Traffic Optimization for Signalized Corridors (TOSCo) Phase 1 Project

Vehicle-level Simulation Report

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16. Abstract

The Traffic Optimization for Signalized Corridors (TOSCo) system consists of a series of innovative applications designed to optimize traffic flow and minimize vehicle emissions on signalized arterial roadways. The TOSCo system applies both infrastructure- and vehicle-based V2X communications to assess the state of vehicle queues and cooperatively controls the behavior of strings of equipped vehicles approaching a designated series of signalized intersections to minimize the likelihood of stopping. Assessment of the benefit and the working principles of the TOSCo system is performed by employing two different simulation environments. The *traffic-level* simulation environment implements a simplified version of the TOSCo algorithm, not focusing on the implementation in an actual vehicle, but on the assessment of macroscopic effects such as improved traffic flow or reduced energy consumption. This report constitutes the analysis of *Vehicle-level Simulations,* targeting the implementation of the TOSCo-algorithm in an actual vehicle. Its focus lies on the microscopic elements constituting a real-time enabled system ready to be deployed in a real-life prototype vehicle environment rather than on macroscopic benefits. The ability to test vehicle-ready software in a simulation environment before deployment in an actual vehicle reduces the development time, as incremental improvements can be tested without the need for a prototype vehicle and a test track, and it, therefore, also reduces the costs associated to the development process. The TOSCo vehicle-ready software is assessed in eight distinct traffic scenarios. This simulation report shows that the developed TOSCo algorithm is able to perform as specified in most of these simulation scenarios, thereby optimizing the approach strategy of a string of TOSCo-enabled vehicles towards an intersection. The variation of different simulation parameters for each scenario helped to identify remaining tasks and work items that have to be addressed before implementing the software in an actual vehicle environment. The specification of the speed profiles has to be revisited for cases in which the vehicle is currently decelerating, when computing the optimized profile. It is identified that the definition provided in this report does not take potential initial acceleration into account, resulting in undesirable behavior in case the vehicle is currently decelerating when the profile is generated. This occurs frequently especially in scenarios where the state of the traffic light changes and a vehicle is already decelerating (e.g., a vehicle decelerates while approaching a traffic light that is about to turn red), as this change in *external conditions* triggers a re-computation of the optimized speed profiles. The report closes with a summary of the different simulation scenarios and provides detailed insights to future work and an alternative speed profile definition to alleviate the limitations identified in this report.

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Executive Summary

This report documents the work completed during the Traffic Optimization for Signalized Corridors (TOSCo) Project. This project was undertaken by the Vehicle-to-Infrastructure (V2I) Consortium of Crash Avoidance Metrics Partners LLC (CAMP), in conjunction with the University of Michigan Transportation Research Institute (UMTRI), the University of California-Riverside (UCR) and the Texas A&M Transportation Institute (TTI). The Participants in this project are Ford Motor Company, General Motors, Hyundai-Kia, Honda, Mazda, Nissan, Subaru, Volvo Technology of America, and Volkswagen Group of America. The project is sponsored by the Federal Highway Administration (FHWA) through Cooperative Agreement No. DTFH6114H00002.

The TOSCo system consists of a series of innovative applications designed to optimize traffic flow and minimize vehicle emissions on signalized arterial roadways. The TOSCo system applies both infrastructure- and vehicle-based V2X communications to assess the state of vehicle queues and cooperatively controls the behavior of strings of equipped vehicles approaching designated series of signalized intersections to minimize the likelihood of stopping. The system thereby uses a combination of infrastructure- and vehicle-based components and applications along with wireless data communications to position the equipped TOSCo vehicles to arrive during the “green window” at specially designated signalized intersections. The “green window” is the time within the green interval in which a TOSCo-vehicle can traverse through the intersection without stopping. TOSCo-equipped intersections continually broadcast information about the geometry of the intersection (J2735 MAP message), status of the signal phase and timing at the intersection (J2735 SPaT message) and the presences of any traffic waiting in queues at the intersection. As a TOSCo-equipped vehicle enters the Dedicated Short Range Communication (DSRC) range at the intersection, it would receive the geometric map, Signal Phase and Timing (SPaT) and queue information. Using this information, the TOSCo vehicle would then plan a speed trajectory that would allow it to either pass through the intersection without stopping (either by speeding up slightly, maintaining a constant speed, or slowing down slightly to allow the queued vehicles ahead of it to clear the intersection before it arrives) or to stop in a smooth, coordinated fashion to reduce the amount of time stopped at the intersection. TOSCo vehicles that must stop at an intersection would perform a coordinated launch maneuver when the traffic light switches to green that would allow them to clear the intersection in a more efficient manner. Once the TOSCo vehicles leave communications range of the intersection, they would then revert to their previous operating mode (Cooperative Adaptive Cruise Control (CACC) operations).

Assessment of the benefit and the working principles of the TOSCo system are performed by employing two different simulation environments. The two simulation environments are the ‘traffic-level’ described here and the ‘vehicle-level’ described in the next paragraph, which is the focus of this report. The *traffic-level simulation* environment implements a simplified version of the TOSCo algorithm, not focusing on the implementation in an actual vehicle, but on the assessment of macroscopic effects such as improved traffic flow or reduced energy consumption. The analysis of the traffic-level simulations is detailed in [1].

This report constitutes the analysis of *Vehicle-level Simulations,* targeting the implementation of the TOSCo-algorithm in an actual vehicle. Its focus lies on the microscopic elements constituting a real-time enabled system ready to be deployed in a real-life prototype vehicle environment rather than on macroscopic benefits. Consequently, this report describes and evaluates eight different simulation scenarios employed to extensively test, verify and improve the vehicle-ready TOSCo algorithm. The TOSCo Vehicle-level Simulation environment

is used as part of a defined, iterative development cycle. Different software revisions of various components constituting the TOSCo system can be tested against each other, in a repeatable matter. As such, the Vehicle-level Simulation Environment plays a major role in reducing the development time and costs, as software iterations can be tested and verified in simulation rather than on a closed test track.

