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Reducing Congestion by Using Integrated Corridor Management Technology to Divert Vehicles to Park-and-Ride Facilities

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Reducing Congestion Using Integrated Corridor Management Technology to Divert Vehicles to Underutilized Park-and-Ride Facilities

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16. Abstract
Connected Vehicles (CV) technology offers significant potential for managing traffic congestion and improving mobility along transportation corridors. This report presents a novel approach using integrated corridor management (ICM) technology to divert CVs to underutilized park-and-ride facilities where drivers can park their vehicle and access public transportation. Using vehicle-to-infrastructure (V2I) communication protocols, the system collects data on downstream traffic and sends messages regarding available park-and-ride options to upstream traffic. A deep reinforcement learning (DRL) program controls the messaging, with the objective of maximizing traffic throughput and minimizing CO2 emissions and travel time. The ICM strategy is simulated on a realistic model of Interstate 5 using Veins simulation software. The results show marginal improvement in throughput, freeway travel time, and CO2 emissions, but increased travel delay for drivers choosing to divert to a park-and-ride facility to take public transportation for a portion of their travel.

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Glossary of Terms

CV	Connected Vehicle
DRL	Deep Reinforcement Learning
DSRC	Dedicated Short-Range Communications
ICM	Integrated Corridor Management
IEEE	Institute of Electrical and Electronics Engineers
RSU	Roadside Unit
SAE	Society of Automobile Engineers
SUMO	Simulation of Urban MObility
TMC	Transportation Management Center
USRP	Universal Software Radio Peripheral
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle

Executive Summary

Executive Summary

This research addresses the problem of congestion on freeways, which increases travel time, increases CO2 emissions, and decreases throughput. To solve this problem, we suggest making use of a new Integrated Corridor Management (ICM) strategy, which involves redirecting vehicles to underutilized park-and-ride structures where drivers may park and access public transportation. This is achieved by leveraging emerging Vehicle-to-Infrastructure (V2I) communication capabilities supported by roadside units (RSUs) and vehicles' on-board units.

After modeling the corridor traffic components, we propose a novel, low-cost deep reinforcement learning (DRL) approach that can run on a centralized cloud server hosted at a Transportation Management Center (TMC)[1] to optimize traffic flow along a corridor of interest, such as the I-605 used in our analysis. Specifically, the DRL processes data collected by the RSUs regarding the level of congestion along the corridor and uses that information to prepare and transmit a message to vehicles advising them to leave the freeway and directing them to a park-and-ride structure to continue their journey via public transportation.

To evaluate our DRL approach, we created a realistic corridor simulation based on Interstate 5 (I-5) in the Los Angeles area. The DRL program sends out messages to the connected vehicles redirecting them to a park-and-ride facility at the I-605 and Lakewood Blvd junction (i.e., on ramp and exit) where they can access public transportation to complete their trip. The modeled strategy achieves marginal improvements in throughput (i.e., the overall rate at which vehicles travel through the corridor per unit time), average travel time, and average CO2 emissions, but at the cost of increased travel delay for drivers who were diverted to park-and-ride structures to access public transportation (i.e., bus service). Specifically, we observe up to 4% increase in the overall throughput, 4.7% reduction in corridor travel time, and 3.1% savings in CO2 emission savings, but at the cost of up to 52.6% additional delay for the subset of diverted drivers who elected to take public transportation.

We conclude that CO2 emissions can be further mitigated through adjusting the schedule and frequency of bus service at park-and-ride facilities. That is, tuning the rates at which buses are released from the park-and-ride facility in accordance with the commuters' supply and demand in addition to the congestion patterns. Furthermore, we observe that as more commuters comply with the V2I park-and-ride recommendations the smoother the traffic flow, which highlights the need to devise marketing strategies to encourage more drivers to comply with such messages. Compliance can also be increased as more connected autonomous vehicles take to the road, which could positively influence driving behavior and routing decisions.

[1] A TMC is responsible for managing traffic throughout a certain region and/or corridor of interest, collecting data from sensors (e.g., cameras, induction loops), monitoring traffic flow rate, overriding control if needed, managing incidents, and other tasks. A TMC can be run by any transportation stakeholder, such as a public transportation agency (e.g., Caltrans) or private company.

Contents

Introduction

Considerable advancements have been made in traffic management strategies over the past few decades to enhance user mobility on freeways. Still, the continuous growth of metropolitan regions and increasing mobility needs tend to impede such progress. Pre-pandemic, the recent Urban Mobility Report [1] showed that the total cost of traffic delay in the top urban areas in the U.S. has grown by almost 48 percent over the past decade. In many of these regions (such as in California), freeways experience a great deal of traffic congestion [2], arising from bottlenecks at which high-volume, free-flowing traffic transforms into tightly packed clusters of low-speed vehicles.

