broadcast from Src at the scene of accident. Vehicles that are connected to Src via spatial relays are in the gray shaded region. Boundary and non-boundary vehicles are indicated with blue and green dots, respectively. Black squares indicate vehicles that do not receive spatial message broadcast from Src. Black arrows indicate current direction of the vehicles; (b) the principle of operation of the proposed distributed gift-wrapping algorithm. Assume that NBR(A) = {S,B,C,D,E}, moving direction of A is indicated by the gray arrow, and that A first receives the message from Vehicle S [3].

In order to determine an accurate coverage polygon and its boundary, one needs global knowledge of the network (i.e., location of all vehicles in the network). However, since such information requires excessive information exchange between vehicles which is not desirable in VANETs, we use the distributed gift-wrapping algorithm proposed in [3]. This algorithm is a distributed algorithm; a vehicle, upon receiving a message, can determine independently and in a distributed manner whether it lies on the boundary of the coverage polygon. Note that since it only relies on the local information, the distributed gift-wrapping algorithm is only an approximate algorithm and it tends to over-select boundary vehicles (i.e., some vehicles selected by the algorithm may not lie on the boundary of the polygon). More details about this algorithm can be found in [3]. In addition to the gift-wrapping algorithm, additional rules that consider directions of vehicles are added to the original distributed gift-wrapping algorithm. The resulting algorithm shown in Algorithm 1 is then used to select vehicles to serve as temporary RSUs.

Figure 3.1.1(b) illustrates how the temporary RSUs are selected by Algorithm 1. Upon receiving a message for the first time from Vehicle S, Vehicle A computes the angle θ_i for all of its neighbors (see Figure 3.1.1(b) (left)). Maximum (θ_+) and minimum (θ_-) angles are then identified. In the scenario given here, Vehicles B and C are the neighbors of Vehicle A that have the maximum and minimum angles, respectively and since $|\theta_+| + |\theta_-|$ is less than π and moving direction of Vehicle A falls between θ_- and θ_+, Vehicle A is selected as a temporary RSU.

Algorithm 1 Distributed Gift-wrapping Algorithm for vehicles to act as temporary RSUs.

$\angle(A, S, i) \Leftarrow$ angle between a vector (from Vehicle A to Vehicle S) and a vector (from Vehicle A to Vehicle i) where $\angle(A, S, i) \in [-\pi, \pi]$.

$Nbr(A) \Leftarrow$ set of all neighboring vehicles of Vehicle A.

$d_A \Leftarrow$ moving direction of Vehicle A with respect to a line connecting from Vehicle A to Vehicle S.

When A receives the message for the first time from Vehicle S

for all $i \in Nbr(A) \setminus \{S\}$ **do**

    $\theta_i \Leftarrow \angle(A, S, i)$

end for

$\theta_- \Leftarrow \min\left(\min_i(\theta_i), 0\right)$

$\theta_+ \Leftarrow \max\left(\max_i(\theta_i), 0\right)$

if $|\theta_+| + |\theta_-| < \pi$ and $d_A \in [\theta_-, \theta_+]$ **then**

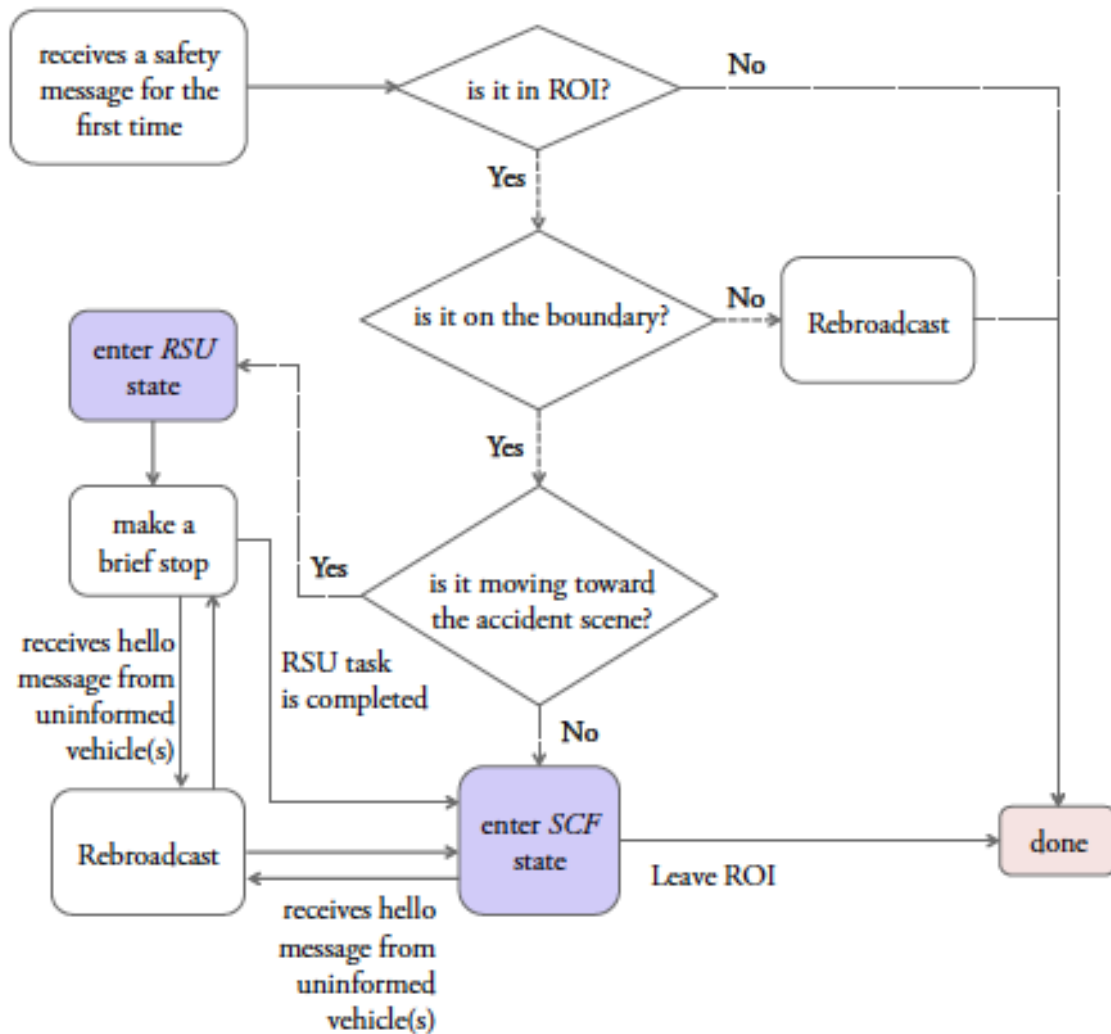 $A \Leftarrow$ temporary RSUs

end if

Figure 3.1.2: Flow diagram describing the distributed algorithm for selecting a temporary RSUs and the tasks performed by temporary RSUs.

B. Tasks of a temporary RSU
As shown in the flow diagram in Figure 3.1.2, informed vehicles that are on the boundary of coverage polygon and moving toward the scene of accident act as temporary RSUs for a certain period of time. These vehicles make a brief stop and periodically rebroadcast the safety message to mimic the role of the conventional roadside units. Vehicles that receive such message rebroadcast from these temporary RSUs (i.e., RSU-vehicles) follow the same procedure as shown in Figure 3.1.2. It must be noted that when one considers a different (possibly non-safety) application such as instant messaging, content download, etc., the tasks of temporary RSUs may be changed – the temporary RSUs may stop for a different amount of time depending on the application; their stop duration may be preempted if the applications they support end; or instead of rebroadcasting the safety message, they may need to forward the messages to only particular vehicle(s).

V. SIMULATION SETTING

Traffic mobility model used in the simulations is based on the CA-based mobility model developed in [4] and parameter values used in the simulations are summarized in Table 3.1.1. In the simulator, to maintain a constant vehicle density in the network, a new vehicle is immediately added to the network once a vehicle exits. We assume that this new vehicle is uninformed (i.e., it does not receive the safety message from prior rebroadcasts of the message).

TABLE 3.1.1: PARAMETER VALUES FOR SIMULATION STUDY.

Parameters	Values
Size of the road structure	0.5km × 0.5km, 1km × 1km 2km × 2km, 3km × 3km
Length of a road block	125 meters
Vehicle density	100 veh/km^2
DSRC penetration rate	$\{10\%, 20\%, \ldots, 100\%\}$
Simulation time	15 minutes (5-minutes warmup period)
Maximum speed	15 m/s (36 km/h)
Cycle duration	45 seconds
Green light ratio	50|50
Signal offset	10 seconds
Stop time of RSU-vehicles	10 − 60 seconds

A. Traffic Pattern
Based on the commuting pattern in highly populated cities such as New York City (NYC), we observe that the traffic pattern can be categorized into four categories: (i) Morning Rush Hour Traffic (8-10 am); (ii) Lunch Hour Traffic; (iii) Evening Rush Hour Traffic; (iv) Midnight Traffic (1-3 am).