The Vehicle-level Simulation Environment is based on interlinked computers, running the vehicle-ready implementation of TOSCo (the Development-Environment computer), the vehicle-dynamic models (the Simulation-Environment computer) and the Virtual Driving Environment (the Driving-Environment computer). The vehicle software is implemented using a rapid prototyping environment called *Automotive Data- and Time-Triggered Framework (ADTF),* executing the software as if running in an actual vehicle. The vehicle dynamics models are simulated using a *MATLAB / Simulink*-based model. The microscopic traffic simulator VISSIM provides the means to simulate the Virtual Driving Environment. In each simulation, multiple instances of the TOSCo -system are created on the Development-Environment so that interactions between different entities can be tested as well. A set of TOSCo-enabled vehicles driving behind each other while approaching the intersection is referred to as a *TOSCo-string*.

The TOSCo vehicle-ready software is assessed in eight distinct traffic scenarios to evaluate proper operation of the different operating modes. Each scenario employs the same road network and intersection equipped with a traffic light operating on a fixed schedule. The scenarios differ in the introduction time of the TOSCo-enabled vehicles and in the allowed speed limit on the approach lane. The underlying idea for these scenarios is to verify the observed vehicle behavior against the expected scenario outcome.

1. Constant Speed Scenario: TOSCo vehicles are able to pass the intersection without speeding up. To improve throughput, when vehicles are driving at a speed below the lane speed limit, TOSCo operations would increase the vehicle speed up to the speed limit.
2. Speed-up Scenario: Similar to the Constant Speed Scenario, except that vehicles have no other choice than to speed up in order to not run the red light. The scenario also includes a *string-split,* that is the first vehicles of the TOSCo string are able to pass when speeding up to speed limit, whereas the last vehicles of the TOSCo string have no option other than to come to a full stop and to wait for the next cycle.
3. Slow-down Scenario: The reverse scenario compared to the Speed-up Scenario, in which the vehicle would arrive too early, unless they slow down to a speed which allows vehicles to pass the intersection without coming to a stop.
4. Coordinated Stop and Launch Scenario: This scenario causes vehicles to come to a full stop and then wait in front of the red light as slowing down to some lower speed might seem unfeasible from an external perspective. As soon as the light switches to green, the vehicles in the TOSCo string are initiating a *Coordinated Launch* (CL) in which all vehicles pick up speed simultaneously, thereby increasing throughput at the intersection.

Traffic scenarios 1 – 4 include TOSCo-enabled vehicles only. Non-TOSCo-enabled vehicles are not simulated as part of these scenarios. Although somewhat unrealistic, these scenarios provide the baseline to ensure proper operations of TOSCo before including mixed traffic scenarios which are addressed in the simulation scenarios described below. In these mixed traffic scenarios, a string of TOSCo-enabled vehicles is approaching a number of queued vehicles at the intersection. Although not equipped with the TOSCo functionality, these vehicles are transmitting Basic Safety Messages (BSM) and are therefore referred to as DSRC-only vehicles.

5. Speed-up with Dissipating Queue Scenario: Identical to scenario 2 but a queue of DSRC-only vehicles is currently dissipating from the intersection. The TOSCo string has to react to an adapted (decreased) green window.

6. Slow-down with Dissipating Queue Scenario: Identical to scenario 3 with the addition of DSRC-only vehicles leaving the intersection when the TOSCo string is approaching. This scenario may cause TOSCo-vehicles to come to a full stop, in case the DSRC-only vehicles diminish the duration of the green window available for the TOSCo-enabled vehicles to pass the intersection while green.
7. Coordinated Stop and Launch with Dissipating Queue Scenario: Identical to scenario 4 with stopped DSRC-only vehicles at the intersection when the TOSCo string arrives. This causes the TOSCo vehicles to stop not at the stop bar (as in Scenario 4) but behind the queue of already waiting DSRC vehicles. As soon as the traffic light switches to green, the TOSCo vehicles perform a coordinated launch behind the DSRC-only vehicles.
8. Creep at Intersection Scenario: This scenario is dedicated to a situation often encountered in real life in which a vehicle stops at a red light, turns right on red and enables the remaining vehicles to creep forward. This scenario is setup so that an arriving TOSCo string must come to a full stop. Once stopped, the first vehicle of the queue of DSRC-only vehicles turns right on red so that the remaining vehicles are able to creep forward. Once the traffic light turns to green, the vehicles shall resemble the launch behavior encountered in scenario 7.

These scenarios are simulated for different simulation parameters throughout the development process of the TOSCo-vehicle-level software. Different parameters are varied for each scenario, focusing on very specific aspects of the functionality in each iteration. This report highlights these variations in more detail, representing the findings and consecutively identified work items for an actual in-vehicle implementation.

Based on thee simulation scenarios presented in this report, the following findings and open work items were identified:

- The TOSCo Vehicle-level Simulation Environment is a very helpful tool to effectively reduce development time and costs. Vehicle software can be tested and verified before moving into an actual vehicle environment.
- The TOSCo algorithm is able to perform as specified in most of the basic simulation scenarios outlined above, without the need for further modifications.

The variation of different simulation parameters for each scenario helped to identify remaining tasks and work items that have to be addressed before implementing the software in an actual vehicle environment:

- The specification of the speed profiles has to be revisited for cases in which the vehicle is currently decelerating, when computing the optimized profile. The current definition does not take potential initial acceleration into account, resulting in undesirable behavior in case the vehicle is currently decelerating. This occurs frequently, especially in scenarios where the state of the traffic light changes and a vehicle is already decelerating (e.g., a vehicle decelerates while approaching a traffic light that is about to turn red), as this change in *external conditions* triggers a re-computation of the optimized speed profiles.
- The target speed to which vehicles are slowing down to in case of Scenarios 3 and 6 is currently predetermined by the speed profile methodology. This procedure is, however, not advisable as it decreases the solution space, especially in scenarios where the target speed does not concur with the ambient approach conditions.
- For any conditions in which the stopping duration is very short (mainly caused by the previous observation), not all vehicles within the TOSCo string might come to a full stop. In this situation, the current specification does not allow for a transition to a coordinated launch mode.

- Communication ranges of the Roadside Unit (RSU) have to be adapted to the speed limit to provide sufficient space for optimizing vehicle behavior. With increasing posted speed limits, the communication range needs to increase as well. Approaching vehicles need to be provided with enough time to adapt a computed optimized strategy in a comfortable manner. The shorter the communication range, the smaller the resulting solution space. Ensuring a sufficiently large communication range of the RSU can be realized by employing directional antennas or by other suitable means.
- The employed speed profiles do not reflect the deceleration- or acceleration-behavior as expected by a driver. Rather than adopting a monotonously increasing acceleration level up to a predetermined peak value, to then monotonously decrease the acceleration level (half-sinusoid), a calculated acceleration level should be maintained over a certain duration before decreasing the acceleration level. This will not only increase the optimization space of the TOSCo algorithm but also more closely resemble the deceleration behavior of manually driven vehicles, therefore increase user acceptance.