As such, transportation planners have given special attention to the notion of integrated corridor management (ICM) [3], which encourages the adoption of global traffic management strategies. In practice, this involves consolidating the various traffic components deployed along the corridor (e.g., ramp meter controllers) into a single interconnected system with a global view of traffic condition along the entire corridor, allowing upstream traffic components to be tuned to relieve downstream bottlenecks. In other words, an ICM strategy can coordinate various traffic control units to optimize their operations along the entire freeway, rather than just on pre-specified settings or in localized areas [4]. Moreover, emerging connected vehicle (CV) technology is expected to substantially benefit ICM, where using Dedicated Short-Range Communications (DSRC), vehicle-to-vehicle (V2V), and vehicle-to-infrastructure (V2I) standards [5], vehicles will be able communicate with each other and the surrounding transportation infrastructure. Projected benefits from incorporating such connectivity are manifold. For instance, RSUs could transmit traveler information messages to inform commuters of the state of traffic [6], buses could transmit messages requesting signal priority at key corridor segments [6], and vehicles could communicate with nearby vehicles and RSUs for travel planning and accessing safety measures such as platooning and adaptive cruise control [5]. The potential of CVs has been recognized by the National Highway Traffic Safety Administration, which recently proposed a new Federal Motor Vehicle Safety Standard mandating the installation of DSRC-based communication equipment for new vehicles [8, 9].

The combined potential of ICM strategies and CVs could be even greater by taking advantage of underutilized resources through the power of wireless connections. Among these underutilized resources are park-and-ride facilities that could enable affordable and accessible public transportation from specialized parking lots to serve commuters and enhance traffic flow by reducing the number of vehicles on the road [7]. Recent reports have shown that most of the 302 park-and-ride facilities in California do not come close to their maximum capacity, even at peak hours; they are only 65 percent full on average and stakeholder agencies lose money on parking services [11, 12].

In this report, we analyze and demonstrate the potential benefits of effectively incorporating park-and-ride supply and demand dynamics within ICM traffic optimization strategies to enhance overall traffic flow along the corridor. Our methodology centers on a centralized learning-based approach that utilizes traffic information from the corridor and parking availability data from relevant park-and-ride facilities to devise a corridor-wide strategy, in which advisory messages are broadcast from various RSUs along the corridor. We anticipate that these advertisements will familiarize more people with park-and-ride facilities and encourage them to use their associated services (e.g., access public transportation), and ultimately improve efficiency, corridor flow, and commuters' experiences. The key contributions of this report include:

1. Development of a realistic traffic model for a congested highway corridor, which incorporates highway-related transportation infrastructure, V2I units, and park-and-ride structures.

2. Creation of a proof-of-concept hardware test, demonstrating how V2I facilitates propagation of useful traffic information for our ICM strategy from the commuters’ end all the way to our centralized server and vice versa.

Development of a novel methodology based on deep reinforcement learning (DRL) to optimize traffic flow and CO2 emission reductions along the corridor. Through a realistic simulation of the I-5 using the Veins simulator, our experiments show that our DRL approach provides promising results on learning optimization policies that improve throughput, decrease overall freeway travel times, and reduce CO2 emissions. Our results also show that further enhancements are still needed to address the added delays experienced by the subset of commuters who adhere to the messages guiding them to park-and-ride facilities and boarding public transportation.

Background

DSRC Technology

DSRC is a wireless standard proposed by the Federal Communication Commission that reserves 75 MHz of bandwidth in the 5.9 GHz frequency band for vehicle-to-everything (V2X) communications [8]. In brief, a typical DSRC architecture adopts the standard Institute of Electrical and Electronics Engineers (IEEE) 802.11p protocol as described in [8] to act as a solid base for the V2X and V2V messaging sublayers, governed by the Society of Automobile Engineers (SAE) J2735 and SAE J2945.1 protocols. The DSRC network layers and their corresponding protocols are summarized in Table 1.

Typical DSRC systems are deployed across onboard units in vehicles and RSUs which can establish communication links and exchange relevant information [8]. In our work, we use DSRC to exchange traffic information between onboard and RSUs to guide the traffic flow optimization process.

Table 1. Network layers and their corresponding protocols

Network Layer	Protocol
Application	IEEE 1609.1
Messaging Sublayer	SAE J2735 (V2X), SAE J2945.1 (V2V)
Security	IEEE 1609.2
Network and Transport	IEEE 1609.3
Upper MAC	IEEE 1609.4
Lower MAC	IEEE 802.11p
Physical	IEEE 802.11p

Veins Simulator

To simulate V2I communications, we used an open-source vehicular network simulation framework called Veins (Vehicles in Network Simulation), which is built atop two popular simulators: OMNeT++, an event-based network simulator, and a microscopic traffic simulator called Simulation of Urban MObility (SUMO) [9]. SUMO simulates the road geometry, routes, vehicle flows, and driving behaviors that can all be controlled using the

Traffic Control Interface [10]. OMNeT++ simulations are built from modules that communicate by exchanging messages; users can define network topologies and model communication protocols at multiple levels of detail [11].

Veins is an OMNeT++ project that defines a dynamic network topology from moving SUMO vehicles, models the DSRC communication stack in OMNeT++, and provides an API to control and read values from the underlying SUMO traffic simulation via the Traffic Control Interface [9]. Any new simulation module can utilize these functionalities, which provides a high degree of flexibility when developing V2X simulations. We chose the Veins framework primarily because it is open-source and for its flexibility.

Existing Practice

Connected Vehicles

The emerging CV technology is expected to enhance mobility and improve road safety. A prominent line of study in CV research is to use V2V coordination to organize groups or platoons of vehicles all traveling together to improve traffic flow [12]. However, these approaches tend to focus on optimization from the CV's local perspective and performance without careful consideration to the system-wide traffic conditions. One study [12] explored the benefits of utilizing three mobility improvements: cooperative adaptive cruise control, speed harmonization (i.e., connected vehicle platoons moving in sync), and queue warning (i.e., warnings sent to CVs on the possibility of a car queue forming downstream) in a highway scenario. The study concluded that individual vehicle safety was improved but at the cost of sacrificing overall highway throughput. We leverage CV technology from a different perspective to control the transmission of traffic information from the RSUs to highway vehicles, making our approach complementary to existing CV approaches such as those adopting platooning methods.