In the mobility model used in this report, we assume the evening rush hour traffic where most of traffic travels in northbound direction. We also assume that the scene of accident is located at the top-center of the network and the safety message broadcasted by the source should be disseminated to all vehicles in the region.

B. Transmission Range

To take into account the possible obstruction of signal propagation due to buildings and highrises in urban cities, we assume two different types of communications: direct line-of-sight (LOS) and a non line-of-sight (NLOS) communications. LOS and NLOS have transmission ranges of 250 and 140 meters, respectively. Any two vehicles can communicate directly (i.e., in single-hop fashion) if and only if they are within the corresponding transmission ranges. In addition, we assume accurate GPS information in our simulations (i.e., a vehicle has perfect knowledge of positions of itself and all of its one-hop neighbors).

C. Metrics

In this report, two performance metrics are used to evaluate the advantages of the proposed solution. Since the post crash notification application is considered as an example in this report, message reachability metric is used to indicate the message dissemination rate achieved by the proposed solutions; i.e., fraction of vehicles that are informed when the proposed solution is implemented. It should be mentioned here that improvement in network connectivity comes at the expense of a slight increase in travel time. Vehicles that act as temporary RSUs need to make brief stops, resulting in an increase in travel time. To capture such an effect, average velocity of vehicles is considered.

    1) **Message Reachability Metric:** We use message reachability metric to evaluate the performance of our scheme against the standard scheme (i.e., no vehicles stop and serve as RSUs). Message reachability metric is defined as the fraction of vehicles in the network that receive the message. Note that the message reachability is different from network reachability metric. In other words, while the network reachability measures the maximum number of vehicles that are connected at a given point in time (i.e., a static metric)[7], message reachability metric is a transitive measure of network reachability (see [4]).

    2) **Average vehicle velocity:** Average vehicle velocity is used to capture how much the RSU's stop time affect the overall traffic flow in a city. Both average velocity of all vehicles and only those vehicles that act as temporary RSUs are reported.

Vi. SIMULATION RESULTS

The simulation results are shown in Figure 3.1.3. Observe that the proposed "Cars as RSUs" scheme considerably outperforms the standard scheme; with the proposed scheme, the message reaches almost twice the number of vehicles in network (i.e., the message reachability improves from 34% to almost 67% in a 100 veh/km^2-dense network and 20% DSRC penetration rate, which corresponds to a 97% improvement).

Such an improvement is mainly due to the fact that with RSU scheme, vehicles that serve as RSUs stay in the network for a longer period of time (i.e., ratio of informed vehicles is higher) and since there are more informed vehicles (i.e., vehicles that have received the message), there are more message rebroadcasts which reach the uninformed vehicles (i.e., vehicles that have not received the message) with a higher probability. Note that the increase in network connectivity of the proposed scheme comes at the expense of a slight degradation in travel time (i.e., decrease in average vehicle velocity). Since vehicles make brief stops occasionally, our simulations have shown that velocity of a vehicle, on average, decreases by 0.27 km/h. This translates to

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[7] which is equal to the fraction of vehicles that belong to the largest connected component of a network

a 1.48% decrease in average vehicle velocity and 1.51% increase in travel time. This, however, is a small increase as compared to the increase in travel time due to accident-induced congestion. It is worth nothing that although the proposed scheme might not significantly outperform the standard scheme especially in the scenario with only 10% penetration rate, the scheme proposed is able to retain the safety message in the ROI for a long period of time (i.e., more than 300s). Observe that with the standard scheme, the informed vehicles spend little time in ROI and are likely to leave the ROI before they are able to rebroadcast the message to other uninformed vehicles. As a result, the message reachability decreases with time and the message dies out after some time (i.e., 200s after the first broadcast in our case).

Figure 3.1.3(left) shows the reachability of networks with and without RSU-vehicles for different DSRC penetration rates. Observe that significant improvement in terms of network reachability can be achieved when RSU-vehicles are implemented only in a network with sparse and moderately-dense DSRC-equipped vehicles (i.e., 10%-40% penetration rate). The improvement is most pronounced in moderately-dense network; i.e., a network with a certain density. When a network has very few DSRC-equipped vehicles, not much improvement is reported since RSU's stop time may not be long enough for the temporary RSUs to encounter other uninformed vehicles. In addition, it should be noted that, in a very sparse network, the coverage polygon (see Figure 3.1.1(a)) usually has a small size. Vehicles that act as temporary RSUs may be located very close to the accident. Although an uninformed vehicle receives a safety message from one of these RSUs, the message may no longer be useful as they are already close to the accident scene, having passed the last exit or alternative route that exists before driving into the congestion induced by the accident. On the other hand, when there are many DSRC-equipped vehicles in the network (i.e., a DSRC-equipped-dense network), the network is already well-connected and no vehicle is needed to act as temporary RSUs. By having some vehicles in a DSRC-equipped-dense network stop as RSUs not only degrades the message reachability but also impedes the overall traffic flow. Figure 3.1.3(right) shows almost 8% increase in average time a vehicle spends in the ROI and 24% decrease in average vehicle speed when the network is dense.

It is worth nothing that while message reachability may increase with the vehicle density (since dense traffic leads to a decrease in vehicle speed), we have observed from the simulations that a change in the total number of vehicles in the network (i.e., density of equipped and unequipped vehicles combined) has far less effect on message reachability as compared to the impact caused by a change in the number of DSRC-equipped vehicles.
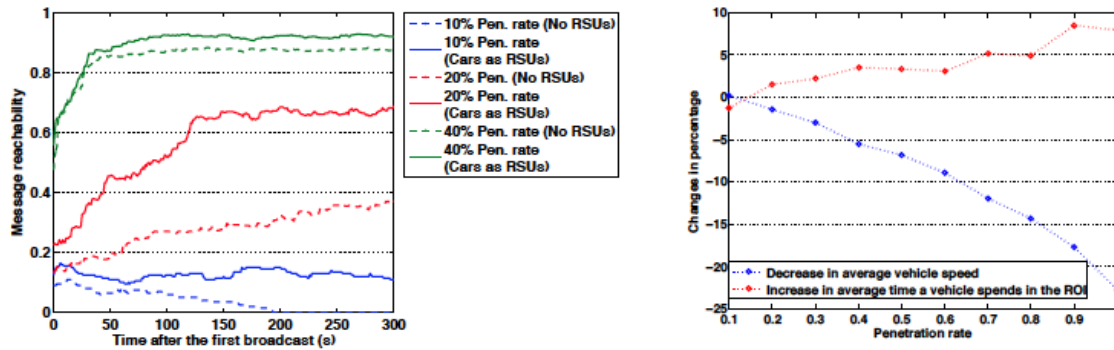
Figure 3.1.3: Impact of vehicle density on the message reachability (left figure) and average vehicle speed and average time a vehicle spends in the ROI (right figure) when the proposed scheme is implemented. Substantial improvement is observed only in sparse and moderately-dense DSRC-equipped network. The results are based on a 1 km x 1 km Region of Interest and 30s of RSU-vehicle stop time.

VII. EFFECT OF DIFFERENT PARAMETERS

A. Effect of the size of Region of Interest (ROI)

Our simulation results show that the message reachability of both schemes decreases with the size of the Region of Interest (ROI). This is due to the fact that size of the coverage polygon (see Figure 3.1.1(a)) of networks with the same density does not change with the size of ROI. Since message reachability metric is a relative measure, it follows that the fraction of vehicles that are in the coverage polygon (hence, the message reachability) decreases when the size of ROI increases. In addition, when one considers additional rebroadcasts from the temporary RSUs, similar conclusions can be drawn: the number of uninformed vehicles that are informed by the rebroadcasts from these RSUs does not vary with the ROI size; hence, the message reachability is higher when the ROI size is small. For example, for a density of 100 veh/km^2, 20% DSRC penetration rate, and 30s RSU-vehicle stopping time, message reachability 2 minutes after the broadcast increases from 27% to 60.75% for 1 km x 1 km ROI, whereas for a 3 km x 3 km ROI, it increases from 6.39% to 15.35%.

B. Effect of Stop time of RSU-vehicles

Figure 3.1.4 shows the significant effect of stop time of RSU-vehicles on the message reachability. Observe that when the stop time is too short, RSU-agent scheme gives comparable performance to the conventional scheme without the RSU-vehicles. This is because the RSU-vehicles do not stop long enough to encounter other uninformed vehicles. As a result, the message reachability increases with the stop time until the stop time reaches a certain value (i.e., 30 seconds in this case). Any additional stop time beyond 30 seconds does not increases but instead decreases the message reachability because the RSU-vehicles are unlikely to encounter uninformed vehicles after having stopped for some time (i.e., 30 seconds in this case). It is therefore more beneficial for these vehicles to continue to move and possibly further rebroadcast the message to uninformed vehicles in other areas in the region of interest. Note also that too large stop time not only degrades the message reachability, but it also increases the travel delays of the vehicles that act as temporary RSUs. Note that the optimal stop time depends both on the vehicle density, size of Region of Interest (ROI), and topology of the network. While 30 seconds seems to be the optimal stop time for the network with 20% DSRC penetration rate (see Figure 3.1.4(a)), a smaller stop time (i.e., 20 seconds of

stop time) would be needed for the maximum message reachability at 40% DSRC penetration rate network (see Figure 3.1.4(b)).

