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Smart Signal Control System for Accident Prevention and Arterial Speed Harmonization under Connected Vehicle Environment

Xianfeng (Terry) Yang[1], Gang-Len Chang[2], Zhao Zhang[1], and Pengfei (Taylor) Li[3]

Abstract
The intent of this paper is to develop a system that can integrate connected vehicle (CV) data and traffic sensor information to concurrently address the need to improve urban arterial safety and mobility. Under the mixed traffic pattern of CVs and human-driven vehicles (HVs), the system aims to achieve three primary objectives: proactively preventing rear-end collision, reactively protecting side-street traffic from red-light-running vehicles, and effectively facilitating speed harmonization along local arterials. The embedded safety function will integrate CV and roadside sensor data to compute the distribution of dilemma zones for vehicles of different approaching speeds in real-time. Such data fusion will enable the proposed system to offer the advice of either "stop" or "go" to both CVs and HVs so as to prevent rear-end collisions and side-angled crashes. Given the locations and speeds of CVs, and the number of vehicles monitored by sensors, the proposed system can further compute the time-varying intersection queue length. Then the embedded mobility function will optimize the arterial signal plan in real-time and produce the speed advisory for approaching vehicles to facilitate their progression through intersections. Results from extensive simulation experiments confirm the effectiveness of the proposed system in both reducing potential intersection crash rates and improving arterial progression efficiency. The proposed control framework also proves the effectiveness of using dilemma zone protection sensors for traffic mobility improvement.

How to effectively design traffic signal control systems to improve the safety and mobility of urban arterials has long been recognized as a vital issue by the traffic community. With the recent advancements in wireless communications and computing techniques, connected vehicle (CV) technology has reached a level of maturity and further sheds new light on real-time signal control. Vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication platforms allow CVs and roadside infrastructures to exchange real-time traffic data (*1*). Deployments of such technology have shown great promise in crash avoidance, injury prevention, and congestion relief at intersections. With a high penetration rate of CVs within the traffic, it is possible to remove traffic signals completely at intersections and only utilize CV data as input for signal control. However, it can be expected that both CVs and human-driven vehicles (HVs) will co-exist on the road for a long time (*2*). Therefore, how to deal with such mixed traffic patterns, with fusion of CV information and traffic sensor data, in both safety and mobility control functions becomes an urgent task at the current stage.

In daily operations, signalized intersections may experience two types of crashes: side-angle crashes and rear-end crashes. As reported in the literature (*3*), trapping vehicles within the dilemma zone, where vehicles can neither stop before or pass the stop line safely, is one of the most common causes of side-angle crashes. By extending yellow time, the dilemma zone can be eliminated. However, a longer yellow time may create an "indecision" zone in which drivers are not able to make the right

[1]Department of Civil and Environmental Engineering, University of Utah, Salt Lake City, UT
[2]Department of Civil and Environmental Engineering, University of Maryland, College Park, MD
[3]Department of Civil and Environmental Engineering, Mississippi State University, MS

Corresponding Author:
Address correspondence to Xianfeng (Terry) Yang: x.yang@utah.edu

pass/stop decisions. To protect drivers from being trapped in dilemma/indecision zones, existing efforts include both proactive and reactive control methods. The core logic of proactive control is to either provide an advanced warning message to drivers to reduce their speed (*4*, *5*) or adjust signal green times (early termination or extension) before max-out to prevent trapping vehicles in dilemma zones (*6*, *7*). Different from proactive control, reactive protection strategies aim to prevent side-angle accidents when vehicles fail to stop safely before the signal alters to the following phase. All-red extension is a commonly used reactive protection function that offers an extended all-red interval to accommodate red-light-running vehicles (*8*). Based on field-collected or simulated data, existing studies have reported the effectiveness of both proactive and reactive dilemma zone projection strategies in reducing red-light-running vehicles (*9*, *10*) and the number of side-angle crashes at intersections (*11*, *12*). However, preventing a rear-end crash with real-time signal control remains, in contrast, a challenging issue in the literature (*13*). Although field experiments (*11*) showed that signal green-extension has some potential for reducing rear-end crash rate, a more effective strategy for influencing driver behaviors has not been fully studied yet.

In respect of improving arterial mobility performance, existing operational measures can be divided into two categories: real-time signal control and green light optimized speed advisory (GLOSA). In the first category, the main principle is to make real-time adjustments to intersection signal timings according to collected traffic data. Actuated and adaptive control models (*14*) have been widely studied and implemented in practice. Under a CV environment, enriched real-time data from CV trajectories can also enhance the prediction/estimation of traffic flow so as to improve systems' mobility performance (*15–22*). The second category, GLOSA, is to suggest advisory speeds for approaching vehicles to stay in the progression band, where the arterial can be running with either a pre-timed signal coordination plan or a coordinated–actuated signal with green extensions. Notably, the advisory speeds can be passed to vehicles by V2I and variable speed limit (VSL) technologies under a mixed CV and HV traffic pattern. One such application, named Application for the Environment: Real-Time Information Synthesis Program, was initiated by the U.S. Department of Transportation (DOT) (*23*). With CV technology, each vehicle can receive signal phase and timing (SPaT) data from roadside units (RSUs) and revise its own speed profile within the control boundary (*24*). Moreover, such speed harmonization can help reduce fuel consumption by 7% to 13% (*25*). Unlike the CV technologies, which target individual drivers, VSL signs can broadcast advisory speeds to all incoming vehicles.