The remainder of this report is structured as follows:

Chapter 1 introduces the basic concepts of the TOSCo system and provides a high-level overview of the structure of the document. A detailed presentation of the simulation workflow and the development process is provided in Chapter 2 along with a presentation of the Simulation Architecture. The chapter outlines the operations of three simulation computers and the interlinked simulation software. Optimizing the approach of a TOSCo-enabled vehicle is based on a set of speed profiles which are computed based on the environment conditions such as remaining distance to the stop location, state of the traffic light and the queue length caused by vehicles potentially waiting before the intersection. Chapter 3 provides the mathematical derivation of these profiles. Chapter 4 represents the analysis of the TOSCo algorithm in the different simulation scenarios introduced above. Each section within the chapter is thereby written in a similar manner, by first introducing the expected behavior of the scenario and then comparing the expectation with the findings of the simulation run. Different parameter variations are introduced, where required. The findings are summarized in Chapter 5, also providing an outlook to future work to further improve the TOSCo algorithm.

A series of appendices then follow the main body of the report. These appendices support specific topics that are within the main body of the report and are referenced where applicable.

1 Introduction

The Traffic Optimization for Signalized Corridors (TOSCo) system is a series of innovative applications designed to optimize traffic flow and minimize vehicle emissions on signalized arterial roadways. The TOSCo system applies both infrastructure- and vehicle-based V2X communications to assess the state of vehicle queues and cooperatively control the behavior of strings of equipped vehicles approaching designated series of signalized intersections to minimize the likelihood of stopping. Along with Signal Phase and Timing (SPaT-message) and intersection map (MAP-message) data, information about the state of a queue, if present, is continuously recomputed and broadcast to approaching connected vehicles using the SPaT. Leveraging previous Crash Avoidance Metrics Partners LLC (CAMP) / Federal Highway Administration (FHWA) work on Cooperative Adaptive Cruise Control (CACC), approaching vehicles equipped with TOSCo functionality use this real-time infrastructure information to plan and control their speeds to enhance the overall mobility and reduce emissions outcomes across the corridor.

One significant outcome of this project has been the development of the TOSCo Simulation Environment. As part of this project, the research team developed an innovative simulation environment to support the development and assessment of TOSCo functionality. The environment consists of two separate entities: a vehicle simulation environment and an infrastructure simulation environment. The vehicle simulation environment gives the TOSCo team the ability to test and verify algorithm code that will eventually reside in TOSCo-enabled vehicles. The infrastructure simulation environment was developed to test and verify detection and processing algorithms that reside on infrastructure devices [1].

This report focuses on the design of the Vehicle-level Simulation Platform, assisting the development of the vehicle-level algorithms. The simulation environment is key to reducing development time and project costs, as algorithms can be tested before integrating the system into an actual vehicle.

The remainder of this report is organized as follows:

- Chapter 2 discusses the Vehicle-level Simulation Environment developed to support this project and its operations
- Chapter 3 outlines and details several simulation strategies for a vehicle to approach and depart a traffic light
- Chapter 4 presents the results and detailed analysis of the simulation experiments
- Chapter 5 summarizes the findings and identifies areas for future work to further improve vehicle approach and departure strategies

A series of appendices then follow the main body of the report. These appendices support specific topics that are within the main body of the report and are referenced where applicable.

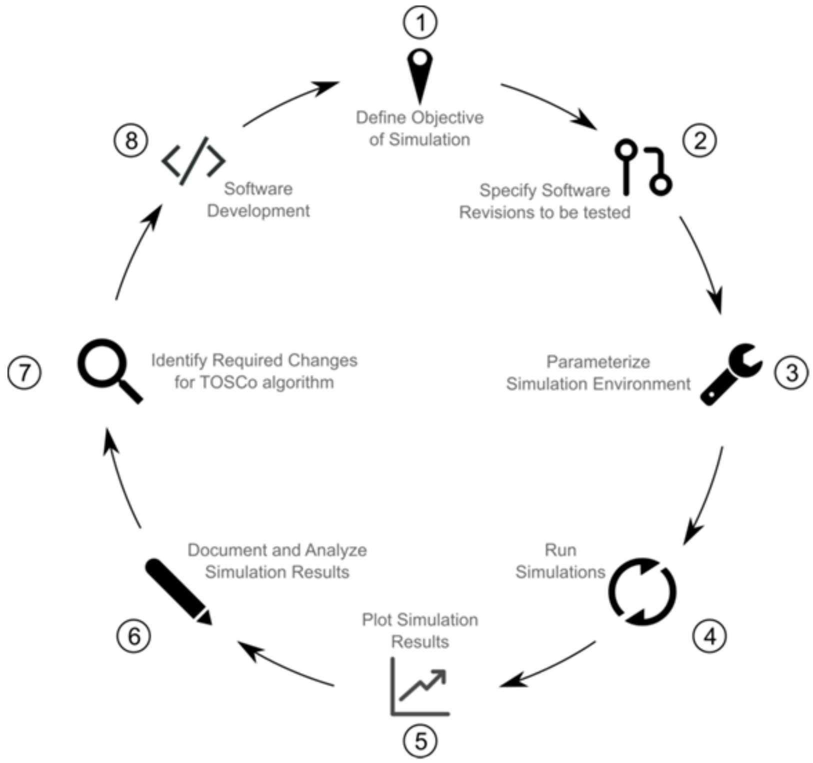
2 Vehicle-level Simulation Environment

The capability to test prototype in-vehicle software without requiring an actual vehicle is key to rapid and economic development of novel applications. The development process of the TOSCo system employs an extensive simulation environment consisting of several separate components and simulation software which are interlinked to create test results for specific revisions of the TOSCo algorithm. Section 2.1 outlines the underlying workflow in which the simulation environment is employed to assist the development of the TOSCo system. The architecture and interlinkage of the different components that constitute the simulation environment is detailed in Section 2.2. The subsequent sections focus on the three core components of the simulation environment. The vehicle-dynamics and synchronization component are detailed in Section 2.3. The instantiation of multiple TOSCo vehicle-level entities is outlined in Section 2.4. The simulation of the driving environment and the infrastructure component responsible for broadcasting traffic light information is detailed in Section 2.5.