(a)   (b)
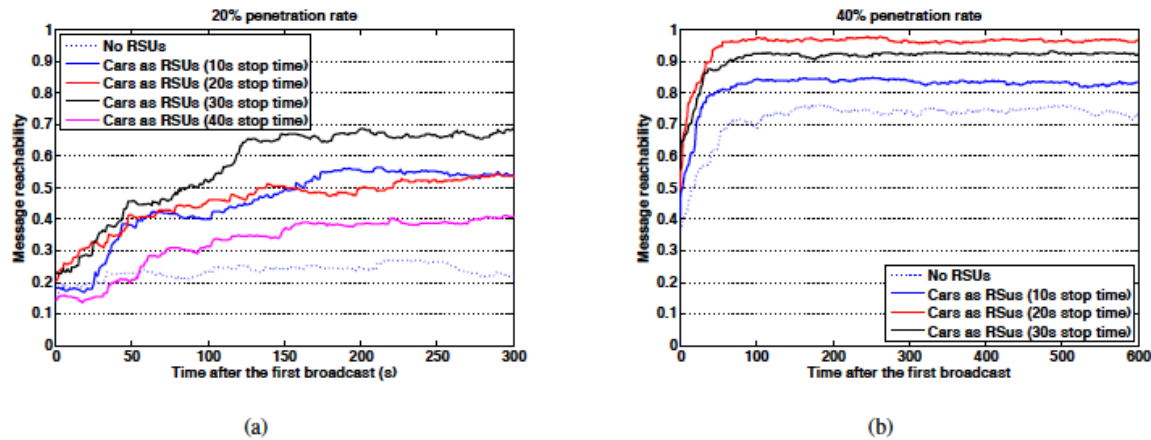
Figure 3.1.4: Impact of the RSU-vehicle stop time on the message reachability of the network with and without RSU-vehicles. Substantial improvement is observed only in sparse and moderately-dense network. The results are based on a 1 km x 1 km Region of Interest and vehicle densities of 100 veh/km^2 with 20% and 40% DSRC penetration rates on the left and right figures, respectively.

C. Effect of Mobility Pattern

Figure 3.1.5 shows the significant effect of mobility pattern of the vehicles on the message reachability. The proposed RSU-vehicle scheme provides significant improvement when most of the traffic moves toward one particular direction; as the fraction of northbound traffic increases, the improvement of the RSU scheme also increases. For example, when 85% of traffic is northbound, the message reachability increases from 34% to 67% which corresponds to an improvement of 97%. This suggests that the proposed RSU-scheme will work very well during the rush hours. For example, during the evening rush hours in Manhattan, a large fraction of people commute from their workplaces in downtown to their homes in the uptown area (i.e., dominant northbound traffic).

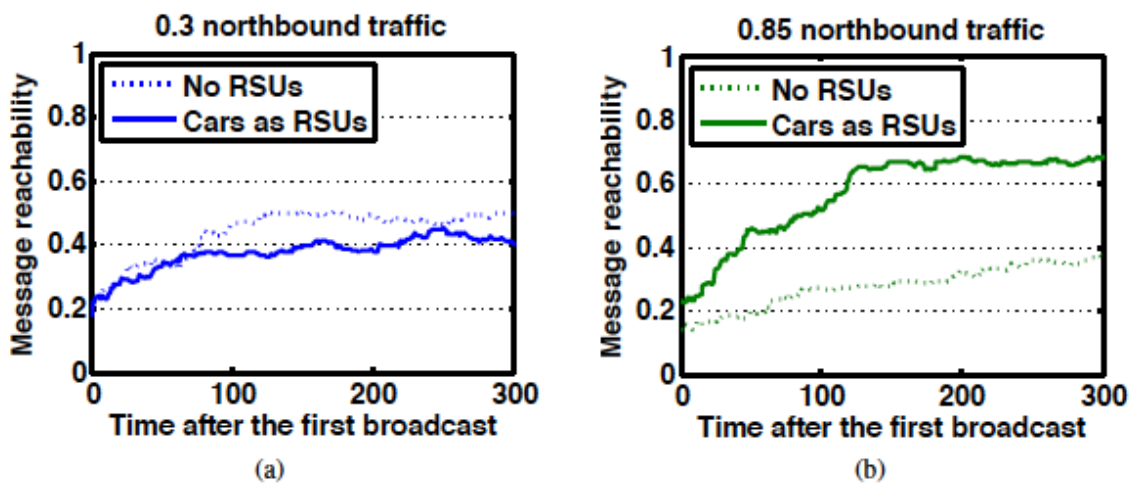(a)   (b)

Figure 3.1.5: Impact of the mobility pattern on the message reachability of the network with and without RSU-vehicles. The improvement of RSU-vehicle scheme over the conventional scheme

increases with the increase in northbound traffic. The results are based on a 1 km x 1 km Region of Interest network with vehicle density of 100 veh/km^2, 20% DSRC penetration rate, and 30-second RSU-vehicle stop time.

VIII. DISCUSSION

Consider the current way emergency situations are handled in urban areas: e.g., if there is an ambulance or fire truck trying to reach an emergency area, all the vehicles on the road move to the side of the road making way for the ambulance or fire truck to pass. This clearly delays all the vehicles agreeing to do this sacrifice as they slow down and move to the side of the road which probably takes anywhere from 30-60 seconds. This collective sacrifice can save the life of a sick patient or people who are trapped in a building on fire. In this report, we use this example as a motivation for the proposed solution: a vehicle sending a safety message waits for an implicit acknowledgment before continuing its trip. If the ACK is not received, then the vehicle stops and keeps broadcasting the message till it receives an ACK (or until the scheduled broadcast duration ends). This way, the vehicle serves as a temporary RSU, thus enhancing the message reachability and network connectivity substantially.

The proposed system is extremely attractive due to its cost-effectiveness and its ubiquity, especially in the current environment where the deployment of roadside infrastructure is very limited. In a sense, the proposed solution is "a poor man's solution" to a very real and acute problem, namely the projected low penetration rates of the DSRC technology at the initial stages of DSRC deployment. As such, the main idea behind the proposed solution is to exploit the self-organizing network characteristics of a vehicular network whereby the fleet of cars can solve a formidable problem by themselves through cooperation without additional equipment or infrastructure. By using certain vehicles as temporary roadside units, this temporary infrastructure could be provided ubiquitously without requiring additional equipment. This approach not only improves connectivity of vehicular networks in the early stages of DSRC development, but it can also accelerate the adoption of the DSRC technology. For the successful operation of the proposed solution the following issues will need to be addressed: i) Cooperation from state or local traffic management institutions (an example of this is Zipcar [41]); ii) guaranteeing the correct and reliable operation against faults and/or malicious attacks; iii) incentives or other mechanisms for policy enforcement; iv) being able to use other alternatives to ZipCar (such as taxis, buses, etc.); and v) penetration rate of DSRC technology. Our ongoing work is focused on addressing these issues.

While the cooperative approach presented here might appear altruistic for current day driving practices, it is not difficult to see that the presented approach could also be used by autonomous vehicles of the future. It is well known that companies like Google and several car manufacturers such as GM, Volkswagen, Nissan etc. are currently looking into autonomous vehicles as a potential new technology. The authors of this report believe that in the long run autonomous vehicles will have to use radios (such as DSRC radios or a similar communications technology) for V2V communications as this has tremendous benefits for even autonomous vehicles. The approach presented in this report could thus be used for autonomous vehicles as well in which case human decisions will not be required and the car selected to serve as an RSU will do this automatically.

IX. RELATED WORK

A comprehensive comparison between different types of RSUs is presented in [42]. Both analytical and simulation results reveal that relay and mesh nodes, as opposed to base stations, can be more cost-effective solutions even though a much larger number of such units are required to deliver the same level of performance as offered by the base stations. In addition, the authors also suggest that adding a small amount of infrastructure is vastly superior to even a large number of mobile nodes capable of routing to one another.

An interesting paper by Trullols et al. [43] uses the approach employed by the maximum coverage problem for addressing this issue. The authors identify that roadside infrastructure should be placed at intersections rather than the middle of road segment. Two strategies on the RSU placement locations are proposed: one that maximizes the number of vehicles served by RSUs, and the other that maximizes the number and the contact time between vehicles and RSUs. While the above studies are based on simulation data, a realistic trace of traffic is used to evaluate different schemes for RSU placement in [44]. The authors use a greedy algorithm to determine the minimum number and locations of RSUs that can serve all vehicles in Jeju city, Korea.

Several studies address the issue of effective communications between vehicles and RSUs. For example, an RSU-based solution for Collision Warning System (CWS) in urban areas is suggested in [45]. The authors propose an algorithm to determine when the RSUs installed at intersections should broadcast warnings to vehicles proceeding to the intersection. Zhang et al. propose in [46] a scheduling scheme for RSUs to provide a balance between serving downloads and upload requests from fast-moving vehicles on highways. An interesting paper by Eckhoff et al. propose to utilize parked vehicles as relay nodes to address the disconnected network problem. Extensive simulations and real life experiments show that parked cars can increase cooperative awareness by over 40% [47].

