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A Cooperative V2V Alert System to Mitigate Vehicular Traffic Shock Waves

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Abstract

Vehicle traffic on highway systems are typically not uniformly distributed. In our work, we introduce a protocol that exploits this phenomenon by considering the formations of shock waves and opportunities in adjacent lanes. The objective of this protocol is to reduce the impact of a shock wave by using event-driven messages between vehicles that provide drivers with velocity or lane switching recommendations. We show how our protocol uniformly distributes vehicle densities across multiple lanes while maintaining lane fairness, and reduces the number of vehicles entering a shock wave point. Simulation results show we are able to further reduce the overall travel times and increase the average velocity.

Keywords:

Vehicular Networks, lane-changing, shock waves

I Introduction

Vehicles play an instrumental part in our daily lives, and have transformed the way we live. Vehicles are used to transport goods as well as to transport people across short or long distances for various purposes. Throughout the years the number of vehicles around the world has been on a steady increase. This trend is especially true in the US. Figure 1 shows the rise in the number of registered vehicles in the US around the past fifty years [5]. Currently, there are over 260 million vehicles registered in the US. This large number of vehicle ownership leads to a high volume of traffic along roadways, which exasperates the issue of traffic congestion.

Traffic congestion has been a major issue over the years, particularly in larger cities. This issue contributes to high economic cost with respect to the amount of time people waste, the extra fuel that is expended, and property damage due to accidents. Traffic congestion also generates a large amount of air pollution [13]. Traditionally, the solution to traffic congestion has been to expand the road network to meet the increased traffic demand. However, this solution is becoming unfeasible due to the extraordinary cost of expanding the infrastructure, and the fact that people live around the bulk of these areas make planning and building additional capacity very complex [1]. Unfortunately, the current road infrastructure is not being

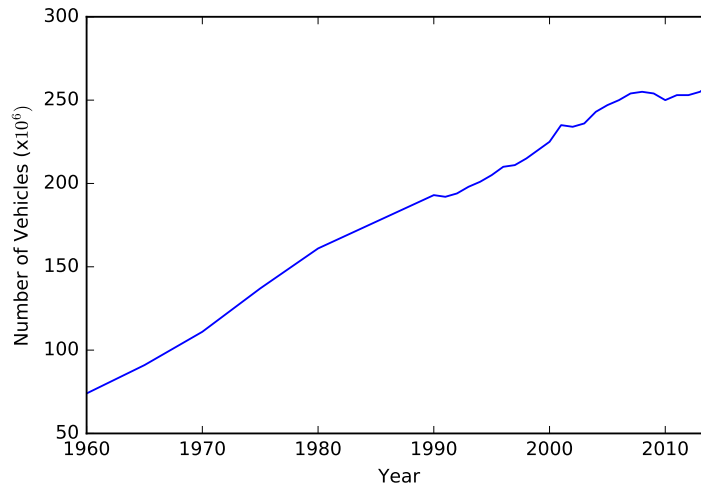


Fig. 1: Number of registered cars per year in the US

used to its full potential due to the fact that in uncoordinated vehicular traffic a significant amount of road capacity is not efficiently used. Vehicles tend to only travel in free flow mode in low densities and when interactions between vehicles are small [8].

Vehicle communication is a promising technology that will open the way for applications that will change how drivers travel. The data that vehicles can share via wireless communication makes it possible for vehicles to travel more efficiently.

In this work we present a novel protocol that uses traffic information shared amongst vehicles in uncoordinated traffic to uniformly distribute vehicles along highways.

The remainder of this paper is organized as follows: In Section 2 we discuss the related work. In Section 3 we discuss several situations that can lead to the degradation of traffic flow. In Section 4 we introduce our protocol to improve the flow of traffic. In Section 5 we present an evaluation of our protocol in various circumstances. Finally, we conclude our work in Section 6.

II Related Work

Improving traffic efficiency has also been an area of interest. Intelligent Transportation Systems (ITS), which rely on wireless communication technologies has shown to provide traffic benefits. Wireless communication in ITS exist between vehicles (V2V) and vehicles to infrastructure (V2I) enabling the exchange of relevant traffic information [7, 9].

In [10], a highway system that relies on Variable Speed Limits (VSL) is proposed. The main aim of the paper was to address safety, however the authors found that placing VSLs along a highway decreases the slope of the flow-density, and increases the critical occupancy so support of higher values permitting higher traffic flows at the same traffic density. In [12], the authors demonstrate how communication between vehicles enables vehicles to travel with shorter headways resulting in an increased capacity.