In summary, despite promising efforts having been put into improving either intersection safety or arterial mobility, existing control models for these two purposes are often carried out with separate devices and sensors. Integration into one set of equipment to concurrently satisfy both safety and mobility needs has not been well addressed yet. In recent years, Park et al. proposed a system that integrates the dilemma zone protection with a VSL-based speed harmonization function (*26*). Their simulation experiments confirmed the effectiveness of the proposed system for offering protection to the red-light-running vehicles, and for improving traffic mobility with respect to fewer stops, reduced stop delays, and lower fuel consumption. The shared utilization of deployed hardware devices also allows responsible agencies to best use available real-time signal operational resources. This study will follow the same line and extend the system's capability into the CV environment. The contributions of the new system are threefold: 1) it fuses real-time data from both roadside microwave sensors and CVs to estimate queue evolutions at intersections; 2) it integrates an efficiency improvement function into the dilemma zone protection system by optimizing signal coordination plan and vehicle advisory speeds; and 3) it offers solutions to prevent potential rear-end crashes at intersections.

System Architecture

Figure 1 shows the overview of the proposed system architecture, which contains five key components: 1) long-range microwave detector for tracking the speeds and locations of all vehicles within the detection zone; 2) RSU for supporting V2I communications; 3) VSL signs for providing advisory speed for incoming HVs to ensure safe stops or smooth progressions along the arterial; 4) in-cabinet computer for processing collected data, operating embedded algorithms, and making control decisions; and 5) signal controller for providing current SPaT and receiving instructions for all-red extension or offset adjustment from the in-cabinet computer.

Figure 2 illustrates the data flowchart of the proposed system. The long-range microwave sensor can detect the speeds and locations (i.e., distances to the stop line) of both HVs and CVs within its detection zone. However, lane-based information (how vehicles are distributed among different lanes) is usually not obtainable. The RSU will collect CV trajectories in real-time and send advisory speeds back to CVs when necessary. The signal controller will provide SPaT information to determine when and how to activate control modules including dilemma zone protection, real-time queue evolution estimation, real-time signal control, and rear-end crash

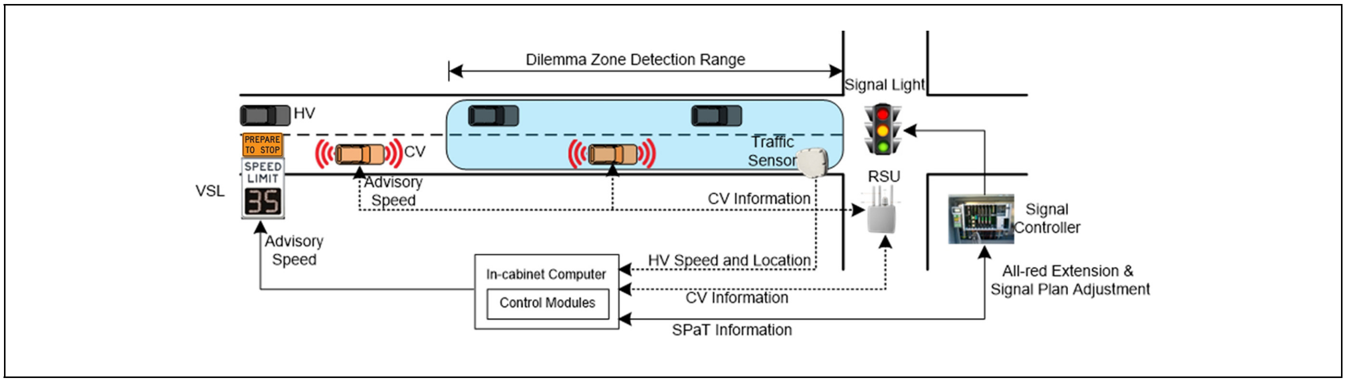

Figure 1. Overview of the proposed integrated signal control system.

prevention. Detailed information on the design of each module will be introduced in the follow section.

Control Modules and Model Development

Module 1: Dilemma Zone Protection

This module is used to monitor all vehicles within the detection zone and provide an all-red extension to those trapped in the dilemma zone. In a previous study, Park et al. (*20*) utilized the following logistic regression expression to predict each vehicle's passing probability at the onset of a yellow interval:

$$P_{\text{pass}}(i,t) = \frac{1}{1 - e^{-\beta_0 - \beta_1 v_i(t) - \beta_2 d_i(t)}} \tag{1}$$

where

$P_{\text{pass}}(i,t)$ is the passing probability;

$v_i(t)$ and $d_i(t)$ are the speed and location (distance to the stop line) of vehicle i at time t; and

β_0, β_1, and β_2 are parameters calibrated with field data.