While the aforementioned studies shed light on the RSU placement problem and the communications between vehicles and the RSUs, it should be noted that, to the best of our knowledge, there are no existing studies on the use of vehicles as RSUs.

X. CONCLUSION

In this report, we propose a biologically-inspired new approach to implementing Roadside Units. Instead of using a costly roadside infrastructure (such as RSUs) or high-packet-latency Cellular networks and WiFi, we leverage the use of DSRC-equipped vehicles to serve as temporary roadside units. Based on the designed local rules, a DSRC-equipped vehicle independently determines whether it should serve as an RSU; and if so, it stops for a small duration and rebroadcasts the message. Results show substantial improvement in terms of message reachability which is crucial for safety message dissemination application in VANETs. It is worth mentioning that even though the benefits reported in this report are based on a specific safety application (Post Crash Notification), our preliminary results show that the same concept could be used for other safety and efficiency applications of VANETs also.

While the solution proposed to the RSU deployment problem is interesting, perhaps even a more interesting global conclusion is how the biologically inspired approach to

solving fundamental transportation problems can be generalized and used as a powerful approach and tool for solving several important transportation problems. Our ongoing work is currently looking into other instances of the same approach for solving other outstanding transportation problems.

**Part 3.2:
Solution to the Partial Penetration Problem – Policy perspective**

I. Executive Summary

A new technology known as Virtual Traffic Lights (VTL) was recently proposed as a self-organizing new paradigm for traffic management. This new technology uses the vehicle-to-vehicle (V2V) communications as its premise. VTL can revolutionize traffic management in urban areas as it can substantially reduce commute time of urban workers, increase productivity, and lead to a greener environment. In a VTL environment, vehicles self-organize to elect a leader which serves as a virtual traffic light to decide the right of way at that intersection, thus replacing the current physical traffic lights. Implementing VTL technology with partial penetration, however, is an outstanding issue that needs to be addressed. This report addresses this issue by proposing a co-existence model whereby VTL equipped vehicles can co-exist with vehicles that do not have VTL. Simulation results show that the transition model proposed here could provide drivers with strong incentives to adopt the VTL technology [48,49].

II. Introduction

Vehicle to vehicle communications (V2V) using Dedicated Short-Range Communication (DSRC) technology in the 5.9 GHz band have facilitated the development of Virtual Traffic Lights (VTLs) [2]. In a VTL environment, vehicles self-organize to manage the right of way at intersections, obviating the use of current traffic lights, optimizing travel times of urban workers, increasing productivity, reducing carbon footprint of vehicles, and leading to a greener environment. However, given that the introduction of DSRC and VTL technology might happen gradually (with initial penetration rates in the vicinity of $5 - 10\%$), policies should be designed to pave the way for a smooth transition from the current traffic light system to a VTL system [50]. In this report, we propose such a coexistence model for the transition period whereby VTL-equipped vehicles can benefit from the VTL technology while they co-exist with vehicles that do not have VTL equipment. The co-existence model will be used to show how certain policy decisions during designated periods (e.g., during rush hours) can expedite and provide incentives for adopting the VTL technology by rewarding VTL vehicles while slightly penalizing the non-VTL vehicles.

III. VTL Coexistence Model

The coexistence model proposed in this report is inspired by the High Occupancy Vehicle (HOV) lane paradigm whereby some lanes on a highway, for instance, are reserved for the exclusive use of vehicles carrying passengers. An example of the proposed VTL coexistence model is shown in Figure 3.2.1. Observe from the figure that streets and intersections that are high- lighted in green color are reserved exclusively for the VTL- equipped vehicles. The intersections on the VTL-exclusive streets, with an exception of the intersections highlighted in red color, also operate based on the VTL paradigm [1]. In other words, the current traffic lights at those intersections will be replaced by the virtual traffic lights; vehicles that approach one of these intersections will communicate among themselves and decide to elect a leader that will manage the traffic flow at that intersection. Note that the physical traffic lights are still being used at other intersections including the ones highlighted in red color. The intersections highlighted in red color therefore manage both VTL-equipped vehicles and vehicles that do not have VTL equipment (i.e., non-VTL vehicles). These intersections are necessary as they allow non- VTL vehicles to cross the VTL exclusive streets.
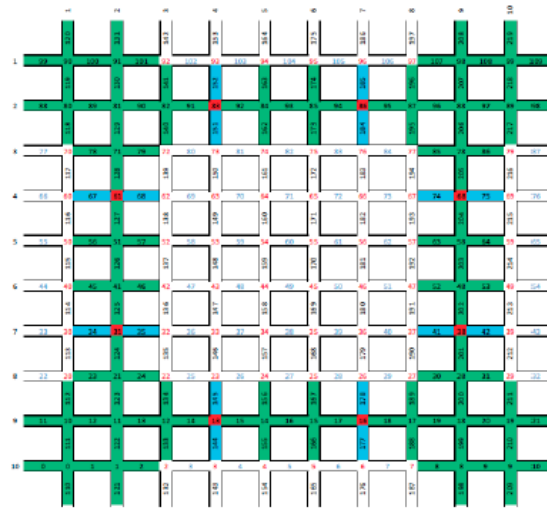
Figure 3.2.1: Example of a road network in which some streets (highlighted in green color) and intersections (also in green color) are reserved for the exclusive use of VTL-equipped vehicles during rush hours.

By reserving some streets exclusively for the use of VTL vehicles, it is clear that the VTL-equipped vehicles will benefit from this policy enforcement while the non-VTL vehicles get penalized, as they are restricted to use only some of the roads. Benefits in terms of reduction in travel time of VTL vehicles can be attributed to two reasons: i) the VTL vehicles may travel at a higher speed on the VTL-exclusive streets since these streets are of a restricted use and tend to have less traffic and ii) a more effective traffic management at intersections provided by VTL reduces the waiting time of VTL-equipped vehicles to cross the intersections and thus reduce the overall travel time. In turn, this setting may penalize and increase the travel time of the non-VTL vehicles; i.e., the non-VTL vehicles might have to travel over a longer distance to avoid the exclusive streets and experience higher level of traffic congestion even on the normal roads.

IV. Results

We resort to SUMO traffic simulator [51] to study the tradeoff mentioned in the previous section. A 10x10 Manhattan Grid network with two-way one-lane streets is assumed in the simulations and three configurations with different number of VTL-exclusive streets are considered as shown in Figure 3.2.2. In all configurations, an evening rush hour traffic pattern is assumed whereby all vehicles originate from a point within the 3x3 inner square grid (indicated by the dotted red rectangles in the figures) and they move toward their destinations located on the boundary of the grid network. In the simulations, one vehicle is generated each second for a period of 1,500 seconds. With this generation rate, the number of vehicles in the road network stays almost constant at 250 during the peak period. While the network topology assumed here might not resemble the actual road topology in real cities, it serves as a proof-of-concept example in our preliminary study to determine the feasibility of the proposed VTL coexistence model.
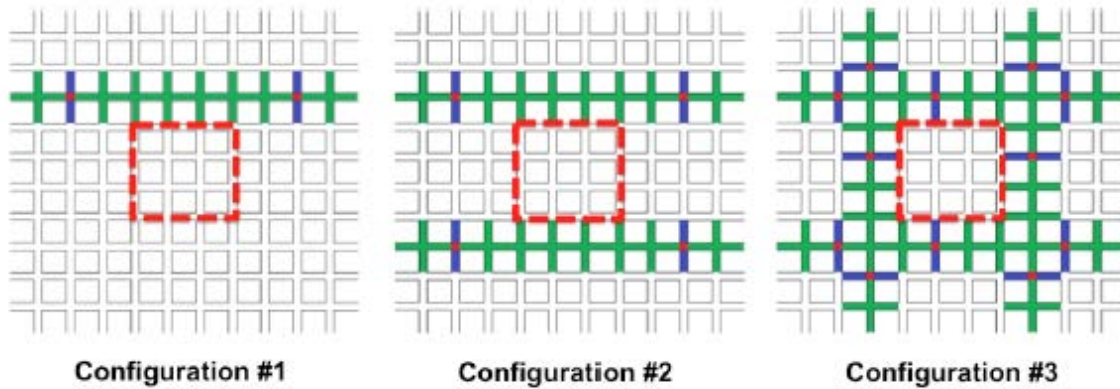
Configuration #1   Configuration #2   Configuration #3

Figure 3.2.2: Road Configurations considered in the study.

Figure 3.2.3 shows the simulation results in terms of mean travel speed of VTL and non-VTL vehicles. The red horizontal line indicates the average speed of 13.2 mph when the current physical traffic light system is implemented and no streets are reserved for VTL exclusive use. Observe that when the drivers start to adopt the VTL technology, the scheme already provide significant benefits to VTL-equipped vehicle and penalizes the non-VTL vehicles even in the scenario with a single VTL-exclusive street (i.e., the average travel speeds of VTL-equipped and non-VTL vehicles changes by +14% and -39%, respectively). This kind of reward and penalty system provides strong incentives for adopting the VTL technology.