Managing lane maneuvers in traffic has also been an area of interest. Wolterink et. al [15] proposed a concept that relies on roadside units (RSU) and vehicle communication to predict vehicles positions in advance of an on-ramp and relying on RSU to facilitate merging gaps for on-ramp traffic. In [4], the authors propose a traffic model that provides lane fairness through communication in a situation where two lanes merge into one. Vehicles coordinate their actions based on a first-come-first served basis allowing vehicles to merge fairly.

In our work we rely on properties from macroscopic car following principles density, flow, and velocity. We use vehicles velocity to estimate the flow and density between communicating vehicles, and recommend opportune lane changes to distribute the vehicle densities across multiple lanes when possible.

III Problem Statement

In this section we introduce situations that can lead to break downs in traffic. In particular we discuss shock waves or *phantom jams* and bottlenecks, and how vehicular communication is utilized to mitigate the impact of these events.

Traffic bottlenecks are a product of high traffic demand and physical perturbations such as construction sites, crashes, or a reduction of lanes. At a bottleneck the capacity drops and the number of vehicles arriving at the bottleneck tend to exceed the capacity. Similarly, traffic shock waves are coupled with the occurrence of high traffic demand and unexpected driver actions. In dense traffic an action that causes a driver to slow down, even very briefly, can result in a temporary overload that leads to the formation of a shock wave upstream, and congestion [3, 14].

Figure 2 demonstrates the formation of a shock wave in a simple one-lane road scenario. From left to right the graph depicts the same road segment at consecutive time steps. In the first time step, the leading vehicle slows down for some unknown reason, as depicted by the red arrow against the driving direction. In the next time step the vehicles that follow must adapt their speeds in order not to crash into the lead vehicle. Hence, the new velocity of the following vehicles must be decreased below that of the leading one. During the following time steps, this prescription to brake travels upstream forming a shock wave. Stop-and-Go traffic often seems to appear out of nowhere, resulting in congestion.

From Figure 2, one can see that vehicles are limited by their line of sight, and can only react to an event such as braking when the occurrence is in view. This results in the necessity to brake hard to avoid a collision, and subsequently accelerating to leave the congested area. This results in a waste of energy and an increase in vehicle emissions.

The traffic density on a long road segment is not uniformly distributed, at some locations the density of vehicles can be high while at intermediate sections there are lower densities. This phenomenon also occurs across lanes with multi-lane highways. Often if vehicles do not change lanes at an opportune time this action can cause traffic to break down as well. Our work takes advantage of this phenomenon by relying on communication between vehicles to share information across long distances, extending a drivers awareness

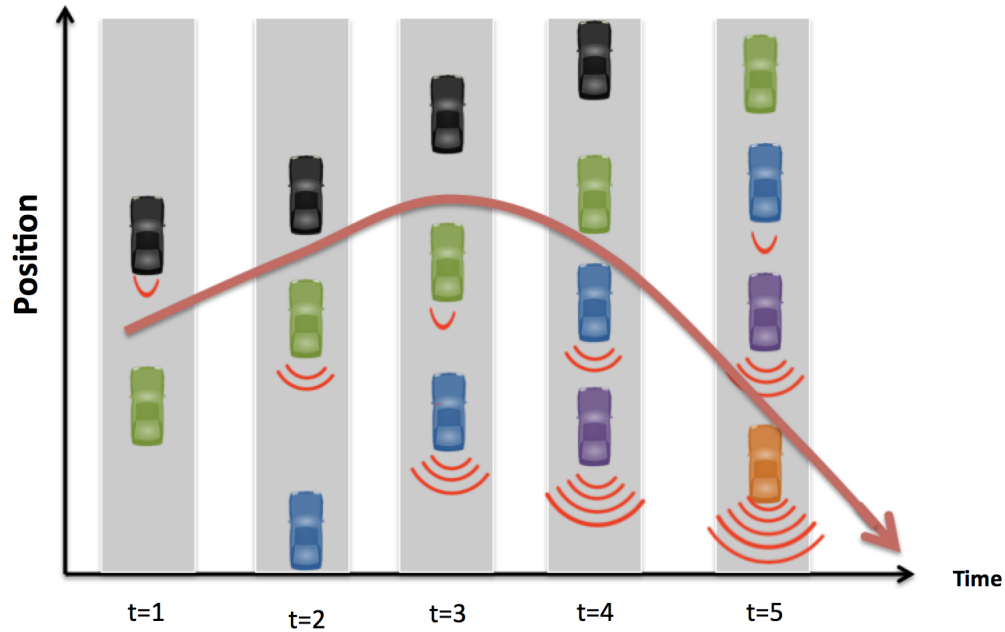


Fig. 2: Formation of shock wave over time

beyond the driver's line of sight. Having information in advance of a traffic disturbances provides us with the opportunity to react to the situation ahead of time with more insight than without communication.