Dynamic Rerouting

Ramp metering is a well-explored approach to traffic management, so our work focuses on improving corridor traffic using dynamic rerouting to direct vehicles to underutilized park-and-ride facilities. Liu et al. [17] established a framework for evaluating ICM methods and conducted a study on diverting upcoming traffic to side roads using variable message signs along the freeway, using throughput and travel time as evaluation criteria. They demonstrate that diverting traffic reduces travel delay for freeway vehicles but increases traffic on side roads, so careful evaluation of these trade-offs is required. Our ICM approach follows this study and uses highway throughput and vehicle travel time as our evaluation criteria as well.

A simulation study conducted by Ortega et al. [18] demonstrated that using a park-and-ride facility instead of continuing one's journey can increase total trip time. This indicates that we need to consider whether our method could provide benefits other than travel time savings, such as emissions reductions or increased highway throughput.

Deep Reinforcement Learning in ICM Strategies

Several works have leveraged DRL to optimize traffic flow along corridors. Studies conducted by Fares and Goma [14] and Hashemi and Abdelghany [16] utilized DRL to estimate the state of the traffic road network with relative success. In addition, Liu et al. [26] established a Markov decision process framework to develop a means of estimating freeway traffic. These examples serve as a foundation for developing our scenario and using deep learning to optimize the ICM strategy. However, they do not fully exploit all the benefits of ICM, V2I, and park-and-ride facilities.

Developing the Freeway Model

To ensure our study accurately reflects real-world traffic conditions, we constructed a highly realistic model of a highway section that captures realistic traffic patterns. By carefully selecting a specific segment of highway and using historical traffic data, we were able to create a precise and reliable simulation. In addition, we used an existing park-and-ride structure in our model, thereby avoiding any need to consider the impacts of additional construction.

We conducted our study on a section of I-5 in Los Angeles County, a freeway that consistently ranks among the most congested corridors in California [20] and even the United States [26]. We chose the 10-mile northbound stretch between I-605 and California State Route (SR) 60. We used SUMO's OSMWebWizard tool [10] to convert an OpenStreetMap rendering of I-5 into a SUMO road network as shown in Figure 1. For this study, we considered vehicles travelling northbound from the I-605 to the SR 60.

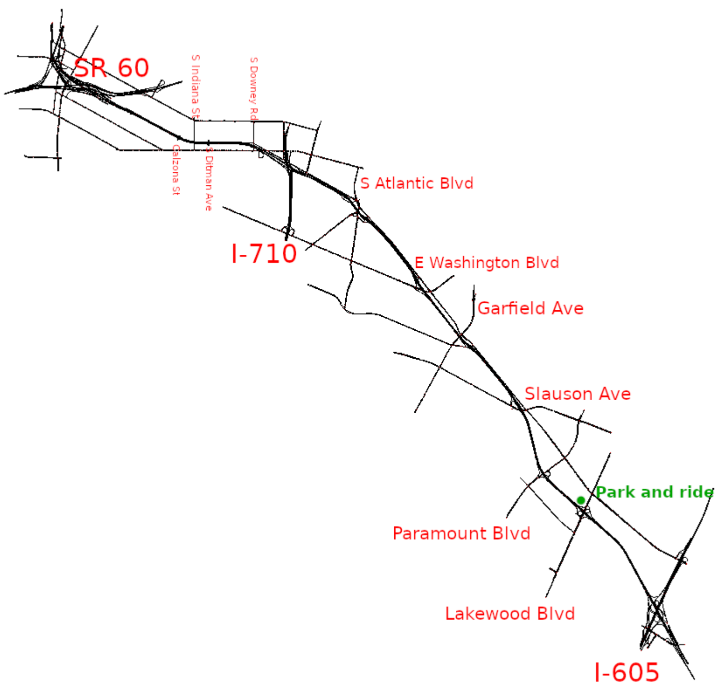

Figure 1. I-5 model.

This corridor includes junctions to local roads and a couple of busier freeways, which provides a diverse set of on ramps and exits with varying traffic volumes. Ramp volumes and average daily traffic data were collected from the Caltrans Traffic Census Program [21] to generate realistic traffic flows. Average daily traffic volume was taken from the 2015 survey due to the completeness of the data for the junctions in this corridor. To model the on-ramp traffic, we generate vehicles at each simulated ramp following a probabilistic model of generation.

Our model includes the North Lakewood park-and-ride structure just off Lakewood Blvd., shown in green in Figure 1. For this study, we assumed that bus service is available that can ferry passengers to the SR 60 intersection every 10 minutes throughout the simulation. These buses do not get rerouted to any other exits and proceed directly to their destination. We also assumed that the Lakewood park-and-ride structure can accommodate up to 400 parking spaces for drivers and that their passengers intend to use the buses.

Simulation Results

In our initial simulations, we observed situations in which diverting traffic to the North Lakewood park-and-ride structure yields improvements to mainline flow (i.e., the main corridor), CO2 emissions, and overall traffic speed but at the cost of increased total travel time for drivers diverted to park-and-ride structures to access bus service. To begin, using the traffic scaling parameter provided by SUMO, we increase the number of vehicles until congestion became apparent. This occurred when the number of vehicles entering the highway section was doubled with congestion being heaviest at the I-605 and I-710 junctions due to merging traffic.