Nevertheless, as more consumers adopt the VTL technology, the advantage provided by VTL-exclusive roads diminishes (i.e., VTL-equipped vehicles do not gain any reduction in travel time in a scenario where a large fraction of VTL vehicles and only a few VTL-exclusive streets). This is because the large volume of VTL-equipped vehicles causes traffic congestion on the VTL-exclusive streets and traveling on these streets is no longer beneficial to the VTL-vehicles. In such scenarios, it might be desirable to reserve additional streets for VTL exclusive use (e.g., configurations 2 and 3 in Figure 3.2.2). While the results shown here indicate how different road configurations affect the overall travel speed experienced by vehicles, a more detailed investigation on this topic is necessary before the policy makers come up with an appropriate coexistence model that can be used during the transition period.
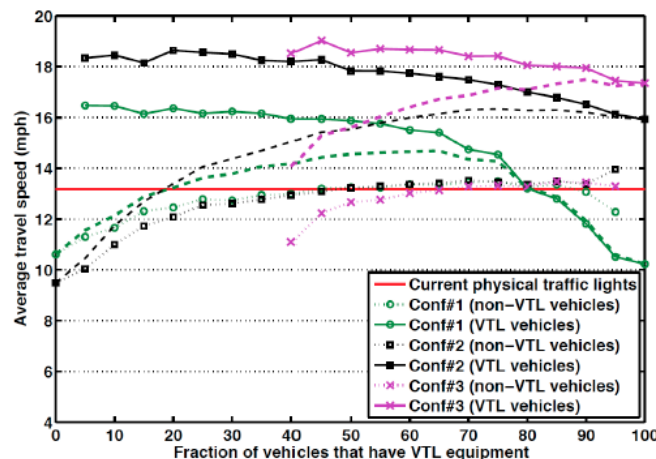
Figure 3.2.3: Average travel speed of VTL-equipped and non-VTL-equipped vehicles when three different coexistence models shown in Figure 3.2.2 are used. The dotted lines represent the weighted average when both VTL-equipped and non-VTL vehicles are considered.

V. Conclusions

Vehicle-to-vehicle (V2V) communications have facilitated the development of self-organizing traffic control, namely Virtual Traffic Lights (VTL). However, one of the major concerns in implementing the VTL system is the fact that all vehicles are required to be equipped with radio devices for V2V communications and VTL equipment. This report addresses this outstanding issue by proposing a transition model in which VTL-vehicles benefit from the VTL technology while coexisting and sharing the streets with current non-VTL vehicles. The proposed co-existence model seems very promising as it shows how judicious policy decisions by Department of Transportations of different countries could expedite the adoption of the Virtual Traffic Lights technology. Simulation results have shown that the proposed model could provide the drivers of vehicles strong incentives to adopt the VTL technology much faster than otherwise.

**Part 4:
Development of the VTL Prototype**

I. Executive Summary

Virtual Traffic Lights (VTL) is a recently proposed self-organizing traffic control scheme that has the potential to mitigate traffic congestion in urban areas. This report reports a prototype design effort on Virtual Traffic Lights using Android-based smartphones. The experiments performed show the feasibility of implementing VTL using smartphones' WiFi devices.

II. Introduction

A promising approach for mitigating traffic congestion was proposed recently [2]. This new approach is known as Virtual Traffic Lights (VTL) and it leverages the envisioned ubiquitous presence of vehicle-to-vehicle (V2V) communications. While the technology for V2V communications, namely Dedicated Short Range Communications (DSRC) technology, has been standardized and is expected to be a mandate in the next 2- 3 years in the United States, the current availability and the global use of this technology is very limited.

Because of the similarity between DSRC standard and the IEEE 802.11a and the proliferation of Wi-Fi hand-held devices, in this report, we propose to implement the VTL concept as a smartphone application which makes use of the already available hardware components such as navigation system (i.e. GPS and map), radio device (i.e., WiFi), a processing unit (i.e., microcontroller), and a display. Note that while the VTL design and architecture can be applied to all smartphone development platforms, in this work, we focus on implementing it on Android-based smartphones due to the following reasons: i) cost: all iOS developers are required to go through the iOS Developer Program which costs at least $99 to enroll [52]; ii) dominant share of market: as of the end of 2012, Android had a 68:3% market share [53]; iii) platform flexibility: the development can be done on any operating system; and iv) availability of tools and online support system. It is our hope that the Android-based VTL implementation will play an important role in demonstrating the benefits of the VTL paradigm and encourages researchers as well as policy makers to take a serious look at this new way of dealing with urban traffic congestion.

III. Principle of Operation

The premise of the Android-based implementation presented in this report is the self-organized traffic control paradigm proposed in [2]. In this paradigm, conflicts at intersections are detected and resolved in an ad hoc manner without any help from infrastructure. By using vehicle-to-vehicle communications (i.e., each vehicle sends out periodic hello messages to inform nearby vehicles of its presence, current position, and velocity), each vehicle can determine if there is an ensuing conflict at the intersection it is about to approach. When a conflict is detected, vehicles involved in the conflict perform the following three steps:
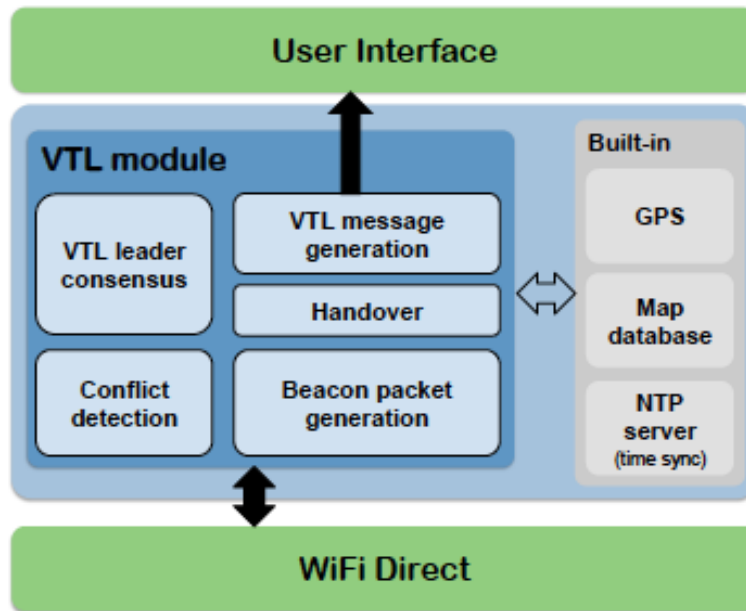
Figure 4.1. Design and architecture of Virtual Traffic Light implementation on Android-based smartphones.

A. Leader Election Process
As vehicles approach the same intersection (when, a conflict is detected), vehicles on the same road must agree on electing one of them (usually the closest one to the intersection) to act as the cluster leader and all cluster leaders must agree on electing one of the cluster leaders to act as the VTL leader for the intersection. Once the VTL leader has been identified, it announces its leadership to all cluster leaders who, upon receiving such announcement message, reply with acknowledgment packets. The elected leader will serve as temporary traffic light infrastructure and is responsible for creating and broadcasting traffic light information. Other vehicles act as passive nodes, listen to and obey the traffic light information broadcasted from the leader. To avoid unnecessary leader election process, the leader is presented with red light and stops at the intersection while leading it.

B. Generation of Traffic Light Information
Once a leader is elected, it determines how long each approaching direction should receive the right of way (i.e., phase layout of the traffic light). This phase layout could be pre-programmed or dynamically configured based on several parameters such as the amount of traffic in each direction, level of congestion at the intersection, priority of roads, etc. To enable a fair utilization of the intersection, the number of cars waiting in each road should also be taken into account. Phase preemption could also be enabled - once the VTL leader detects that the road with the green light has no additional vehicles attempting to cross the intersection, the current phase is interrupted and the green light is given to the next connecting road [2].

C. Leader Handover
When the green light is in the leader's lane, a new leader must be elected to maintain the virtual traffic light infrastructure. The new leader can be elected by two possible mechanisms: - i) the current leader hands over the leading task to one of the vehicles stopped before a red light at the intersection or ii) the new leader election is performed if

there are no stopped vehicles at red lights. It has been shown by extensive simulations that the aforementioned traffic control scheme (i.e., Virtual Traffic Light (VTL) system) could provide up to 60% improvement in traffic flow [2]. It should be noted that the VTL system operates under the assumption that all vehicles are equipped with DSRC radios and vehicle-to-vehicle communications problems (such as packet collisions, packet drops due to obstruction in RF propagation) are not severe and do not disrupt the VTL leader election. In addition, all vehicles are assumed to be equipped with a GPS device that shares the same digital map and has lane-level accuracy.