2.1 Simulation Workflow

The Vehicle-level Simulation Environment provides the opportunity to rapidly test, modify and then re-test specific aspects of the TOSCo algorithm without having to deploy a specific version in a vehicle and run several tests on a closed track. Next to reduced costs, the ability of simulating the core TOSCo components also provides determinism as simulation runs yield the same results as long as identical initial parameters are used. This property allows for incremental delta tests, in which the cause of a particular result can be identified by gradually modifying a single parameter only, while keeping all others unchanged. However, only if the objective of the simulation to be carried out is clearly defined, it can be employed purposefully in the context of the development process of the TOSCo system. Consequently, a well-defined simulation workflow is required to assist the development.

Figure 1 depicts the workflow utilized in the context of Vehicle-level Simulations. Prior to running a simulation, its objective needs to be clearly defined ①. For this purpose, a project-internal wiki system is used to state the analysis domain of the simulation. The corresponding software revisions to be tested for the various simulation components are specified in step ②. Different software revisions are maintained in a decentralized revision management system based on git [2]. Revisions can thereby be uniquely identified by automatically generated secured hashes (SHA). This process may be repeated until the overall number of required simulation runs is specified. Afterwards, the different simulation components need to be parameterized according to the previous definitions ③. Running the simulations in step ④ is associated with the generation of a unique run-number that is referenced in the wiki system. Simulation runtime (on average 20 min per scenario) thereby varies with the simulation scenario. If required, the simulation environment also allows for a recording of videos of the scenario. This is especially important as, due to the number of simulated vehicles, simulation runtime does not advance in real time. After each successful simulation run, a custom Python scripting generates standardized plots ⑤ that are used in the subsequent documentation ⑥ within the wiki system, thereby constituting a standardized simulation report. The simulation log files, recordings and diagrams are automatically uploaded to a cloud storage facility.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

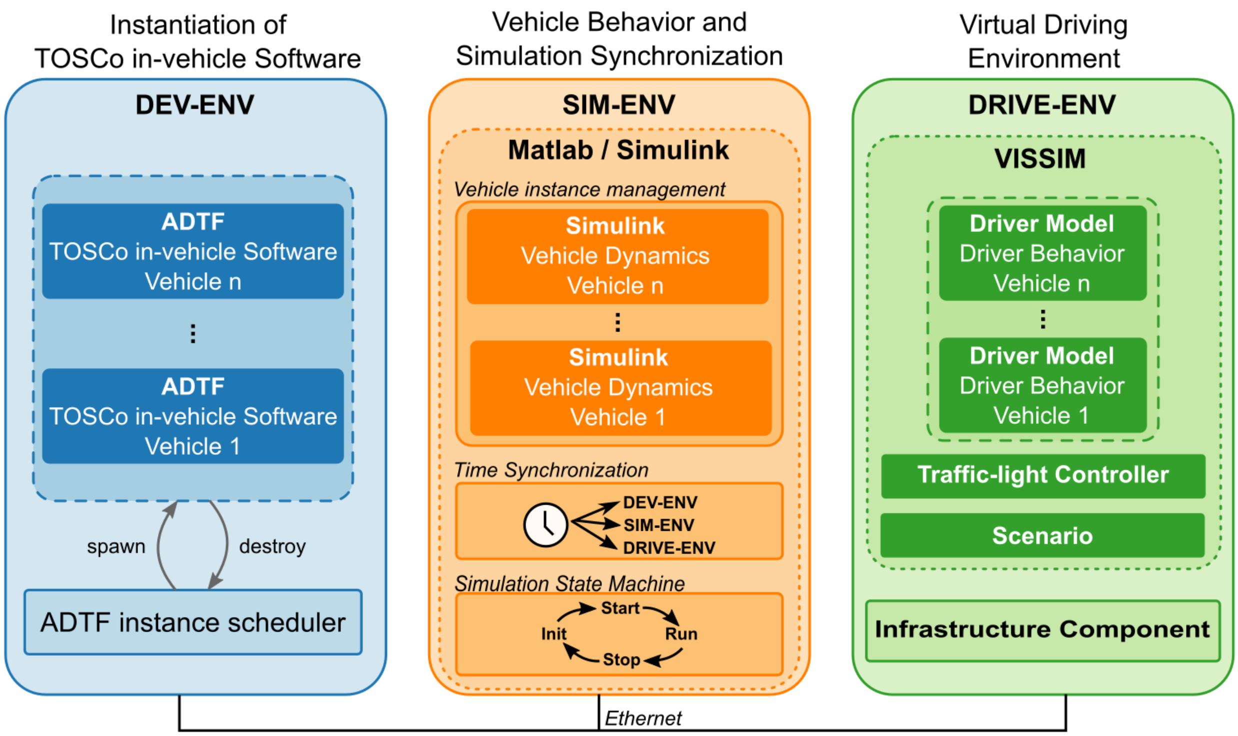
Figure 1: Simulation Workflow

Each report is subsequently analyzed and required changes to the TOSCo algorithm are identified ⑦. These are implemented in the next software development iteration ⑧, resulting in a new revision to be tested in a new simulation cycle.

The simulations presented in this document were conducted in accordance with the depicted simulation workflow. Chapter 4 thereby presents some of the plots generated in step ⑤, with which a representative analysis is carried out for different simulation scenarios. Each analysis results in a list of potential next steps and further improvements, which are summarized in Chapter 5.

2.2 Simulation Architecture

Two different simulators have been developed as part of the TOSCo Project: The *Traffic-level Simulation* [1], focusing on assessing benefits of the TOSCo algorithm on a macroscopic level, and the *Vehicle-level Simulation*, focusing on assisting the development process of the in-vehicle software of the TOSCo algorithm. Different objectives for both simulators result in different levels of implementation granularity of the TOSCo algorithm. Macroscopic analyses of the Traffic-level environment with several hundred vehicles in a corridor necessitate a somewhat simplified implementation of the TOSCo optimization strategy to decrease the required simulation runtime. The Vehicle-level Simulation, on the other hand, aims at employing exactly the same implementation of the TOSCo algorithm that could at a later stage be deployed in an actual prototype vehicle-environment. Hence, the Traffic-level Simulations can abstract and simplify certain vehicle interfaces, as long as the underlying generated speed profiles comply with those generated in the Vehicle-level software, at the benefit of increasing simulation speed. The Vehicle-level Simulations, on the other hand, simulate vehicle interfaces and vehicle dynamics in more detail so that the developed software can be operated in a real vehicle as well. Common to both simulation levels is the software for simulating the driving environment simulation, called *Verkehr in Städten – Simulationsmodell* (VISSIM) which allows for the simulation of the different granularities on the same underlying road network.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 2: TOSCo Vehicle-level Simulation Architecture