In this scenario, we diverted vehicles to the park-and-ride structure using three different exits at a fixed probability that we call the compliance parameter, which reflects the randomness associated with drivers choosing to follow or disregard the advertised instructions. If the vehicle chooses to be diverted, there is an equal probability for it to take any of the three exits: I-610, Lakewood Boulevard, or Paramount Boulevard.

After running the simulation for a fixed amount of time, we evaluated the average travel time, average CO2 emissions, and the number of vehicles that reach the SR 60 intersection for the following types of vehicles:

- cars that intend to travel the entire corridor without exiting,
- cars that intend to travel from I-605 to SR 60 but are diverted, and
- buses leaving the park-and-ride structure that drive to SR 60.

For the diverted vehicles in the simulation, we completed the estimation of their detour costs using Google Maps data and the average bus travel time, and then add these values to each diverted vehicle's travel time. These travel times are then counted toward the overall throughput. We obtain emissions values for each vehicle using SUMO's default HBEFA3 emissions model [10].

Finally, to evaluate the overall change in congestion from the scenario, we recorded the average speed of all vehicles in the simulation. We ran the SUMO simulation for one hour of simulated time assuming 0%, 10%, 25%, and 50% of highway vehicles deciding to exit the freeway to the park-and-ride structure. Table 2 compiles the results of these experiments.

Table 2. Fixed compliance experimental results.

Compliance	Travel Time (sec)	CO2 (kg)	Speed ($\frac{meters}{sec}$)	Count ($\frac{veh}{hr}$)
0%	1063.18	5.33	15.77	1793
10%	1040.60	4.96	16.15	1899
25%	1034.60	4.37	16.53	1992
50%	969.07	3.51	17.48	2188

We find that the more vehicles change their routes the greater the benefits in average reduced travel time, reductions in average CO2 emissions, increased overall vehicle speed, and improved throughput. One limitation of this preliminary study is that our model issues buses at prespecified periods without accounting for the bus's occupancy rate, which may have inflated our overall throughput and emissions values. Additionally, in this scenario vehicles are constantly being diverted, whereas under real conditions, they would only be diverted in response to downstream congestion.

These results suggest that for this congestion scenario, diverting traffic to a park-and-ride structure may yield benefits. A well-designed machine learning algorithm (reinforcement learning in our case) with more fine-grained control may be able to improve the optimization process.

V2I Communication Proof of Concept

To demonstrate the viability of the ICM strategy, we created a hardware test bed, inspired by the work of Schrank et al. [1], that tested the feasibility of V2I communications between a smart parking structure, a cloud server, a RSU, and an onboard unit, which we simulated using various components including a desktop computer and a laptop. The Universal Software Radio Peripheral (USRP) B210 board from Ettus Research, a software-defined radio capable of transmitting and receiving data between 70 MHz and 6 GHz, was used for wireless DSRC communications. The setup diagram is shown in Figure 2.

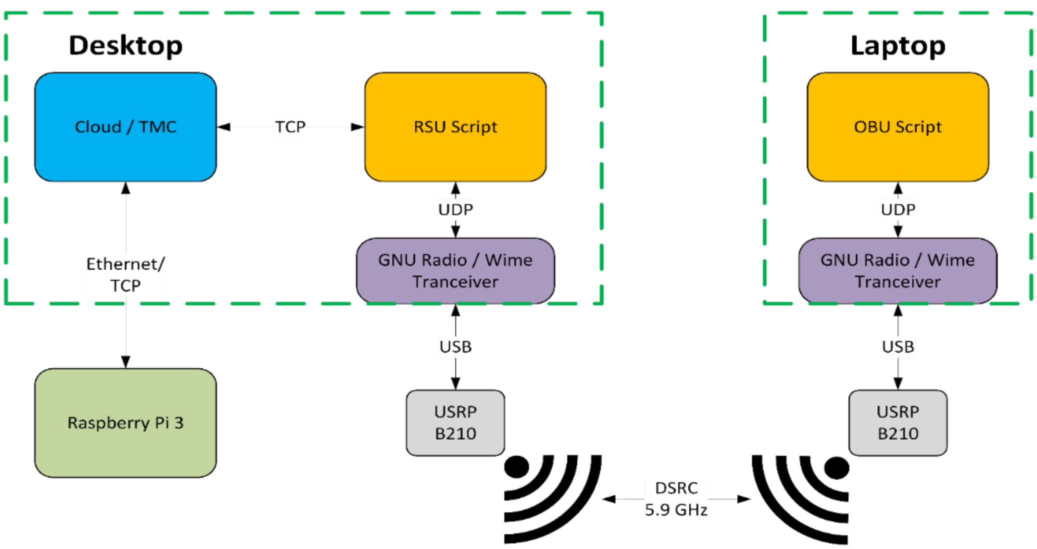

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Figure 2. Diagram of the interconnections for the emulated setup.