IV DRIVE-EX Protocol

In this section we describe our extension to the communication protocol *Density Redistribution through Intelligent Velocity Estimation* (DRIVE). The network protocol proposed in this paper complies with the IEEE 802.11p standard for Wireless Access in Vehicular Environments [2].

Drive-EX is a connectionless protocol that broadcast messages when a vehicle slows down or the velocity falls below a threshold. Like the original DRIVE protocol, Drive-EX consists of three phases, the notification phase, the reception phase, and the forwarding phase. However, the notification and reception phases have been extended to process information from adjacent lanes. We assume that vehicles are equipped with optic sensors so that they can determine which lane they occupy.

In the event that a vehicle must decrease its velocity, a message that contains vehicle information is broadcast to neighboring vehicles. Vehicles on reception of the slow down message that are further downstream from the messaging vehicle broadcast their traffic state information as well. The following vehicle in the same lane as the vehicle that is slowing down either adapts its velocity or switches to an adjacent lane based on recommendations from the Drive-EX protocol. Prior to a lane change maneuver, the system coordinates the execution of the lane change with vehicles in the target lane via V2V, and vehicles following in the departed lane abstain from changing lanes for a predetermined period of time. However, if a vehicle follows the slow down recommendation the slowdown message is rebroadcast until a time to live is reached or until the system determines that there are no actions to be taken.

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

Notification Phase

Vehicles that slow down below a threshold Δv_n or traveling below the minimum expected velocity v_{min} trigger a message to be broadcast. Vehicles in adjacent lanes receiving this message broadcast a message as well.

$$m_h = [id, x_s, y_s, x_o, y_o, t_o, v_o, v_{o,t-1}, f] \quad (1)$$

where $h \in H$ is a unique message identifier, and id is a unique identifier of the vehicle originating the message. x_s and y_s are the GPS coordinates of the sender, and x_o and y_o are the GPS coordinates of where the message was created. The other values in the message are the time stamp of message creation t_o , the velocity of the message originator v_o , and the $v_{o,t-1}$ a second prior to the creation of the message. f is a flag to represent the message type, where $f \in [SLOW, LANE, CHANGE]$. SLOW is the type of message that is broadcast when a vehicle experiences a reduction in velocity. LANE is the message type that a vehicle broadcast when it receives a SLOW message from a vehicle that is in an adjacent lane and in a downstream position. The CHANGE message type is broadcast when a vehicle follows a lane change recommendation and is used to coordinate the execution of lane changes with vehicles.

Algorithm Reception Phase

```

v: local vehicle
m: received message
if  $m_{type} == SLOW$  then
  if  $m_{lane} == v_{lane}$  AND  $m_x > v_x$  then
    store  $m$  in slow down queue
  else if  $abs(m_{lane} - v_{lane}) == 1$  AND  $m_x < v_x$  then
    broadcast LANE message with  $v$  state
  else
    drop  $m$ 
  end if
else if  $m_{type} == LANE$  then
  if  $abs(m_{lane} - v_{lane}) == 1$  AND  $m_x > v_x$  then
    store  $m$  adjacent lanes queue
  else
    drop  $m$ 
  end if
else if  $m_{type} == CHANGE$  then
  if  $m_{lane} == v_{lane}$  AND  $m_x > v_x$  then
    remain in lane for time  $t$ 
  else
    drop  $m$ 
  end if
end if

```

Reception Phase

On reception of a notification message m_h , the system determines the type of the message and processes the message accordingly. If a SLOW type message is received, the system determines its position with respect to the originator of the message. If the receiving vehicle is in an adjacent lane, and in front of the messaging