The Vehicle-level Simulation Environment consists of three separate computers running on a Microsoft Windows operating system connected via a local Ethernet network as depicted in Figure 2. Its underlying architecture has been adopted from the CAMP Cooperative Adaptive Cruise Control – Small Scale Test (CACC SST) Project [3]. At the core stands the *Simulation Environment (Sim-Env)* which runs a MATLAB / Simulink instance simulating vehicle dynamics and synchronizing the simulation entities across all three computers, as detailed in Section 2.3. The *Development Environment (Dev-Env)* is a separate computer running multiple instances of the vehicle-ready software implementation of the TOSCo system, implemented in a framework called Automotive Data- and Time-Triggered Framework (ADTF) [4]. Its operation is detailed in Section 2.4. Each virtual vehicle instance is driving in a virtual environment generated by the aforementioned VISSIM simulation software component on the *Driving Environment (Drive-Env)* computer. It is also running the infrastructure component generating information about the current state of the traffic light. Operations of the *Drive-Env* are detailed in Section 2.5.

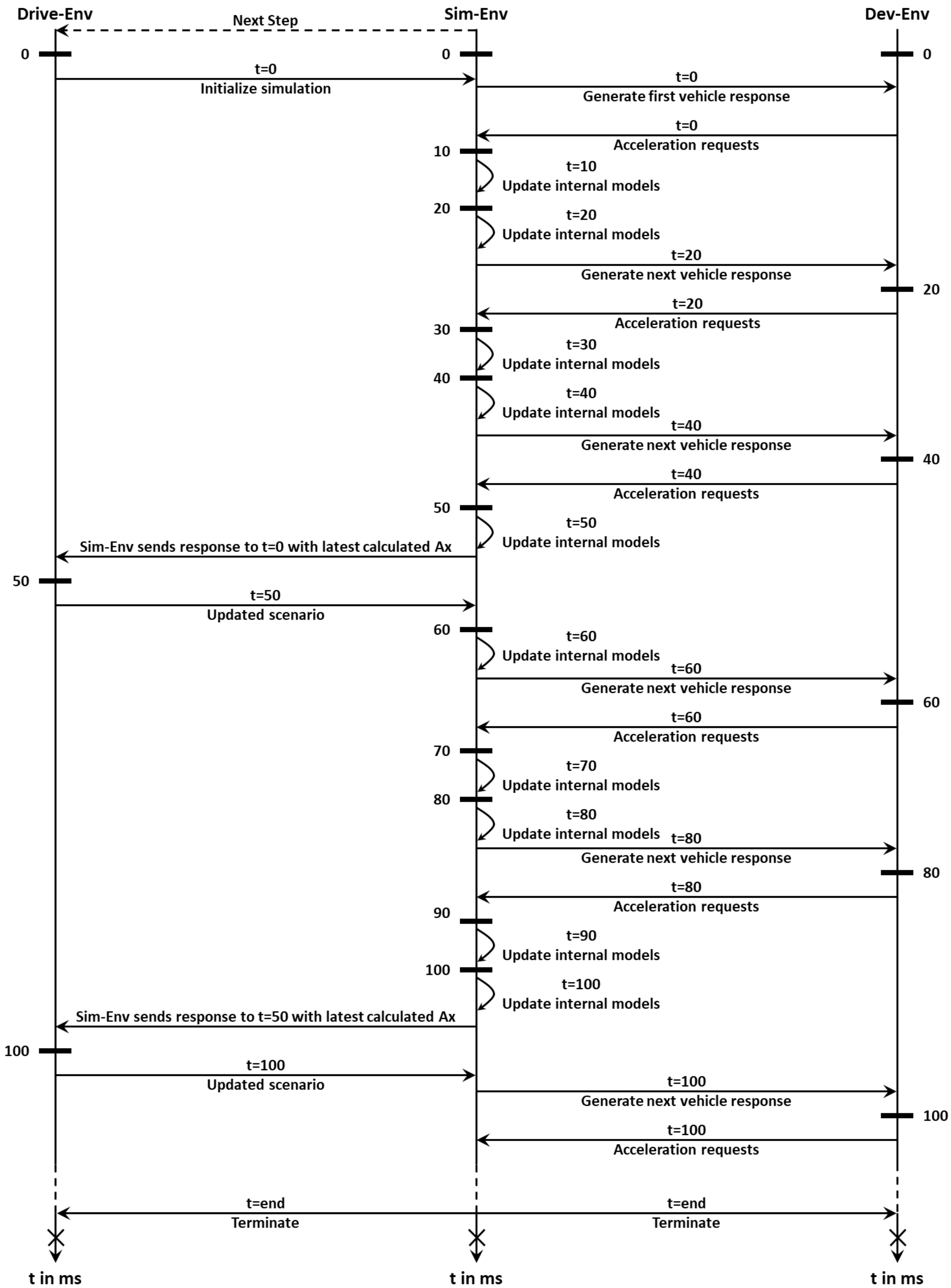
In contrast to the simulation environment employed by the CAMP CACC SST Project [3], effects resulting from the inter-vehicle communications are not simulated as part of this report. Due to the relatively short required communication ranges (maximum 200 m) and very limited number of communicating vehicles in a scenario (maximum of nine communicating vehicles), congestion effects resulting in message drops due to hidden-node effects are not taken into account.

2.3 Simulation of the Vehicle Dynamics and Synchronization of Simulation Entities

At the core of the simulation environment stands the *Simulation Environment (Sim-Env)*, running a MATLAB / Simulink model responsible for representing the vehicle behavior of each TOSCo-equipped vehicle in the simulation scenario and for synchronizing the other two simulation computers.

Prior to running a simulation, a custom MATLAB-script has to be manipulated to select the desired simulation scenario. Specific parameters, such as the simulation runtime, each TOSCo-equipped vehicle's driver's set speed and the desired time gap can be selected individually for each scenario.