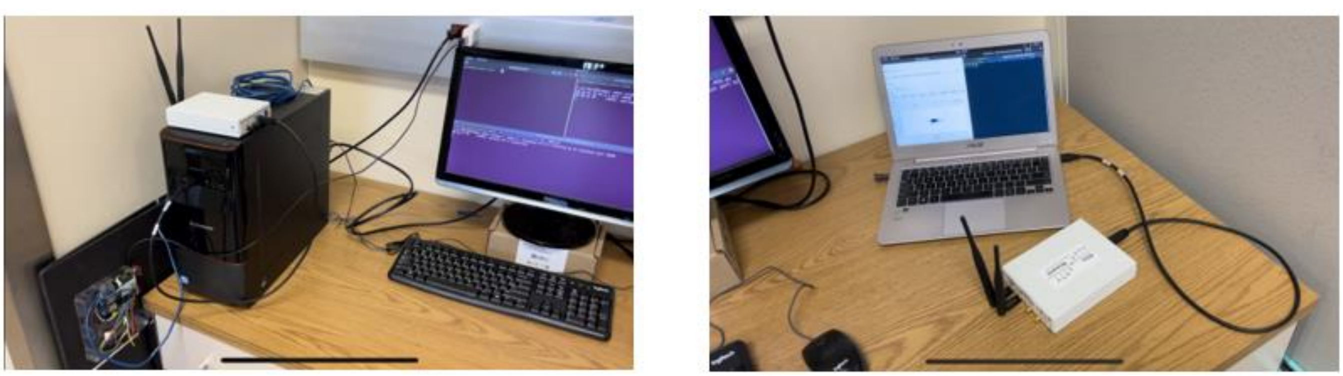


Figure 3. Implemented setup of the USRP modules as a) broadcast and b) receive.

A Raspberry Pi 3, representing a smart parking structure, was connected to a desktop via an Ethernet cable. The desktop ran a Python script representing a cloud server capable of communicating with the Raspberry Pi. A separate Python script, representing a RSU, was also running on the desktop and communicated with the USRP B210, broadcasting or listening on the DSRC 5.9 GHz band. Figure 3a shows this part of the setup.

In addition, the setup included a laptop that was connected to another USRP B210, allowing for both broadcast and reception on the DSRC 5.9 GHz band. This component of the setup is depicted in Figure 3b. To interface with the USRP B210, we utilized the Wime Project's WiFi transceiver module [23], which is an open-source, complete physical layer implementation of 802.11p in GNU Radio. We modified the module to enable the transmission and reception of user datagram protocol (UDP) packets from the local machine, as illustrated in Figure 4. Specifically, to transmit information for wireless transmission via the USRP B210, the Python script writes to a UDP socket at localhost:52001. To read received information from the USRP B210, the Python script reads from a UDP socket at localhost:52002.

DSRC Tests

In the first test we sent information from the park-and-ride structure to a vehicle's onboard unit. Information on parking space availability is sent to the cloud server which forwards it to the RSU, which forwards it to the laptop representing a vehicle on the highway.

The Raspberry Pi sends a dictionary of parking space info to the cloud server, which forwards the data to the RSU. The RSU wirelessly broadcasts the message to the awaiting laptop using DSRC. Screenshots demonstrating this data propagation are shown in Figure 4a and Figure 4b.

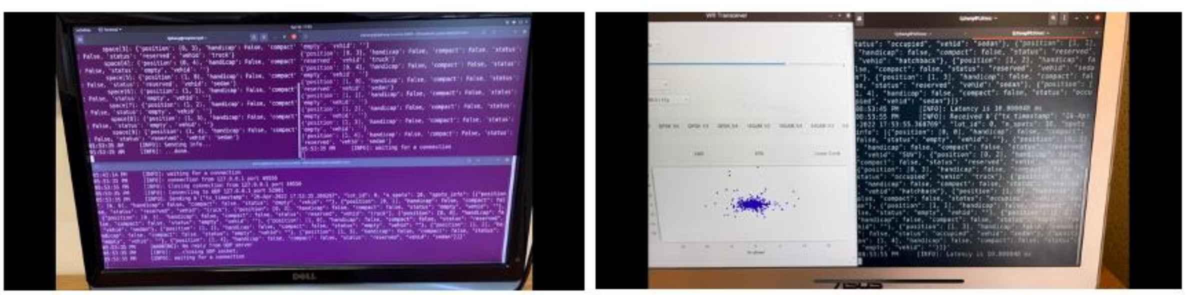


Figure 4. a) and b): Screenshots showing the bi-directional communication.

In the second test we sent data from the laptop to the cloud server to represent collecting basic information from a connected vehicle which is then forwarded to the cloud server. Screenshots demonstrating this data propagation are shown in Figure 5a and Figure 5b.

Figure 5. a) and b): Showing on-board unit communication for vehicle information propagation.

Practical Implementation

This hardware proof of concept clarifies the ICM mechanisms needed to detect traffic conditions and alert drivers to reroute to a park-and-ride structure. Briefly, what is needed is V2X communications to be supported between RSUs and the onboard units of connected vehicles for DSRC messages exchange. A cloud server can then aggregate this information from the connected RSUs (e.g., via LTE communications) to derive a park-and-ride broadcasting strategy for the CVs along the corridor. That is, based on the traffic information collected from the corridor sensors and the metadata from DSRC messages, the cloud server aggregates information from the RSUs, computes a messaging advertisement strategy to be broadcasted from these RSUs. We implemented our tests to emulate this flow of information from a vehicle all the way to the cloud server and back. In these tests, we sent data directly from one script to another, but in practice, standard DSRC message types are needed in both cases.