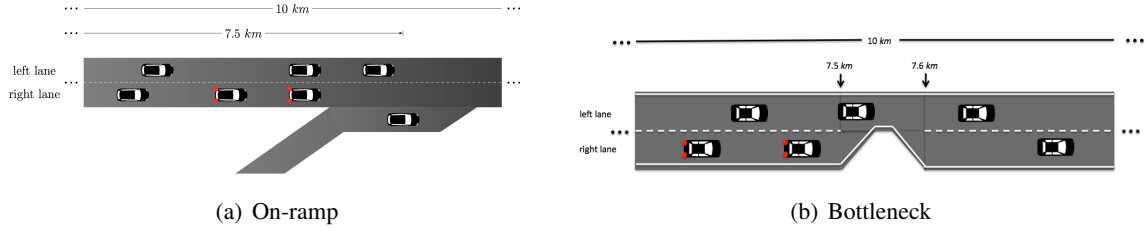


Fig. 3: Simulated road segments

vehicle, a LANE message with the vehicle's state is broadcast. LANE message broadcasts are performed opportunistically to prevent multiple vehicles from responding to the same SLOW message and causing a broadcast storm. If a vehicle is in the same lane as a SLOW message vehicle the message is stored in a Slow Message Queue to be processed by the system. LANE messages are only of interest to vehicles that are in lanes adjacent to the message and in a position subsequent to the messaging vehicle. Vehicles that meet this condition store the LANE message in a Lane Message Queue. CHANGE messages only apply to vehicles that occupy the lane that the messaging vehicle recently departed. Vehicles that receive this message avoid performing any lane changes for a time period t to prevent a high number of lane change occurrences.

Every second, the system checks the most recent received messages from its Slow Message Queue and Lane Message Queue. The protocol then estimates the traffic condition between vehicles in its current lane and uses information from vehicles in adjacent lanes to estimate the traffic state of other lanes as well. If a slow down is detected in a vehicle's current lane Drive-EX computes a slow down recommendation for the vehicle to avoid a shock wave. Drive-EX compares the computed velocity to the velocity of other lanes by only considering vehicles that are beyond the line of sight further downstream. An incentive factor α is applied to the velocity in adjacent lanes. If the system determines that a vehicle can improve its velocity with the α , a lane change maneuver is recommended. The value of α has an impact on the vehicle's tactical lane changes. Otherwise the system will recommend a velocity reduction. The protocol uses the LRW model to predict the traffic state between two communicating vehicles. Details of the computation of the shock wave velocity can be found in [6]. The DRIVE-EX recommendation is computed as follows:

$$rec = \begin{cases} LC & m_{v,SLOW} < \alpha m_{v,LANE} \\ SD & m_{v,SLOW} \geq \alpha m_{v,LANE} \end{cases}$$

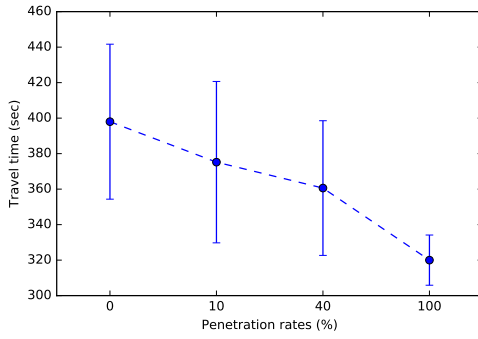
where rec is the system's recommendation. $m_{v,SLOW}$ and $m_{v,LANE}$ are the velocities from the SLOW message and LANE message respectively. LC is a recommendation to switch to the lane of the messaging vehicle, and SD is a recommendation to remain in the current lane and adjust velocity for a specified period.

Forwarding Phase

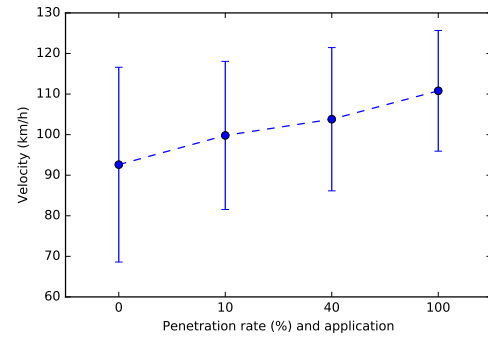
In this phase, if a vehicle follows a slow down recommendation from a SLOW message the vehicle rebroadcast the received message at least once; however if a vehicle switches to a new lane, the vehicle does not forward the slow down message. Instead the vehicle broadcasts a to LANE message to other vehicles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

V Evaluation

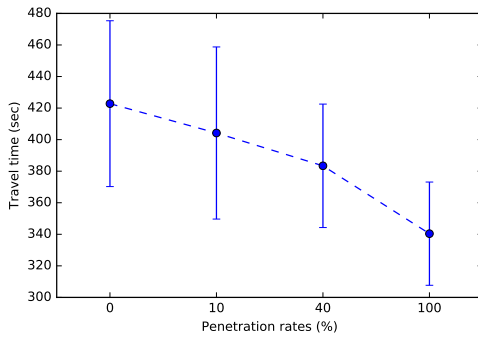
In this section, we evaluate the performance of the our proposed protocol via simulation. We first describe the simulation setup, followed by the results.