Section 2.3.1 details the synchronization process maintained by the Sim-Env. A summary of the different modules of the Simulink model is provided in Section 2.3.2.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 3: Synchronization of Simulation Components

2.3.1 Synchronizing the Vehicle-level Simulation

The Simulink instance maintains a state machine controlling the operation of the simulation, as depicted in Figure 2. When starting a new simulation run, the Simulink model is compiled and initialized. Connectivity with the other two simulation computers is checked and the simulation is started.

While running, the Simulink instance controls the advancement of the simulation time for the other two simulation computers by sending a “next simulation step” command, as detailed in Figure 3.

Each simulation software constituting the Vehicle-level Simulation Environment supports the principle of discrete-event simulations. This regime allows for rapid advancement of the simulation time as the time advances not linearly but “jumps” to the next timestamp at which some calculation is required [5]. Each component, however, runs at different inter-event time gaps. Whereas VISSIM only updates its internal models every 50 msec, the ADTF updates every 20 msec. Simulink is parameterized to exhibit the shortest inter-event duration of 10 msec, in order to reduce errors associated to predictions in the different sub-models detailed in Section 12 and to provide a common synchronization point between ADTF and VISSIM.

Figure 3 depicts the sequence chart resembling the synchronization of the different simulation software. The simulation within Simulink commences when VISSIM responds to the first “next step” command the Sim-Env and reports initial vehicle positions. It should be noted that the time to respond to the first request from the Sim-Env might take some seconds depending on the simulation duration in VISSIM without any TOSCo vehicles in the simulation[1]. While VISSIM then waits for the following “next step” command to proceed to a simulation time of 50 ms, it maintains the current simulation time of 0 ms until that point in time. Upon receiving the response from VISSIM, the Simulink instance transmits the initial vehicle positions and states to the ADTF instance. Once a corresponding instance of the TOSCo algorithm software linked to each created vehicle has been created (see Section 2.4), a response with an acceleration request to be applied[2] is sent to Simulink.

The models implemented on the Sim-Env are hence provided with all required information to update the sub-models associated to each vehicle (see Section 2.3.2) and to advance to the next simulation timestamp of 10 ms. Since no further synchronization with either VISSIM or ADTF is required at this timestamp (due to the different aforementioned update frequencies), the Simulink model advances to a simulation timestamp of 20 ms. At this event, the next input from ADTF can be generated by requesting the next acceleration request from the TOSCo systems instantiated on the Dev-Env, as depicted. Upon receiving an answer, the Simulink model is advanced to a simulation timestamp of 30 ms. This procedure continues until Simulink reaches a simulation timestamp of 50 ms, at which time VISSIM needs to be updated. Simulink therefore sends a request to VISSIM to advance each vehicle with the acceleration values computed by each vehicle model, to which VISSIM responds with updated position information for each vehicle. Up until this point, VISSIM maintained a simulation timestamp of 0 ms as it was waiting for new input to advance to a simulation timestamp of 50 ms.

All simulation components continue to advance in this fashion until the a-priori defined final simulation timestamp is reached and Simulink terminates the simulations on the other two computers.

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[1] For all simulation scenarios, the traffic light schedule is maintained. As a result of different introduction timestamps, TOSCo vehicles arrive at the stop location at different times throughout this schedule, e.g., arrive at the traffic light when it is red. The simulation in VISSIM thereby advances at an increased speed until the first vehicle is introduced into the scenario.

[2] In a real vehicle, this acceleration request would be realized by the corresponding vehicle-systems such as the engine-ECU and other system.

2.3.2 Vehicle-level Sub-models

As outlined above, multiple TOSCo vehicles will be simulated simultaneously within the simulation environment. For this purpose, Simulink maintains separate instances of the following sub-models[3] for each vehicle in the simulation, as depicted in Figure 2. The Simulink model thereby consists of four dedicated sub-models for each vehicle. These are detailed in the CAMP Cooperative Adaptive Cruise Control – Small-scale Test (CACC-SST) Report [3] and summarized below:

1. **GPS Sensor Model**: Within the Virtual Driving Environment in VISSIM, vehicles are travelling within a Cartesian coordinate system in which a vehicle's position is given as an x- and y-offset from the driving environment's reference point. In the context of actual road tests, however, vehicle positions as reported by a Global Navigation Satellite System (GNSS) receiver are expressed within the World Geodetic System 1984 (WGS84) [6]. These coordinates provide a latitude and longitude measurement for a position referenced in the Earth-fixed, Earth-centered terrestrial coordinate system. To resemble the behavior of a GNSS-receiver installed in a test vehicle, the GNSS Sensor Model generates a virtual latitudinal and longitudinal position for each vehicle at a rate of 10 Hz. Within the simulation environment, vehicle positions are provided without an error. To be able to test the TOSCo algorithm under more realistic conditions, positioning errors can be applied to the generated position (Refer to Section 3.1.1.4.1 of [3]).
2. **Radar Sensor Model:** As detailed in the TOSCo System Specification [7], each TOSCo-enabled vehicle is equipped with a front-facing radar sensor. Data input generated by this sensor therefore also has to be modelled by the Sim-Env. The model receives the positions and speed values of all vehicles within VISSIM and hence generates an object list for each vehicle. This list contains measurement information about all detected objects (i.e., other vehicles). The mode thereby accounts for shadowing effects, bumper-offsets[4], sensor field of views and measurement inaccuracies, as detailed in Section 3.1.1.4.2 of [3].
3. **Vehicle Sensor Model:** This model simulates the signals provided by a vehicle's internal Controller Area Network (CAN) system. The signals generated are the vehicle's speed, yaw rate, accelerations, turn signal states and brake switch information. (Refer to Section 3.1.1.4.3 of [3]).
4. **Vehicle-Dynamics Model:** Vehicle-responses to acceleration input have to be reflected in the current vehicle state. The model is initialized with the vehicle speed and acceleration provided by VISSIM for the first simulation timestamp and then advances based on a Linear Bicycle Model to compute "true" acceleration and speed of the vehicle. The model thereby only takes longitudinal accelerations into account and a linear friction model is employed [3]. Different first order lags for acceleration and deceleration phases are considered along with possible road grades (Refer to Section 3.1.1.4.4 of [3]).

[3] All sub-models are running within the same Simulink Instance. A single implementation block within the simulation is be able to generate data for more than one vehicle.

[4] The reported distance information for each object is offset from the vehicle's center position provided by VISSIM to the middle of a vehicle's rear bumper.