In more technical details for the interested reader, the SAE J2735 standard [6] defines many message types for V2X communications; none are designed specifically for our use case, but a couple message types are flexible enough to be adapted. For an RSU broadcasting an advisory message to reroute to a park-and-ride structure, one could use the traveler information message (TIM) [6], which is used to broadcast various advisory or road sign info messages. The TIM can be configured to be active on a minute-by-minute basis and even has limited support for custom strings, which can be useful for informing drivers about the nearest park-and-ride. For collecting state information, an RSU could collect a basic safety message (BSM) [6] from vehicles nearby and aggregate the data. Part 1 of the BSM frame is mandatory and reports the vehicle’s position and velocity. Part 2 of the BSM frame is optional but could be customized with additional information that is of importance to the RSU or ICM strategy, such as emissions information or vehicle type. The cloud server functions similarly to a TMC [24] but with the additional role of a park and ride management system. Communicating to the TMC from an RSU or a smart parking structure can be done over LTE; there are examples of RSUs being equipped with bidirectional LTE radios such as one developed by Siemens [25].

System Model

This section describes how we modeled the possible travel times experienced by vehicles traveling along the integrated corridor and presents evaluation metrics.

We analyzed the integrated corridor by examining consecutive sections, or links, along the corridor and associated park-and-ride structures. We considered the number of lanes in each link, the entry and exit ramps, and the parking capacity of the park-and-ride facilities. When a vehicle enters the corridor, it can either travel directly to its destination or opt for a park-and-ride service (i.e., parking at the park-and-ride structure and boarding a bus to the SR 60 intersection). We estimated the time taken by vehicles to travel from one end of the corridor to the other by considering different components of travel time:

1. For vehicles traveling directly to their destination, we summed the time taken to travel from one link to the next until they reach the end of the corridor.
2. For vehicles using the park-and-ride service option, we break down the travel time into three components:
    a. The time taken to reach an exit ramp from the corridor,
    b. The total time spent in the park-and-ride service, including the time to reach the facility, the waiting time for a bus, and the time spent re-entering the corridor, and
    c. The remaining time to travel through the corridor after using the park-and-ride service.

We then evaluated our traffic management approach by looking at three key metrics: flow rate, average travel time, and CO2 emissions. The flow rate refers to the number of vehicles passing through the corridor during a specific time window. The average travel time is the sum of individual travel times divided by the flow rate. The CO2 emissions are calculated based on the number of vehicles as well as each vehicle's fuel efficiency and travel speed.

By understanding these metrics and modeling different scenarios, we can identify strategies to improve traffic flow, reduce travel times, and minimize CO2 emissions. This information can help policymakers make informed decisions about transportation infrastructure and traffic management systems.

Simulation Objective

In simple terms, our problem can be described as follows: we have an integrated corridor with communication units that can share park-and-ride availability with connected vehicles. Our goal is to find the best strategy, X(t), at a specific time window to inform drivers about the current conditions and suggest park-and-ride alternatives when needed. We want to optimize our strategy based on three evaluation metrics: average travel time (T), flow rate (FR), and CO2 emissions (CE).

To achieve this goal, we will look for the optimal advertisement strategy X*(t) that maximizes the value of a global optimization function F, which considers the metrics mentioned above. One simple approach to create this function would be to use a weighted sum formula, assigning negative weights to the metrics we want to minimize (CO_2 emissions and travel time). It's worth mentioning that this optimization function can be adapted to consider other objectives, such as minimizing fuel costs and park-and-ride charges for commuters. The mathematical formulation for the problem thus becomes:

$$F = \alpha * FR - \beta * T - \gamma * CE$$

$$X^*(t) = F\ (FR, T, CE)$$

Where α, β, γ are the weights assigned for each of the metrics, and $X(t)$ is a redirection strategy governing each of the RSU broadcasts. To solve this problem, we leverage the DRL strategies described in the next section.

Deep Reinforcement Learning

In this section, we present our solution for ICM leveraging CV technology and existing park-and-ride facilities. At the heart lies a DRL model deployed on a centralized server capable of pooling traffic data from various corridor sections, as well as the number of available spaces in a park-and-ride facility. Accordingly, the collected data can be analyzed in real-time to guide the optimization process. The key components of our proposed solution are detailed in the following sections.

Inputs and Outputs

In this study, we aimed to collect certain data during a specific time window to be used as inputs for the learning program. These parameters include:

1. Parking Occupancy Status: Information about available parking spaces for each park-and-ride facility is collected. However, this status may change in real-time, and the information only serves as an indication.

2. Traffic Density: Traffic density at each RSU can be estimated by monitoring the occupancy percentage of nearby induction loop sensors[2] from which a consensus on the degree of congestion can be obtained. The set of density observations can be collected for all RSUs. Density can also be estimated by counting the number of vehicles within the range of DSRCs.

[2] The occupancy percentage of induction loop sensors is called based on the percentage of time in which an induction loop sensor is covered by a vehicle.

3. Speed: Traffic flow speed can be estimated by monitoring the time it takes for a vehicle to travel between consecutive points on the highway. This information can be collected from basic safety messages and averaged over time the window.

The RSUs are placed strategically along the corridor before and after exits, as shown in Figure 6. The program decides whether to instruct the RSUs to broadcast park-and-ride advisories based on an analysis of the collected traffic information.

Figure 6. Proposed RSU placement across the I-5.

Training the Model

The DRL agent is trained using a double Q-learning algorithm with an epsilon-greedy method for exploration and exploitation balance. A replay buffer is implemented to avoid catastrophic forgetting.