When $P_{\text{pass}}(i,t) \geqslant 0.5$, vehicle i is identified as passing vehicle; otherwise it is identified as stopping vehicle.

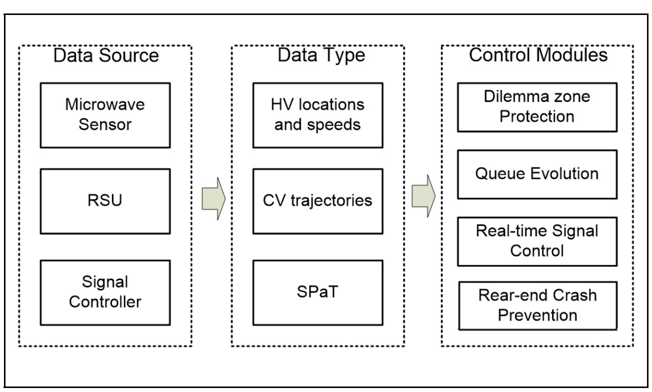

Figure 2. Data flowchart of the proposed system.

However, in real-world applications, observations showed that some vehicles may change their pass/stop decision during the yellow interval. Therefore, a prediction executed at the onset of a yellow interval may fall short of accounting for such behavior. To address this issue, this study aims to predict vehicles' passing probability at ε seconds before the end of the yellow interval, where ε indicates the time needed for data transition and all-red extension activation. An extension of Equation 1 is formulated as

$$P_{\text{pass}}(i,t_\varepsilon) = \max\left(\frac{1}{1 - e^{-\beta_0 - \beta_1 v_i(t_\varepsilon) - \beta_2 d_i(t_\varepsilon)}}, \delta_i(t_\varepsilon)\right) \tag{2}$$

where $\delta_i(t_\varepsilon)$ is a binary variable which indicates whether vehicle i intends to accelerate, and

$$\delta_i(t_\varepsilon) = \begin{cases} 1 & \text{if } v_i(t_\varepsilon) \geqslant v_i(t_\varepsilon - 1) \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

By introducing $\delta_i(t)$, the system can monitor whether a vehicle changes its initial stopping decision to passing during the yellow interval. Given the vehicles' passing probabilities, speeds, and locations, the system can estimate their required passing time by $d_i(t_\varepsilon)$ / $v_i(t_\varepsilon)$. Then the required all-red extension time can be calculated by

$$\text{ARE} = \max_i\left\{\frac{d_i(t)}{v_i(t)} - \varepsilon - \text{AR} + \sigma\right\} \tag{4}$$

where ARE is the required all-red extension time, AR is the pre-set all-red time and σ is additional all-red protection time to overcome the potential estimation error of vehicle passing time.

Module 2: Queue Length Estimation

As accumulated queueing vehicles during a red interval can greatly affect the effectiveness of signal progression and increase the potential for a rear-end collision with short sight-distance, this module aims to predict the

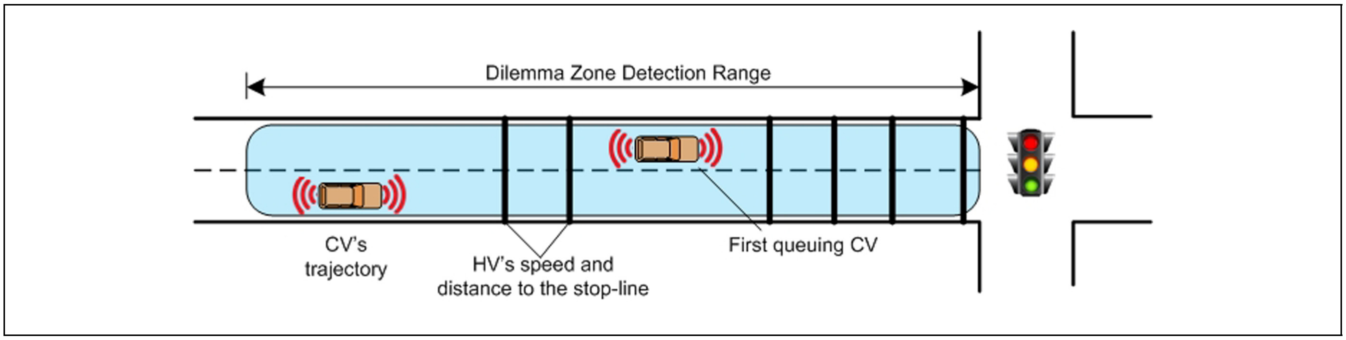

Figure 3. Vehicle trajectory information within the detection zone.

lane-based queue evolution at the onset of a green signal and estimate the required clearance time. Figure 3 shows available real-time information within the detection range (e.g., 900 ft), utilizing the microwave sensor and V2I technology, and including trajectories of CVs and HVs. Notably, the microwave sensor will detect the speeds and locations (distances to the stop line) of HVs but cannot identify their lane distribution.