III. Virtual Traffic Light Architecture and Prototype Design

Overview of the design and architecture used to implement the VTL protocol is depicted in Figure 4.1. In addition to the five key submodules implemented within the VTL module, the implementation includes the user interface component, makes use of and operates based on the input provided by the built-in modules such as GPS, Map database, and NTP server (for time synchronization purpose [8]). Two different map formats are used in the implementation: XML format [51] used in VTL module and GoogleMap format used for display purpose. Note that, in this work, the WiFi Direct[9]2 (i.e., the WiFi infrastructureless mode in Android) is used as the underlying means of communications.

Figure 4.2 depicts the state machine design of our implementation. The VTL module can be in one of the four states as shown in the figure. Upon approaching an intersection, the vehicle, based on its own location and locations of its neighbors obtained from beacon packets (see Figure 4.3(i)), determines if there is an ensuing conflict at the intersection it is about to approach. In the case where a conflict is detected, the vehicle determines, again based on its location and location of its neighbors, whether or not it should serve as the Cluster Leader for the road it travels. In other words, if it is the closest vehicle to the intersection in its own cluster, the vehicle will be elected as the cluster leader; otherwise, it will act as a passive node and obey the traffic light information (see Figure 4.3(iv)) broadcasted from the VTL leader or the cluster leader. It is worth pointing out that the cluster leader may become the VTL leader in one of the two situations: i) among the cluster leaders on the other approaching streets, the vehicle is the closest vehicle to the intersection; or ii) the vehicle receives the handover message from the current VTL leader. In the scenario where neither of these two conditions is met, the vehicle remains as the cluster leader; it sends an acknowledgment packet (see Figure 4.3(iii)) upon receiving VTL Leader packet (see Figure 4.3(ii)) from the elected VTL leader and obeys the traffic light information broadcasted from the VTL leader.

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[8] Note that we have implemented three different time synchronization methods (i.e., through GPS clock, wireless provider clock, and NTP server). Although the NTP server can best address the time synchronization issue, the experiments have shown that the time difference between two phones can be as large as 900 ms. The time synchronization problem thus requires further investigation.

[9] Only Android 4.0 and later versions can support the WiFi Direct mode.
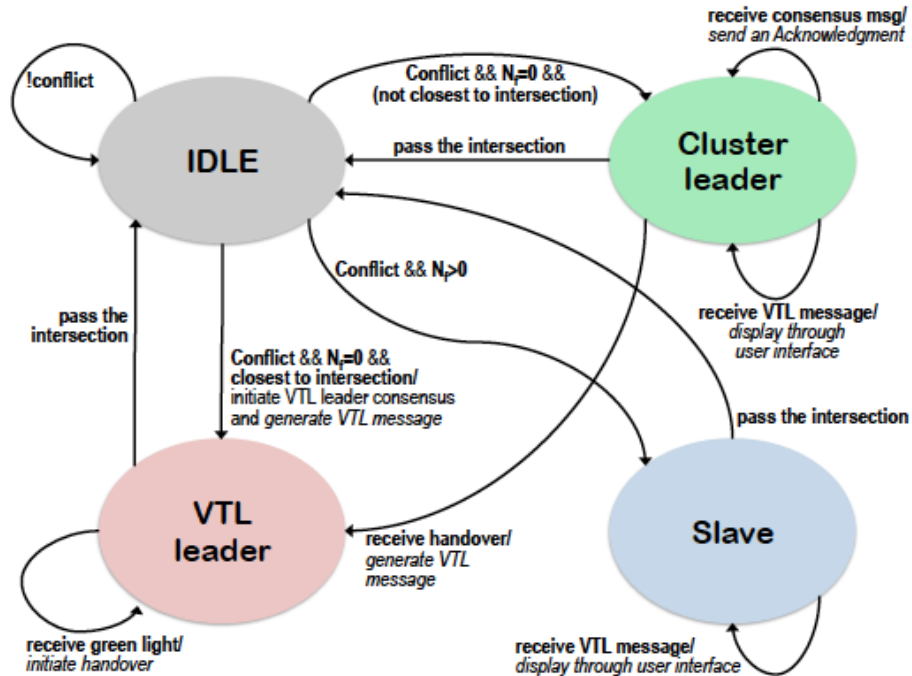
Figure 4.2. State machine of the VTL implementation in Android-based smartphones. Nf denotes the number of vehicles in the front that are approaching the same intersection.

The VTL leader, on the other hand, is responsible for computing traffic signal plan for the intersection it serves, and broadcasting the traffic light information to other vehicles. Upon receiving a green light and when it is ready to cross the intersection, the VTL leader initiates a handover process to delegate the VTL leader responsibility to one of the other cluster leaders at the intersection.

IV. Demonstration

The main objective of the demonstration is to show the operation of the VTL module implemented on Android smartphones. Three phones - two Nexus 4 running Android 4.2 and Galaxy S 3 mini running Android 4.1 - are used in the demonstration and their screenshots are shown in Figure 4.4. In order to verify the operation of the implemented module, we isolate the communications and GPS problems by performing the experiment in a simple and ideal indoor scenario in which the GPS locations of each vehicle (i.e., phone) are emulated and three phones are put next to one another as shown in Figure 4.4.
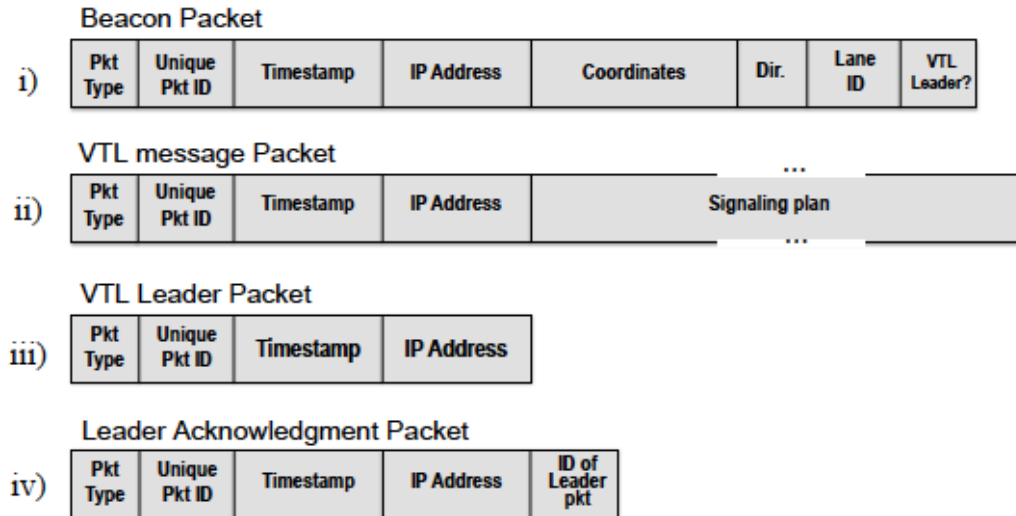
Figure 4.3. Four different types of packet implemented in the VTL protocol.

As depicted in the figure, the user interface consists of 5 elements: i) map, ii) vehicle icons that represent current locations of itself (i.e., indicated by black color) and its neighbors, iii) traffic light color displayed to the vehicle, iv) control buttons to manually change vehicle locations, and v) debugging information to show the status of the VTL operation.
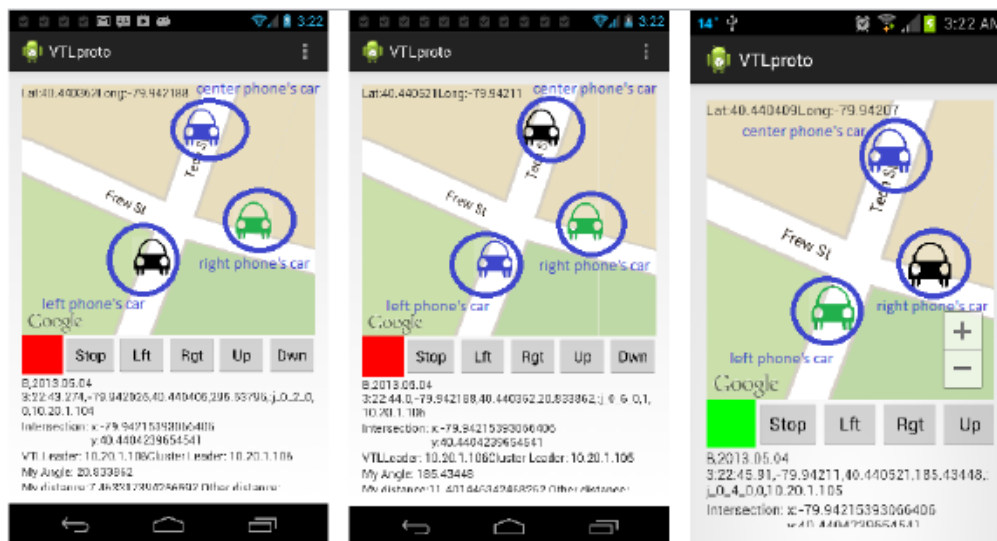

Figure 4.4. VTL user interface on Android-based smartphones. In this scenario, a total of three phones are used. The VTL module in the phone is able to locate itself (indicated by the vehicle in black color) and nearby vehicles (indicated by green and blue colors).