2.4 Simulation of the In-vehicle Software

The core of the TOSCo system to be deployed in a vehicle is the software implementing the TOSCo algorithm. The *Development Environment (Dev-Env)* computer takes on the role of the in-vehicle computer running the main TOSCo algorithm. Whereas in a real-vehicle environment, each vehicle would be equipped with its own on-board computing entity, the Dev-Env is able to instantiate multiple TOSCo systems, each linked to a particular vehicle existing in the Virtual Driving Environment on the Drive-Env and a vehicle model instance on the Sim-Env.

The TOSCo algorithm is implemented within the ADTF framework thus allowing for prototyping of applications by providing extensive debugging, logging and data-flow modelling capabilities [4]. Each building block constituting the TOSCo system is implemented in C++ as standalone software modules and is linked to an ADTF filter, the microscopic logical components of the TOSCo system. While a detailed representation of these building blocks is out of the scope of this document, the TOSCo System Specification Documentation [7] provides a detailed summary of the software specification.

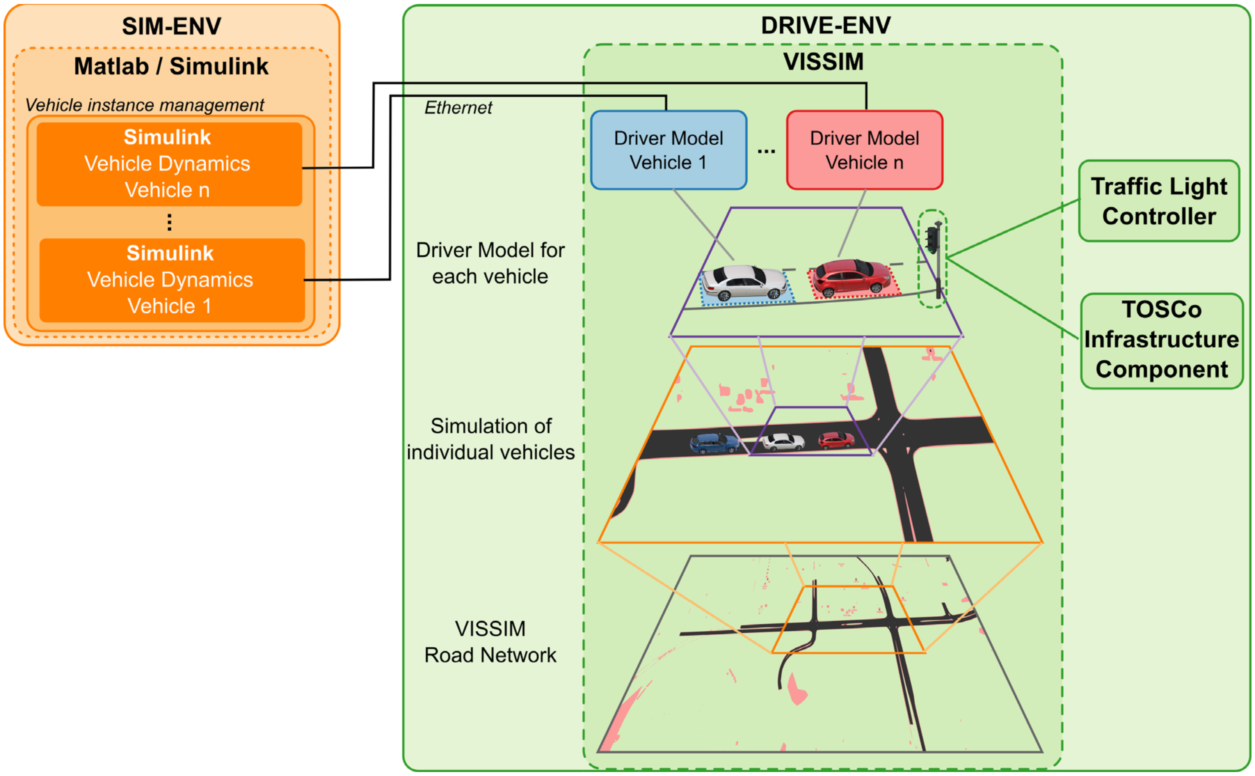
As depicted in Figure 2, a separate instance, called the *ADTF instance scheduler,* is also running on the Dev-Env. Vehicles can be created at different points in time throughout the simulation. Consequently, the instance scheduler is responsible for generating and connecting a new TOSCo algorithm instance upon the appearance of a virtual vehicle in the simulation. For each simulation step, when the Sim-Env schedules the computation of the next simulation timestamp as depicted in Figure 3, the instance scheduler distributes the corresponding vehicle information and states (position, velocity, etc.) to the corresponding TOSCo algorithm instance. After each instance has computed its response, the scheduler collects all results and responds to the Sim-Env. As such, the scheduler instance provides a very similar interface to each TOSCo algorithm instance as would exist in an actual in-vehicle implementation thus abstracting the specific simulation-internal interface between the Dev-Env and the Sim-Env. When the simulation terminates, the instance-scheduler entity is also responsible for terminating each TOSCo algorithm instance.

Each TOSCo algorithm instance provides the same logging mechanism yet generates unique log files for each instantiated vehicle. When the simulation is terminated, a JavaScript Object Notation (JSON) file is generated, comprising of an extensive set of vehicle state information for each timestamp of the simulation. These output files are consecutively parsed and analyzed by the custom Python plotting introduced in Section 2.1. When transitioning to a deployment of the software into the vehicle, the same post-processing methodology can then be applied to data logs generated on a test track.

2.5 Simulation of the Driving Environment and Infrastructure Component

Three software components are running on the *Driving-Environment (Drive-Env)* computer: The traffic simulator VISSIM, the traffic light controller and the infrastructure component.

The employed traffic simulator VISSIM (version 9) is a microscopic discrete-event time-step based simulation environment that targets behavior-based traffic simulations. VISSIM provides an extensive user interface to create and import realistic road-networks. Throughout a simulation, the network is populated with individually modelled vehicles. VISSIM is also used by the Traffic-level Simulations performed as part of the TOSCo Project [1].



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 4: Overview of Components on the Driving Environment Computer

Figure 4 depicts the components running on the Drive-Env and its connection to the Sim-Env. The road network represents the Virtual Driving Environment in which individual vehicles are travelling. The network consists of lanes with attributes, defining the speed limit, allowed turning directions, etc. VISSIM instantiates a *driver model* for each vehicle within the simulation. Within the TOSCo Project, a custom driver model has been implemented allowing for external manipulation of each vehicle by applying the acceleration commands generated by the Dev-Env. The driver model of a particular vehicle maintains an Ethernet connection with a corresponding instance within the Simulink model running on the Sim-Env, as outlined in Section 2.3.