This study divides the detection range into a queueing zone and an arriving zone. The length of the queueing zone can be estimated by identifying the location of queueing vehicles which have zero speed. However, because of the lack of HV lane distribution data, the first step to estimate lane-based queue evolution is to assign queueing HVs to different lanes. As the locations of CVs provide direct observations of queueing vehicles, this model divides the queueing zone into a set of cells by treating locations of CVs and the stop line as boundaries. Defining h as the average vehicle gap in the queue, which is calibrated by field data, HVs can be distributed in each cell by the following optimization model based on their locations, $d_i(t)$.

$$\begin{aligned} &\min \sum_i (g_i - h)^2 \\ &\text{subjectto} \\ &g_i = \min_{k>i}\{d_k(t)\varphi_{kj} - d_i(t)\varphi_{ij} | \varphi_{kj} = \varphi_{ij} = 1\} \quad \forall i \\ &\sum_j \varphi_{ij} = 1 \qquad \forall i, j \end{aligned} \tag{6}$$

where

g_i denotes the distance between HV i and its following vehicle; and

φ_{ij} equals 1 if HV i is assigned to lane j and φ_{ij} of CVs are given.

Notably, the first set of constraints of the optimization model (6) determines the actual gaps of vehicles in each lane, the second set of constraints is to ensure each vehicle can only be assigned to one lane, and the objective function is to minimize the total square of differences between actual gap and average gap. Then the queue length in each lane, q_j, can be obtained. If there is no CV in the queueing zone, the lane assignment of HVs become an open problem which has no unique solutions. In such a case, for the sake of safety, it is assumed that the queue lengths of all lanes equal $\max(d_i(t)| \forall i)$.

As the physical queue length (distance from end of queue to stop line) will still increase for a few seconds after the onset of a green signal, the required queue clearance time, τ_j, on each lane j can be estimated by solving

$$v_j \tau_j = q_j + \lambda_j \tau_j \tag{7}$$

where v_j and λ_j are the discharging shockwave speed and arrival rate of lane j calculated from previous signal cycles.

Module 3: Signal Coordination and Speed Harmonization

This module aims to improve the operational efficiency of the arterial by better coordinating intersections and harmonizing vehicles' speeds. Given the estimated queue clearance time, the control objective of this module is to minimize the stopped delay of upstream arriving vehicles caused by the initial queue at each intersection, along both outbound and inbound directions. For convenience of discussion, the offset of intersection i, denoted as θ_i, is defined as its green onset time difference compared with its downstream intersection along the outbound direction. Then the stopped delay of the first arriving vehicle at intersection i, along outbound direction, $\zeta_{\text{out},i}$, can be estimated by

$$\zeta_{\text{out},i} = \max\left(\theta_i + \max_{j \in \Psi_{\text{out}}(i)}\{\tau_j\} - \frac{L_{\text{out},i} - \max\limits_{j \in \Psi_{\text{out}}(i)}\{q_j + \lambda_j \tau_j\}}{v_{\text{out},i}}, 0\right) \tag{8}$$

where $v_{\text{out},i}$, and $L_{\text{out},i}$ are the advisory speed and link length between intersection i and its downstream intersection along the outbound direction, and $\Psi_{\text{out}}(i)$ denotes the lane group along the outbound direction at intersection i. Similarly, the stopped delay of the first arriving vehicle along the inbound direction, $\zeta_{\text{in},i}$, can be estimated by

$$\zeta_{\text{in},i} = \max\left(-\theta_i + \max_{j \in \Psi_{\text{out}}(i)}\{\tau_j\} - \frac{L_i - \max_{j \in \Psi_{\text{out}}(i)}\{q_j + \lambda_j \tau_j\}}{v_{\text{in},i}},\ 0\right) \quad (9)$$

Then the real-time optimization model for Module 3 can be formulated as follows:

$$\begin{aligned} &\min \sum_i (\zeta_{\text{out},i} + \zeta_{\text{in},i}) \\ &\text{subjectto} \\ &\theta_i^- - \Delta\theta \le \theta_i \le \theta_i^- + \Delta\theta \qquad \forall i \\ &v_{\text{in},i}^- - \Delta v \le v_{\text{in},i} \le v_{\text{in},i}^- + \Delta v \qquad \forall i \\ &v_{\text{out},i}^- - \Delta v \le v_{\text{out},i} \le v_{\text{out},i}^- + \Delta v \qquad \forall i \end{aligned} \quad (10)$$

where

decision variables θ_i^-, $v_{\text{out},i}^-$, and $v_{\text{in},i}^-$ denote the offset, outbound direction advisory speed, and inbound advisory speed in the last signal cycle; and

$\Delta\theta$ and Δv denote the maximal allowable differences of offset and advisory speed, respectively, between consecutive cycles.