Screenshots shown in Figure 4.4 depict the scenario where three vehicles are approaching the intersection from three different directions (i.e., the left, middle, and right vehicles/phones travel in northbound, southbound, and westbound directions, respectively). Since there is one vehicle in each direction, all three vehicles serve as the cluster leader except the left vehicle who also serves as the VTL leader because it is the

closest vehicle to the intersection[10]. The elected VTL leader then presents a red light to its approach and a green light to the orthogonal direction. As a result, the left and middle vehicles are presented with a red light where the right vehicle that travels on the orthogonal road is presented with a green light.

In addition to demonstrating the VTL operation, a set of measurements have been carried out to measure the packet latency which is defined as the duration of time from which a beacon packet is sent from the VTL application in one phone to the time the same packet is received by the VTL application in the other phone. Note that since the receiver thread is not always active (i.e., it becomes active every n ms where n is the receiver sleep time), the beacon packet latency significantly varies with the value of n. Observe from Table 8 that even with the large receiver sleep time of 1 second, the packet latency is small and remains below 0:1 second. This, in turn, suggests that it may be feasible to implement the VTL operation on smartphones; i.e., by the time a vehicle receives a beacon packet, the transmitting vehicle moves less than 1 meter. In addition to latency measurement, it is necessary to measure the communication range provided by the Android's WiFi radio for determining the feasibility of the Android-based VTL implementation.

Receiver sleeptime (ms)	Average (ms)	Std. dev. (ms)
25	2.54	1.63
100	9.97	6.31
1000	77.05	73.87

Table 8: Packet Latency for different receiver sleeptime.

V. Conclusion and Future Work

In this report, we present the Virtual Traffic Lights (VTL) implementation on smartphones using Android OS. The VTL concept is a self-organizing traffic control concept which aims to alleviate the urban traffic congestion problem by leveraging the vehicle-to-vehicle communications. By communicating among themselves, vehicles, in an ad hoc manner, are able to resolve conflicts at intersections and establish the "right of way". Previous simulation results have shown that the VTL can provide up to 60% improvement in traffic flow. In order to demonstrate benefits of the VTL in a real-world scenario, in this report, we propose to implement the VTL on smartphones using Android OS, mainly due to the proliferation of smartphones and the dominant market share of Android operating system.

The promising experimental results reported in this report show that the VTL concept can be implemented using hardware available in the current smartphones. While there are other issues (such as fault-tolerance and security issues) that need further investigation, we believe that the VTL prototype presented in this report clearly demonstrates the feasibility of implementing VTL concept. It is our hope that the promising results presented in this report will provide further motivation for policy makers to pass legislation for the use of VTL as a compelling solution for mitigating urban traffic congestion.

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[10] The VTL leader election process which consists of broadcasting a VTL leader packet by the VTL leader and Leader Acknowledgment packets by other cluster leaders is performed in the background.

Part 5:
Interaction with Pedestrians and Cyclists

I. Executive Summary

A VTL (Virtual Traffic Light) system has been proposed as a solution to solve problems associated with the existing infrastructure in traffic management systems. Despite the promising results of VTL, the VTL technology considers only vehicular traffic (i.e., motorized traffic) and has yet to provide support for pedestrians and bicyclists on the road (i.e., non-motorized traffic). This study attempts to fill this gap by investigating the issue of pedestrian safety at crossings and proposing an integrated solution that enables the existing VTL technology to consider the presences of both motorized and non-motorized traffic in its implementation.

II. Introduction

Pedestrian safety at intersections has remained one of the crucial concerns in providing road traffic safety not only because more than 1000 pedestrian deaths are observed annually but also because this alarming statistics has stayed approximately the same for the past decade despite countless number of traffic engineering measures that have been proposed [54]. In addition to these numbers, it is worth to point out that pedestrian fatalities at intersections contribute major portions of all road-related accidents. In particular, even though intersections represent less than 10% of U.S. surface road mileage, more than 20% of pedestrian deaths occur at intersections and more than 40% of all injured pedestrians were injured at intersections [54]. This therefore suggests the importance for any intersection control management to take pedestrian safety issue into the consideration [55].

In recent years, a new traffic management concept, namely Virtual Traffic Light (VTL), has been proposed. The VTL technology is a self-organizing intersection control that is based on vehicle-to-vehicle (V2V) communications that uses Dedicated Short Range Communications (DSRC) technology in the 5.9GHz. In a VTL system, vehicles self-organize to elect a leader to serve as a virtual traffic light infrastructure that resolves traffic conflict at the intersection by assigning the right of way to vehicles at that intersection, thus replacing the current physical traffic lights. This revolutionary technology has been shown to be able to significantly improve traffic flow at intersections, reduce commute time of urban workers, increase productivity, and reduce carbon emissions [2].

Despite this promising direction and result, current implementation of the VTL technology only address intersection conflicts where the conflicts only involve vehicles (i.e., motorized traffic) and it has yet to provide support for non-motorized traffic (e.g., pedestrians and bicyclists) involved in the conflicts. This report thus attempts to fill this gap by studying the existing techniques that have been proposed to improve pedestrian safety at intersections. These techniques are then integrated with the self-organized VTL traffic control scheme and the integrated solutions are evaluated and compared. Finally, an optimal solution is suggested that can provide sufficient safety for non-motorized traffic at intersections without significantly affecting traffic flow of motorized traffic.

III. Related Work

Pedestrian detection has received much interest over the years and remained at the forefront of the field of computer vision. In many ways, the problem of pedestrian detection is challenging given the complexity of human appearance and behavior. Complex situations can involve occlusion on the part of the pedestrian appearance, multi-pedestrian detection, etc. Interesting works and techniques include Chamfer Distance and template matching [56], Haarlike features and AdaBoost classifiers [57], and Histogram of Oriented Gradients with Support Vector Machines [58]. Pedestrian detection system has also been successfully implemented in commercial products, e.g., Chrysler, Daimler and General Motors.

For instance, the Daimler group uses the template matching technique based on Chamfer distance for pedestrian detection. The main idea behind this approach is to maximize the offline "learning" or "training" phase by learning from a hierarchical set of templates in different directions.
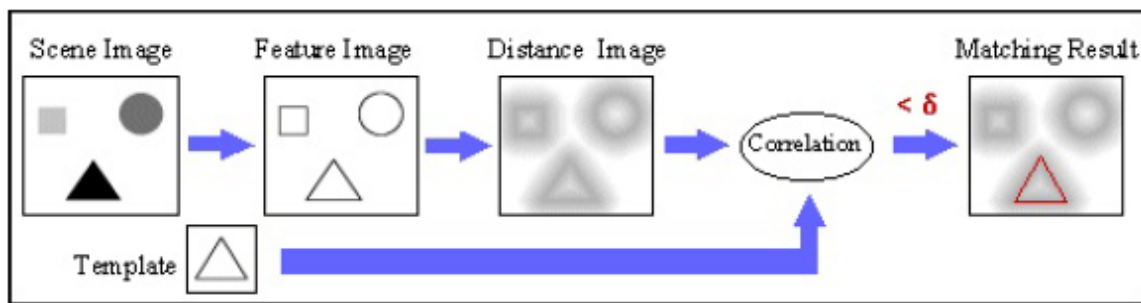

Figure 5.1. Template matching using Chamfer Distance

Another popular technique used is Histogram of Oriented Gradients (HoG) [58]. This technique is known to produce most reliable results in pedestrian detection, among other techniques. The image is divided into blocks and an overlap is maintained between them, so that every block has more than half of its contribution while taking the voted majority in a particular window area. The magnitude of the gradient is binned into bins distributed over 0-180 degrees. Further training can be done by learning an SVM model with the HoG features computed in order to perform a binary classification of the image containing a pedestrian or not.

While there has been ongoing work in pedestrian detection field alone, an integrated solution that combines the pedestrian detection system with intersection control management system does not exist. So far, most of the work is either implemented as an independent system or coupled with an automatic braking system, e.g., Volvo.