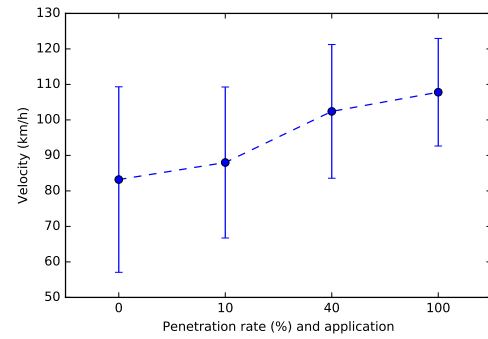
(a) Overall travel time On-Ramp Highway



(b) Average velocities On-Ramp Highway



(c) Overall travel time Bottleneck Highway



(d) Average velocities Bottleneck Highway

Fig. 4: Statistical evaluation of the average velocities and overall travel time for different penetration rates

Simulation Setup

Simulations were carried out using Vehicles in Network Simulation (Veins) [11], which couples a network communication simulator with a vehicle traffic simulator. Two highway topologies were simulated. One consist of a two lane highway of 10 km with an on-ramp at 7.5 km as depicted in Figure 3(a). The other highway topology consist of a two lane highway that is reduced to one lane at 7.5 km for 100 km, and then returns to two lanes, as shown in Figure 3(b). This topology can represent various scenarios where a single lane of a highway is unusable for a small stretch. An example of this scenario can be an obstruction on the road such as a car crash. The simulation is simulated for a total of 2 hours. The traffic model used is the Krauss car-following model with symmetric lane changing rules, either lane can be utilized at anytime and no lane is designated exclusively for passing. Experiments showed that optimal results were achieved with an α value of 0.75, which is used throughout this paper.

The flow at the upstream boundary of the main lane was a constant 1000 vehicles per hour per lane, and the on-ramp flow was a constant 500 vehicles per hour. A single vehicle class was simulated to restrict traffic perturbations to the only on-ramp or driver dallying introduced by the Krauss car-following model. Vehicle communication was modeled after the IEEE 802.11p standard with a communication range of 500 m.

Results

Two analyses have been performed on two different highway configurations with different penetration rates of autonomous vehicles. In our simulation, all autonomous vehicles are equipped with systems such as Cooperative Adaptive Cruise Control (CACC) and fully follow the DRIVE-EX protocol. Vehicles that are not autonomous are considered human drivers who manually adapt their velocities. We compared completely uncoordinated traffic to 10%, 40%, and 100% penetration rates of the DRIVE-EX protocol. The simulation results are shown in Figure 4.

Figures 4a and 4b illustrate the overall travel time and mean velocity with their respective standard deviations with different penetration rates for the highway configuration with an on-ramp. The 100% penetration rates correspond to full road coverage with autonomous vehicles. The overall travel time is decreased by about 20%, from $T_{0\%} = 398.4s$ to $T_{100\%} = 320.7s$. The mean velocity is also improved, increasing by 20% as well from $V_{0\%} = 92.6km/h$ to $V_{100\%} = 110.8km/h$.

Figures 4c and 4d show the overall travel time and mean velocity for the highway configuration with a bottleneck. This analysis shows similar improvements, with benefits increasing as each penetration rate increases. However, the overall traffic performances is less in the case of the bottleneck due to the fact that the capacity of the highway takes a significant drop at the bottleneck position.

VI Conclusion

In this paper we introduce DRIVE-EX, a cooperative protocol that redistributes traffic along a road segment to improve the overall traffic efficiency by reacting to velocity reductions in advance to mitigate the formation of traffic hams caused by shock waves.

The protocol relies on traffic information from downstream to access traffic conditions ahead in a vehicles current lane and immediate adjacent lanes. Vehicles are able to adapt to traffic conditions beyond line of sight and perform optimal lane changes.

Simulation results show that the DRIVE-EX protocol significantly improves the overall traffic situation in various scenarios that can cause shock waves such as the obstruction of a lane due to an accident or on-ramp vehicles. We also show how the traffic state improves as the penetration rate of autonomous vehicles increase.

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