Notably, because of the limited searching space of optimal solution, the above optimization model can be easily solved in real-time.

Module 4: Rear-End Crash Prevention

For preventing potential rear-end crashes at intersections, this module aims to address three cases.

Submodule 1: Vehicles Arriving with Insufficient Sight-Distance while Intersection Has Uncleared Initial Queue after Onset of Green. To deal with this case, the proposed system will utilize the VSL sign to offer an advisory speed for HVs to prepare to stop. Given the lane-based speed evolutions estimated by Module 2 and the location of the VSL sign, d_{VSL}, the variable speed limit (vsl) can be determined by

$$\text{vsl} = \frac{d_{\text{VSL}} - \max_j\{v_j \tau_j\}}{\tau_j} \quad (11)$$

For CVs, the advisory speed will be sent via V2I communication channels.

Submodule 2: Vehicles Arriving with Insufficient Sight-Distance while Intersection Has Uncleared Initial Queue after Onset of Red. To deal with this case, the proposed system will utilize the VSL sign to offer an advisory speed for HVs to prepare to stop. The advisory speed will be changed over time and is calculated based on the current queue length $q(t)$:

$$d_{\text{VSL}} - q(t) = \text{vsl}(t)^* p_t + \frac{\text{vsl}(t)^2}{2a} \quad (12)$$

where a is the field-observed deceleration rate and p_t is the drivers' perception time. Notably, the current queue length $q(t)$ equals the last stopped vehicle's distance to the stop line. For CVs, the advisory speed will be sent via V2I communication channels.

Submodule 3: Some Vehicles within Detection Zone Predicted to Be Stopping during Yellow and All-Red Time. Recall that Equation 1 predicts the passing/stopping behavior of each detected vehicle at the onset of a yellow signal. By identifying the location, denoted as d_s, and speed, denoted as v_s, of the last stopping vehicles, the advisory speed for ensuring a safe stop can be estimated by solving

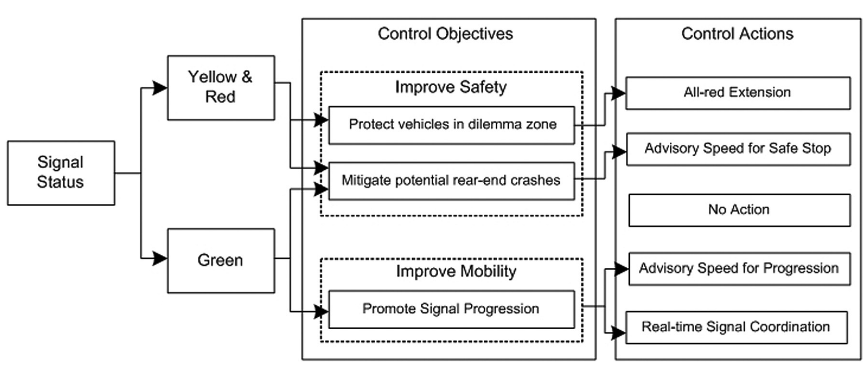

Figure 4. System control actions based on traffic signal status.

$$d_{VSL} - d_s = vsl*p_t + \frac{vsl^2 - v_s{}^2}{2a} \tag{13}$$

System Control Logic and Actions

Figure 4 illustrate the system control logic for integrating those four control modules for concurrently improving efficiency and safety performance of arterial intersections by choosing different control objectives during yellow/red and green time. By defining a set of control scenarios the system may encounter in practice, this section will discuss the control actions in response to each scenario.

Actions During Yellow and Red Interval

When vehicles are arriving during the yellow and red interval, the proposed system may encounter the following two scenarios.

Scenario 1: Vehicles Arriving during Yellow and All-Red Time. Vehicles arriving during yellow and all-red time may neither stop before or pass the intersected area safely for two reasons: 1) the yellow settings are too short and the vehicles are trapped in the dilemma zone; and 2) the drivers are in an indecision zone and make wrong "pass" decisions. Therefore, the proposed system will take the control actions of "all-red extension" and "advisory speed for safe stop," following several key steps:

Step 1: Collect the speed and location of all vehicles within the dilemma zone detection range at ε seconds before the end of the yellow signal.
Step 2: Calculate the vehicles' passing probability using Equation 2 and activate Submodule 3 of Module 3. If all probabilities are below 0.5, stop; otherwise move to Step 3.
Step 3: Use Equation 4 to estimate the required all-red extension time by calculating the largest passing time of vehicles. If the obtained ARE is zero, stop; otherwise, extend the all-red time by ARE seconds.