IV. Pedestrian detection system and VTL

The first part of this study involves an accurate pedestrian detection system that takes as input still images from a device mounted in the car. Based on previous study and work conducted on object and human detection, there are multiple ways to carry out pedestrian detection. Preliminary study on the different approaches within image segmentation included:
- Edge/Contour Lines Detection
- Feature Extraction and Classification (Pattern Recognition)

- Support Vector Machines

Complete use of any one methodology may not prove to be useful. A combined use of feature extraction and learning methods may instead be useful. Edge gradients are a good way to detect the boundaries of the pedestrians; however, possible challenges include detecting pedestrians within varying environmental conditions and at varying distances and orientations. As a result, we propose a new technique that integrates several pedestrian detection algorithms and the main idea of the proposed technique is depicted in the figure below.
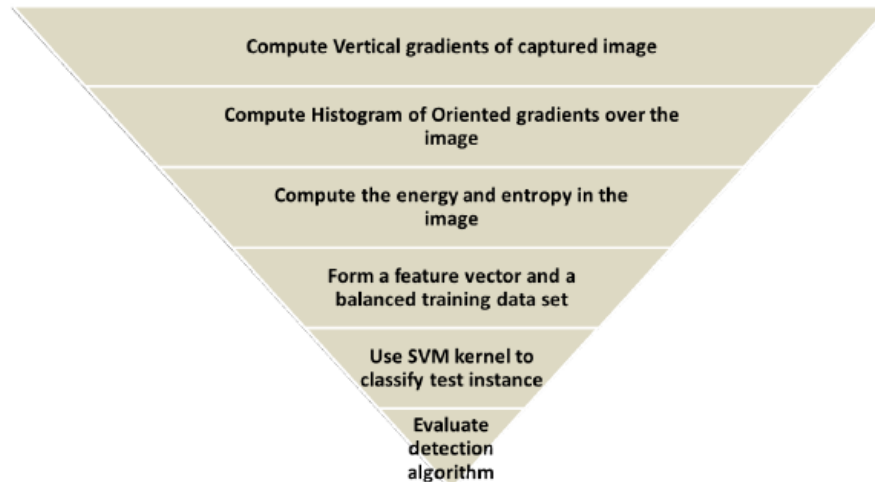

Figure 5.2. Structure of the proposed integrated pedestrian detection technique

The images being used in the proposed system are collected from the MIT CBCL Pedestrian Database. In order to train an SVM model to further classify unseen instances of images, we compute features over multiple images acquired from the Database. A template is maintained for comparison with every vertical gradient of the image. The difference between the template's vertical gradients and the training data will train the SVM to identify an image with low difference of vertical gradients, as a pedestrian image, and vice versa. The image from the dataset is subjected to a first derivative mask to calculate the horizontal and the vertical gradient. The direction of orientation is also computed.

Figures 5.3 and 5.4 shows the actual images and vertical gradients of the images, respectively. Note that the left image contains a pedestrian while the right one does not. Observe that the image containing the pedestrian has more vertical gradients than the negative image.

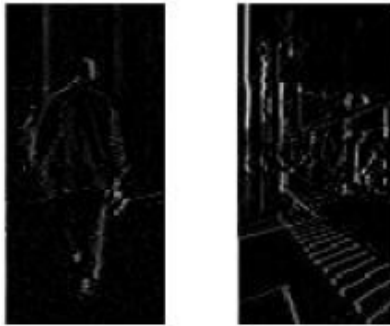Figure 5.3. Example Images used for Training

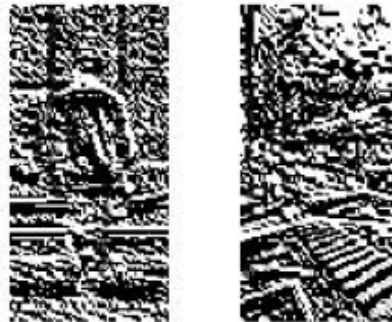Figure 5.4. Vertical Gradients being used as Template for computing features

Figure 5.5. Gradient Orientation for the respective images

Figure 5.5 shows the directional gradients in the two images. The difference image formed by subtracting the vertical gradients of every new input image from the vertical gradient of the template image can indicate whether the input image had considerable vertical gradients or only a few.

Thus, the features being computed to train an SVM classifier are the mean value of the difference between the vertical gradients, the sum of the difference matrix, the entropy or the useful "information" contained in the image, and the HoG features. A negative image, having fewer vertical gradients, would have a larger difference matrix as compared to an image having considerable vertical content. Also, a negative image, on "average" will have a higher entropy measure. The entropy basically captures the amount of "reducible" or "compressible" content in the image. In a positive training instance, i.e. one containing a pedestrian, the vertical gradient image is more or less spatially

correlated. Spatial correlations would result in lower entropy figures. As opposed to this, negative images that contain less correlations in their vertical gradient image, due to absence of prominent vertical edges, thus, resulting in higher entropy measures. This trend helps us differentiate between positive and negative training examples and thus aids classification.

All of the features need not be used all the time. For images that are captured at a relatively close distance may be classified with a high degree of accuracy with just the vertical gradients feature, while those with incrementally larger distances would require more features.

The labels have been obtained from the ground truth that is annotated in the MIT CBCL Database. Features include Histogram values, and statistical measures of inter-cell variability [59]. MATLAB is being used as the tool to train the dataset over the computed features and the function svmtrain and svmclassify are being used to train the model and classify test instances respectively.

Sum of the Difference Matrix	Mean of the Difference Matrix	Entropy	HoG	Label
0	0	0.9877	0.27729	Yes
0	0	0.9877	0.27729	Yes
7311	0.89246	0.93051	0.26375	Yes
-2775	-0.33875	0.98935	0.29071	Yes
4557	0.55627	0.98237	0.28761	Yes
9264	1.1309	0.9979	0.28077	No
-11847	-1.4462	0.9985	0.26761	No
21124	2.5786	0.9969	0.28339	No
10588	1.2925	0.9972	0.28257	No

Table 5.1: Example of training data

Algorithmic task	Time in Seconds
Create Template	0.3988
Feature Extraction for Training Data(First Time)	11.2318
Feature Extraction for Training Data	2.2023
Train SVM Model with Kernel Parameters	3.14386
Classify Test Instance with SVM Model	0.0280

Table 5.2: Time complexity

The SVM kernels such as 'linear', 'quadratic' and 'rbf' were tried, and observations showed rbf kernel to perform the best. A 90 degree of accuracy has been obtained so far, although a higher one would be most preferred.

With the above data, a machine learning model is constructed in MATLAB, with 10-crossfold validation that is carried out on the training data. Table below summarizes the accuracy of the proposed model; i.e., 90% accuracy with 13% false positive rate and 8% true negative rate.

	Pedestrian	No Pedestrian
Pedestrian	46	4
No pedestrian	4	26

Table 5.3: Performance of the proposed model

The SVM classifier will classify an image as positive or negative and produce a binary output +1 or -1, respectively. This binary output is then used as a flag variable that the cars will use to signal to the other cars through DSRC communication whether or not a pedestrian is detected at that intersection. This signaling will be used to extend the "green" signal to the vehicles that would be given right-of-way, also extending the "stop" time for the vehicles that have to wait for the safety of the pedestrian.

In the preliminary implementation of the integrated solution (i.e., VTL plus pedestrian detection), we assume that the pedestrian wait time is zero. In other words, when a pedestrian is present, vehicles at intersections can detect and stop to allow the pedestrians to cross immediately.

The experiments showed some key results that perfectly characterize the nature of the conventional Traffic Light System as shown in Figure 5.6. As the number of cars on the intersection was increased, the throughput, i.e. the total number of cars passing the intersection was seen to increase till the point where congestion occurred, after which it decreased. This can be attributed to the pre-defined red and green intervals that are given to the cars irrespective of the fact whether the pedestrian was present or not as well as whether any vehicle was present on the road or not.

The same experiment when carried out on the VTL-Pedestrian Detection system showed positive results, namely, a higher throughput of the cars passing the intersection, however, after congestion occurs, it shows a decreasing trend, but still remains higher than conventional TLS.
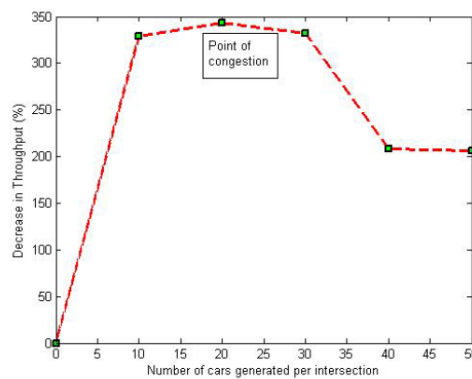

Figure 5.6. Decrease in Throughput in TLS

Figure 5.6 shows the performance of a TLS in an urban environment, where the density increases with peak-hour traffic.

As seen, the traffic flow rate continues to increase till the "point of capacity", i.e. till congestion occurs. Beyond this point, it can be clearly seen that the throughput

decreases.

V. Challenges Faced

The methodology initially selected for pedestrian detection was to slide an edge template over the test image. By using distance transformation, computation of the distance between the pixels of the two images could be possible. By doing so, finding the best match between the edge template selected and the input image could be possible. However, the problem faced with this approach was, to form a cascade of hierarchical templates, each one representing a different orientation of the pedestrian [60]. This process involved high complexity in terms of algorithm, and time. Further, the time taken to train the model is also an important performance measure.

Overall, template matching by this technique involves exhaustive shape-matching using hierarchy of templates. Ongoing in the project, the task of forming a feature vector is also a critical one. The goal is to capture as much information about the pedestrian that distinguishes it from the rest of the background. Features used are vertical gradients, entropy and HoG features. Selecting the most optimal features as a function of the distance would optimize the algorithm.

VI. Conclusion

The integration of pedestrian detection algorithms with the VTL is a novel research direction. With a greater penetration of wireless networks in our daily lives, VTL may soon become a reality. To further make the system more intelligent and safe for the society, accurate pedestrian detection will be a valuable addition. As seen, there can be many possible approaches to pedestrian detection, with the underlying principle for all being edge and gradient detections.

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