Training episodes are defined by a specific length, and the reward function is a weighted sum of three evaluation metrics: throughput of passengers, average travel time per passenger, and average CO2 emitted per passenger. These metrics are accumulated as vehicles exit the simulation. Only mainline vehicles, those traveling from source to sink without rerouting to a park-and-ride structure, and buses carrying redirected passengers are considered for reward evaluation.

The reward function consists of weight modifiers for each metric and subtracts fixed values to account for expected minimum throughput and minimum travel time between source and sink.

The experiment aims to train a DRL model using the I5 Veins simulation until the model converges to a policy. The Veins framework maps SUMO vehicles to OMNeT++ applications and allows communication between the Veins simulation and the Python DRL script.

RSU applications collect vehicle data and send observations to a central TMC that interacts with the DRL agent. The TMC periodically sends RSU observations and rewards to the Python script, which responds with an action vector indicating which RSUs should broadcast a park-and-ride message. The training setup is shown in Figure 7.

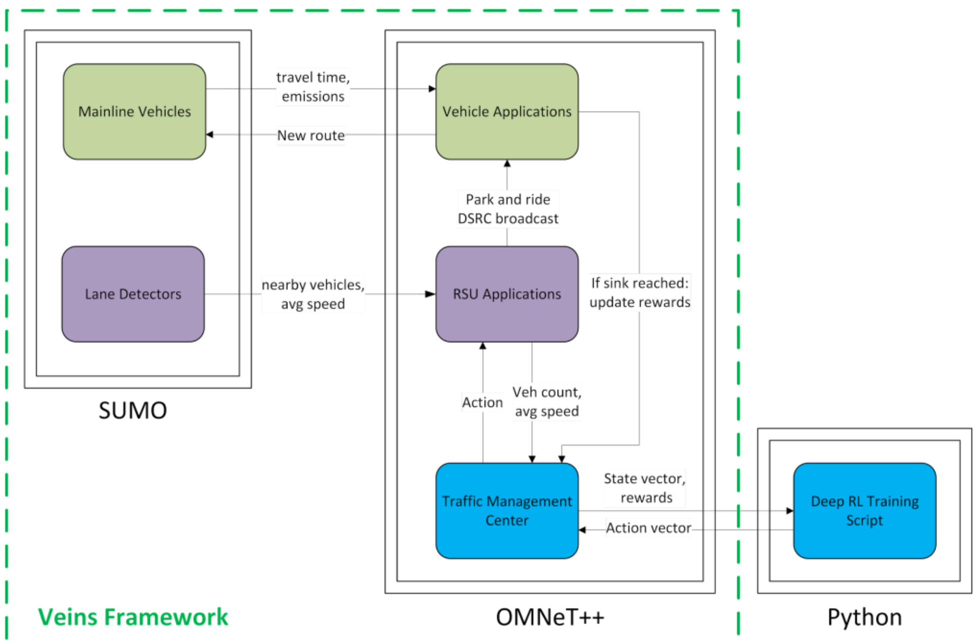
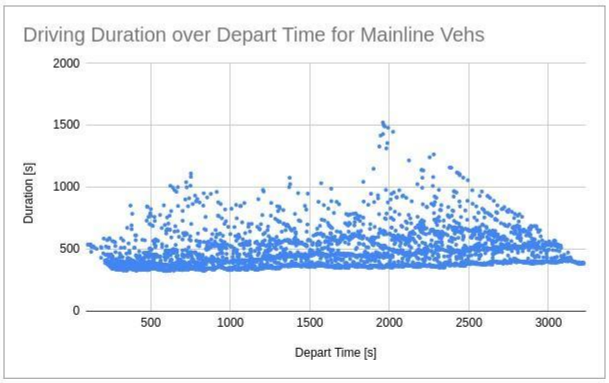


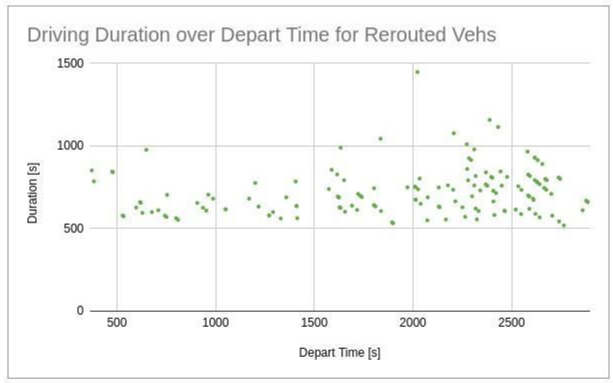
Figure 7. Setup of the training pipeline.

Results

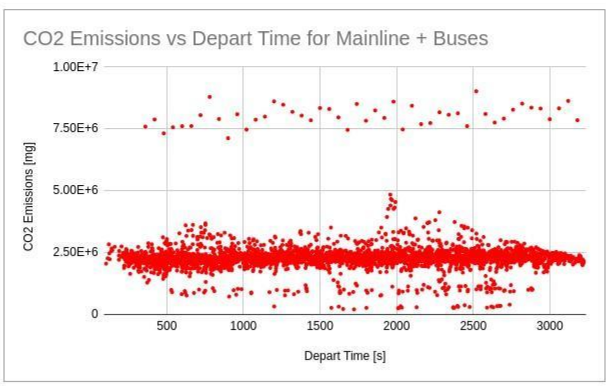
This section discusses the results and observations from our experiment using DRL to direct traffic management. The process was tested on three different scenarios. The goal was to improve highway throughput, reduce average delays, and decrease CO2 emissions. The complete results compare simulations with and without using the DRL method. An example of the analysis is provided for one run in Figure 8 and Figure 9 for no broadcast messaging versus messaging respectively.