Scenario 2: Vehicles Arriving during Red Interval. Vehicles arriving during a red signal interval must join the end of stopping queues at intersections. Because of improper alignment design of intersections or low light conditions, the approaching vehicles may not have sufficient sight-distance to observe the stopping queue ahead. Therefore, if the vehicles are traveling at a high speed, this can lead to potential rear-end collisions. To reduce the risk of this, the proposed system will take the control action of "advisory speed for safe stop" with the following steps:

Step 1: Activate Module 2 to estimate the queue length at the beginning of the red interval; keep updating the queue length based on the information of arriving vehicles.
Step 2: Activate Submodule 2 of Module 3.

Actions During Green Interval

When vehicles are arriving during the green interval, the proposed system may encounter the following three scenarios.

Scenario 3: Vehicles Arriving at Beginning of Green Interval. Vehicles arriving at the beginning of a green interval may be delayed because the intersection needs to take a few seconds to discharge vehicles queued during the red interval. Without sufficient sight-distance, vehicles traveling at high speeds may crash into the vehicles stopping ahead. Under such a scenario, the proposed system will activate Submodule 1 of Module 3 to provide an advisory speed to the approaching vehicles.

Scenario 4: Vehicles Arriving during Green Interval. During the signal green time, the main control objective is to facilitate signal progression along the arterial. To such end, the proposed system will take the actions of "advisory

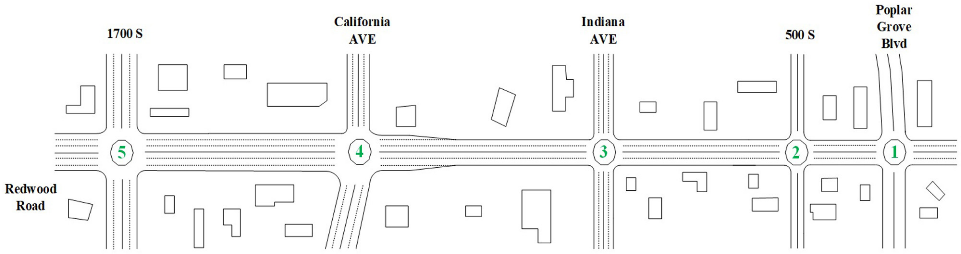

Figure 5. Overview of the study site.

Table 1. Summary of the Collected Intersection Volumes (in Vehicles per Hour)

	EB			WB			NB			SB		
Intersection	L	T	R	L	T	R	L	T	R	L	T	R
1	116	36 304	152	212	40 276	24	164	508 776	104	28	664 820	128
2	32	24 100	44	84	4 236	148	52	700 760	8	36	632 724	56
3	188	132 432	112	128	168 460	164	32	704 804	68	176	700 988	112
4	140	316 556	100	192	184 456	80	164	716 1,088	208	192	748 1,080	140
5	200	124 400	76	68	232 568	268	280	672 1,068	116	116	844 1,020	60

Note: EB = eastbound; WB = westbound; NB = northbound; SB = southbound; L = left; T = through; R = right.

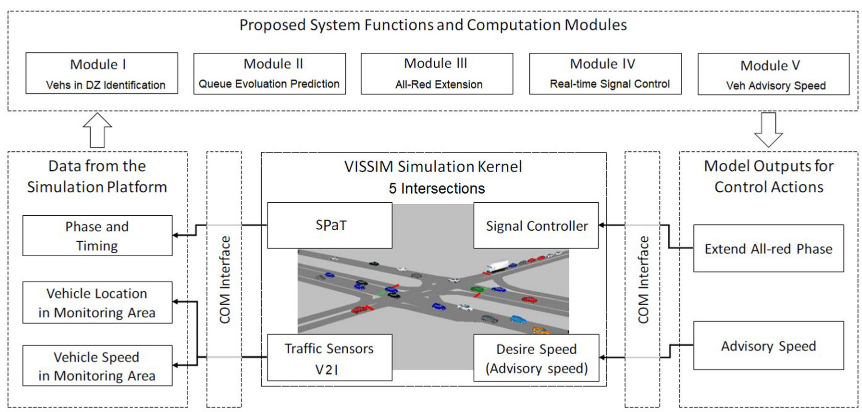

Figure 6. Overview of the VISSIM simulation platform.

speed of progression" and "real-time signal coordination" with the key steps described as follows:

Step 1: If the signal offsets have been adjusted within the last 5 min, set $\Delta\theta$ as 0; otherwise, set $\Delta\theta$ as 5 s.
Step 2: Estimate the queue clearance time using Equation 7.
Step 3: Optimize the offsets and vehicles' advisory speeds using the optimization model listed in Equation 10.
Step 4: Provide advisory speed to HVs and CVs by VSL and V2I, respectively.

Scenario 5: Vehicles Arriving at End of Green Interval. Vehicles arriving at the end of green interval may encounter a yellow signal when they get close to the intersection. Therefore, the following action steps will be taken:

Step 1: Collect the vehicles' speeds and locations.
Step 2: Estimate the vehicles' arrival time at the signal stop line. If the arrival time is within the yellow and -all-red interval, take the same actions as in Scenario 1; otherwise, take the same actions as in Scenario 4.

Numerical Examples

Simulation Platform Set-Up

For evaluating the proposed system's capability for improving both arterial safety and mobility, this study selects a segment on Redwood Road in Salt Lake City for study. As shown in Figure 5, the arterial segment includes five intersections and it is a part of the CV corridor operated by the Utah DOT. All intersections are installed with DSRC (direct short-range communications) RSUs for supporting V2I communications. The prevailing speed is set as 45mph and yellow timing is 3 s.

Table 1 summarizes the intersection turning volumes collected at the arterial on February 15, 2018. The collected data are further used for simulation calibrations. In this study, the research team employed VISSIM as the unbiased simulation tool for system evaluations. Figure 6 shows the architecture of the VISSIM platform operated through a VB.NET-developed VISSIM-COM interface. By defining two vehicle groups, one representing HVs and the other representing CVs, the program detects and records the real-time locations and speeds of vehicles within the detection range. The obtained trajectory data, along with SPaT information, will be sent to the computational program at an interval of 1 s. Depending on the current signal status (i.e., red, green, or yellow and all-red), the embedded modules will take proper actions and provide feedback control to the signal controllers and vehicles via VISSIM-COM.

Notably, one of the key features of the proposed system is its provision of advisory speeds to both CVs and HVs through V2I communication and VSL, respectively. In this study, it is assumed that HVs may or may not follow the VSL, represented by a compliance rate, but CVs will follow the advisory speed they received. In the simulation platform, such actions are replicated by the following steps:

Step 1: Break the simulation process.
Step 2: Identify the type of an oncoming vehicle. If it is a CV, change its speed according to the output of control modules; otherwise move to Step 3.
Step 3: Use a random number generator to determine whether the HV will follow the instruction of VSL.
Step 4: Change the HV's freeway flow speed if it is a complying vehicle.
Step 5: Continue the simulation.

Measures of Effectiveness

In the simulated scenarios, 10% of vehicles are assumed to be CVs and the rest of them are HVs. In addition, HVs' compliance rate to VSL sign is assumed be 40%. Because the proposed system is unique in adopting one set of hardware to support both safety and mobility control functions, the measures of effectiveness (MOEs) cover both aspects:

Safety MOEs.

- Average number of vehicles trapped in the dilemma zone per signal cycle;
- Average number of potential side-angle crashes per signal cycle measured by vehicle trajectories;
- Average number of potential rear-end crashes per signal cycle measured by the number of hard-braking vehicles (deceleration rate $> 10\text{ft/s}^2$);
- Average number of red-light-running vehicles per signal cycle.

Mobility MOEs.

- Average number of stops;
- Average vehicle delay where delay is defined as the difference between actual travel time and free flow travel time (using the original desired speed).

Based on the MOEs defined above, this study tests the following scenarios for comparisons:

- *Base Scenario*: the arterial is under the control of pre-timed traffic control system;
- *Scenario 1*: the arterial intersections are equipped with a dilemma zone protection system (DZPS);
- *Scenario 2*: the arterial is under the control of the proposed system.

Results Analysis

By simulating the arterial network over a 2-h period, Table 2 summarizes the resulting MOEs under different scenarios. By comparing the safety MOEs between the Base Scenario and Scenario 1, it can be observed that implementing DZPS can greatly reduce the average number of potential side-angle crashes (−84.7%). However, the performance differences between these two scenarios, in relation to average number of vehicles in the dilemma

Table 2. System Safety and Mobility Performance under Different Scenarios

MOEs		Base scenario	Scenario 1	Scenario 2
Safety MOEs	Ave # of vehicles in the dilemma zone	1.13	1.12 (–0.6%)**[*]**	0.88 (–22.2%)**[*]**
	Ave # of potential side-angle crashes	0.85	0.13 (–84.7%)	0.13 (–84.7%)
	Ave # of potential rear-end crashes	3.21	3.19 (–0.6%)	1.43 (–55.5%)
	Ave # of red-light-running vehicles	0.49	0.49 (–0.0%)	0.39 (–20.4%)
Mobility MOEs	Ave # of stops along the studied arterial	25.8	26.4 (+ 2.3%)	16.7 (–35.3%)
	Ave vehicle delay over the entire arterial (s)	135.7	148.9 (+ 9.4%)**[*]**	112.7 (–17.0%)**[*]**

Note: # = number.

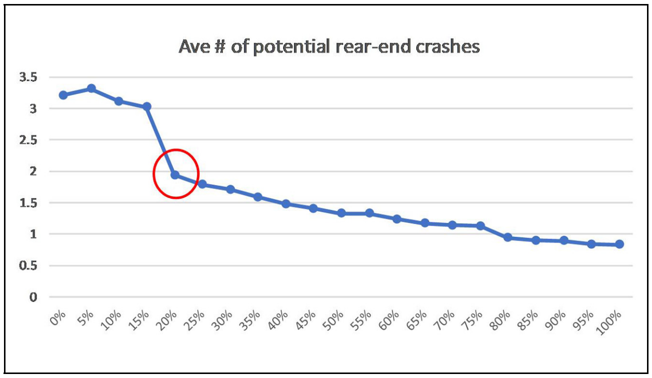

Figure 7. Average number of potential rear-end crashes with different CV rates.