Average Travel Time: 475.5795308 s



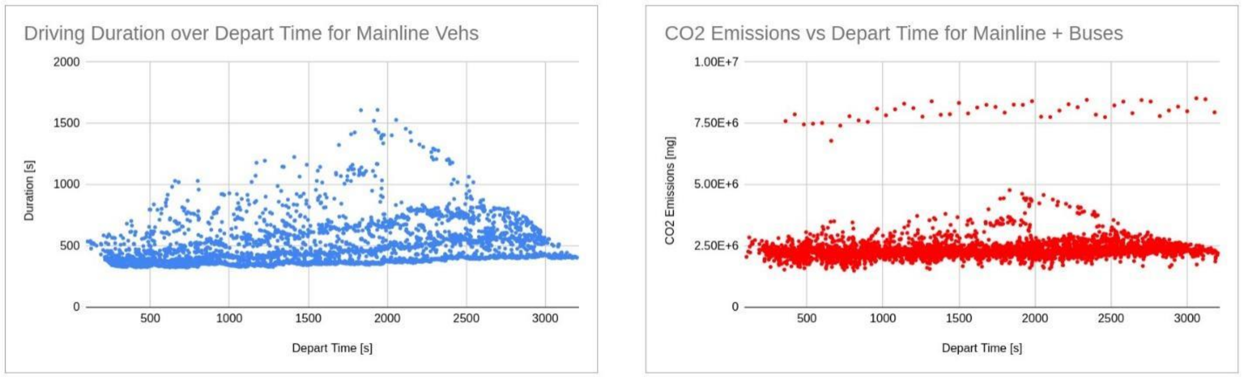
Avg Travel Time for Rerouted Vehs 720.1020408 s
Avg Travel Time for Nonrerouted Vehs 465.9480171 s



Summary	
Rerouted Vehicle Count	147
Nonrerouted Vehicle Count	3732
Total Throughput	3879

Average CO2 Emissions: 2370019.755 mg

Figure 8. Metrics recorded for natural operation (i.e., no broadcast messaging).



Average Travel Time: 488.7252011 s

Average CO2 Emissions: 2442638.161 mg

Total Throughput	3730

Figure 9. Metrics recorded for operation with RSU broadcasting diverting drivers to park-and-ride facilities and bus service.

The results show that real-time messaging to drivers that select the park-and-ride option can improve throughput, reduce delay, and lower CO2 emissions. Though modest, these results reflect the potential from combining integrated congestion management, V2I communications, and real-time information on park-and-ride availability coupled with frequent bus service, as the messaging guided over 100 more vehicles per hour through this short highway segment. We note that better results can be achieved under different traffic conditions. The results are shown in Table 3. The experiment also demonstrated consistent improvements in average CO2 emissions per passenger, mainly due to better use of buses. Further adjustments to the simulation might lead to even greater CO2 emission savings but could also affect traveler delays and the willingness of drivers to reroute to public transportation options.

Table 3. Change of each metric in our simulations.

Experiment ID	Count	Avg Delay	Diverted Delay	Freeway Delay	Avg CO2
64643	+3.99%	-2.69%	+47.34%	-4.67%	-2.97%
44435	+2.95%	-0.13%	+52.56%	-2.55%	-3.00%
27438	+0.53%	-1.6%	+48.46%	-3.26%	-3.09%

Impact

Our ICM approach has demonstrated a promising capacity for improving highway throughput, average delay, and CO_2 emissions. The DRL program mainly redirected traffic to local roads from I-610 and Lakewood Blvd., reducing congestion at the I-610 junction. The program consistently improved average CO_2 emissions per passenger, primarily by better utilizing buses to transport more commuters across the corridor using a smaller number of vehicles. However, while most drivers had improved travel times, those choosing to use park-and-ride services faced increased delays, which are natural given the highway segment studied is very short compared to the whole of the I-5. While this work demonstrated the potential for optimizing traffic flow using these techniques, a full study on a larger highway segment and more in-depth simulation is needed.

Conclusions and Future Directions

This study examined the impact of an employing an ICM strategy that uses V2I communication to redirect vehicles to underutilized park-and-ride structures, to maximize freeway throughput, minimize CO_2 emissions, and reduce travel time. DRL was used with a realistic simulation based on I-5 in Los Angeles. The program redirected vehicles off the highway to specific junctions, achieving improvements in throughput (up to 4%), freeway travel time reduction (up to 4.7%), and CO_2 emission savings (up to 3.1%), but with a cost of delays for drivers diverted to park-and-structures to take public transportation, primarily due to the added time from exiting the freeway, queuing for boarding a bus, and re-entering the highway. Still, promising results from the model highlight the potential in improving traffic, but more work is needed to exploit the method's potential in real-world situations.

Future research could include adjusting parameters like bus frequency, driver compliance with messaging to divert to park-and-ride facilities, and the inclusion of autonomous vehicles. Scaling the approach to larger areas may increase complexity and computer training time, possibly requiring multiple instances of the machine learning algorithm for smaller freeway sections. Moreover, an analysis of potential security concerns (e.g., data spoofing) arising from the use of RSUs for traffic control is needed. As such, a security analysis framework characterizing potential attack models can be developed to assess the resilience of learning-based traffic control.

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