Table 3. System Safety Performance under Different Scenarios

	Total # of hard-braking vehicles		
Scenarios	No protection	With proposed system	Improvement
Scenario 1	304	41	–86.5%
Scenario 2	431	93	–78.4%
Scenario 3	751	105	–86.0%

zone, average number of potential rear-end crashes, and average number of red-light-running vehicles, are not significant. This is because DZPS will activate the all-red extension function once some vehicles cannot safely pass the intersection. Therefore, taking the all-red extension action can greatly reduce the potential of occurring side-angle crashes. However, because the approaching vehicles will not receive advanced notice of the signal status in both scenarios, the performance on the other safety MOEs are quite similar. In contrast, Scenario 2 with the proposed system can greatly outperform the Base Scenario in reducing vehicles in the dilemma zone (−22.2%), number of side-angle crashes (−84.7%), number of rear-end crashes (−55.5%), and number of red-light-running vehicles (−20.4%). Such comparison can prove the effectiveness of the proposed functions in providing advisory speed to stop.

With respect to the mobility MOEs, this study examines both average number of stops and average vehicle delay over the entire arterial. The comparison between the Base Scenario and Scenario 1 reveals that implementing DZPS will cause the traffic congestion to deteriorate slightly, evidenced by the increased number of stops (+2.3%) and delay (+9.4%). This is caused by the intersection capacity reduction because of granted all-red extensions. However, with the proposed signal coordination and speed harmonization functions, Scenario 2 can greatly improve the arterial's mobility performance.

Sensitivity Analysis of CV Penetration Rate

As CV penetration rate also plays a key role in affecting the proposed system's performance, this study further conducts a sensitivity analysis to analyze its impact on reducing the probability of rear-end crashes occurring. As shown in Figure 7, when the CV rate is below 20%, the resulting average number of potential rear-end crashes is around three vehicles per signal cycle. However, after the rate has reached 20%, the corresponding number has been greatly reduced to 1.9 vehicles per signal cycle. By further examining the simulation animations, it has been found that the speed control of CVs can concurrently affect the speed of HVs as they are sharing the roadway. Therefore, one can treat 20% as a critical CV rate to maximize the system's benefit in the studied case.

Intersections with Short Sight-Distance

To further evaluate the capability of Module 4 for reducing the potential occurrences of rear-end crashes at intersections with short sight-distance, this study further simulates the following three scenarios and evaluates the corresponding safety performance of the arterial:

- *Scenario 1*: All intersections are with sufficient sight-distance;
- *Scenario 2*: All intersections have a sight-distance of 250 ft;
- *Scenario 3*: All intersections have a sight-distance of 100 ft.

Based on the results from Table 3, it can be observed that shorter sight-distance can greatly increase the risk of rear-end crashes occurring, evidenced by the largest number of hard-braking vehicles in Scenario 3. The comparison between "no protection" and "with proposed system" reveals that the proposed queue estimation module and rear-end prevention module can effectively provide optimal advisory speeds and make approaching vehicles well prepared to stop before getting close to the intersection.

Conclusions and Future Works

This paper developed an integrated system that can concurrently improve urban arterial mobility and safety performance, grounded on the same set of hardware equipment. Four control modules, dilemma zone protection, queue length estimation, signal coordination and speed harmonization, and rear-end crash prevention, are integrated into the system to achieve three control objectives: proactively preventing rear-end collision, reactively protecting side-street traffic from red-light-running vehicles, and effectively facilitating speed harmonization along local arterials. Depending on the vehicle arrival time and the corresponding signal status (i.e., green, red, or yellow and all-red), the system will take corresponding actions to either prevent crashes or improve signal progression. Selecting a segment of Redwood Road, Salt Lake City as study site, the research team built a simulation platform in VISSIM. Through the VISSIM-COM interface, data were exchanged between outside computational VB.NET programs and the simulation model. Results from extensive experiments confirmed the effectiveness of the proposed system in both reducing potential intersection crash rates and improving arterial progression efficiency. The proposed control framework also proved the effectiveness of using dilemma zone protection sensors for traffic mobility improvement.

Recognizing that HV drivers may have different perception reaction times, one of the authors' future works to extend the proposed system is to develop a data-enabled model to account for such uncertainty. Also considering that VSL signs will be used for supporting both harmonization and crash prevention functions, their impact on drivers' compliance rate is another critical issue that needs to be investigated.

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Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: G-LC, data collection: ZZ; analysis and interpretation of results: XY, PL; draft manuscript preparation: XY, ZZ. All authors reviewed the results and approved the final version of the manuscript.

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