Two different vehicle types can be instantiated in the simulation: *TOSCo-vehicles*, for which a TOSCo-algorithm instance is created and *DSRC-vehicles* which are controlled by VISSIM but represented in Simulink for the radar-model and BSM transmission.

VISSIM also allows for the integration of a separate traffic light controller software, as employed by actual traffic lights. For each traffic light in the simulation, VISSIM instantiates a separate traffic light controller module, running a corresponding individual traffic light schedule. This methodology allows for realistic representation of the traffic lights in the simulation, as the controller is responsible for providing information for the SPaT message as well.

Additionally, the separate *TOSCo Infrastructure Component*, as developed by the TOSCo Project and as detailed in [1], is also running on the Drive-Env. This component resembles a software running on the infrastructure entity responsible for creating the information about the green window and queue length estimation in case of vehicles already waiting in front of the red traffic light. The “green window,” computed by the infrastructure, is based on the estimated time that a queue will clear the intersection during the green interval. The date generated by this component will be transmitted as part of the SPaT.

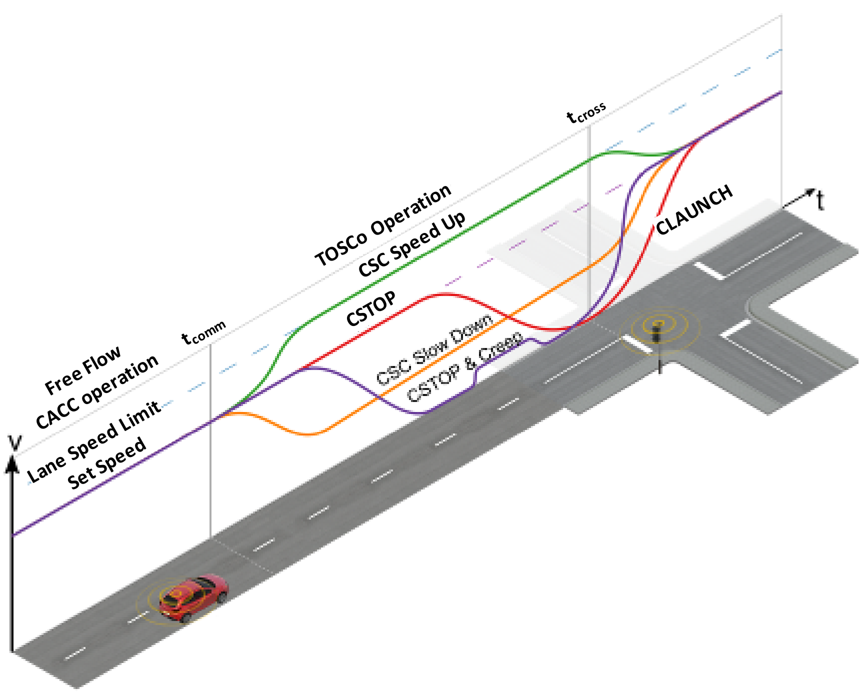
3 Vehicle Approach and Departure Strategies

The TOSCo system optimizes a vehicle's approach towards a traffic light by computing *speed profiles* which are then being followed by the system's longitudinal controller. A speed profile is computed as soon as all information (SPaT and MAP) is received from the infrastructure component, and the TOSCo operating mode is determined. These are briefly summarized in Section 3.1. The computation of the speed profiles corresponding to each TOSCo operating mode are detailed in Section 3.2.

3.1 TOSCo Operating Modes

Upon receiving all infrastructure messages (SPaT and MAP), the mode selection component of the TOSCo system determines the operating mode required to optimize the vehicle's approach to the traffic light. A detailed explanation of the TOSCo mode selection is out of the scope of this document and detailed in Section 4.3 of [7].

Almost every operating mode is associated to the computation of a speed profile. The possible TOSCo operating modes are detailed in Section 2 of [7] and summarized below.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 5: TOSCo Operating Modes and Corresponding Idealized Speed Profiles

Figure 5 depicts most of the TOSCo operating modes and the corresponding speed profiles computed for each mode. Approaching vehicles start receiving messages from the infrastructure component at t_{com} and select a TOSCo operating mode corresponding to the traffic light state and initial velocity. Table 1 summarizes all TOSCo operating modes.

Table 1: TOSCo Operating Modes

Operating Mode	Description
Free Flow *FF*	Vehicles are under CACC-control. No information from the infrastructure component received. No Approach Optimization.
Coordinated Speed Control – Speed Up *CSC_UP*	Vehicle receives information from infrastructure component. Enters CSC_UP if acceleration up to speed limit allows vehicle to cross stop location within green window. A CSC_UP Speed Profile is computed.
Coordinated Speed Control – Slow Down *CSC_DWN*	Vehicle receives information from infrastructure component. Enters CSC_DWN if deceleration to a lower a-priori set speed allows vehicle to cross stop location within green window. A CSC_DWN Speed Profile is computed.
Coordinated Speed Control – Constant *CSC_CONST*	Vehicle receives information from Infrastructure component. Enters CSC_CONST if maintaining vehicle's current speed allows it to cross stop location within green window. A CSC_CONST Speed Profile is computed.
Coordinated Stop *CSTOP*	Vehicle receives information from infrastructure component. Enters CSTOP if vehicle can neither speed up nor slow down and therefore has to come to a full stop at the stop location. A CSTOP Speed Profile is computed.
Stopped *STOPPED*	Vehicle receives information from infrastructure component. Vehicle speed drops below standstill speed threshold after a deceleration phase. Mode is maintained until driver confirms that a different mode may be accessed (e.g., CLAUNCH).
Coordinated Launch *CLAUNCH*	Vehicle receives information from infrastructure component. Enters CLAUNCH if driver confirms launch and when traffic light state switches from red to green. A CLAUNCH profile is computed.
Creep *CREEP*	Vehicle receives information from infrastructure component. Enters CREEP if vehicle currently stopped but preceding vehicle moved forward while traffic light is still red (e.g., because the preceding vehicle turned right on red) and driver confirms state. A CREEP Speed Profile is computed.
Optimized Follow *OF*	Vehicle receives information from infrastructure component. This mode is entered when vehicle is operating within solution space (between *best-* and *worst-case* speed profiles) for the given mode.

Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

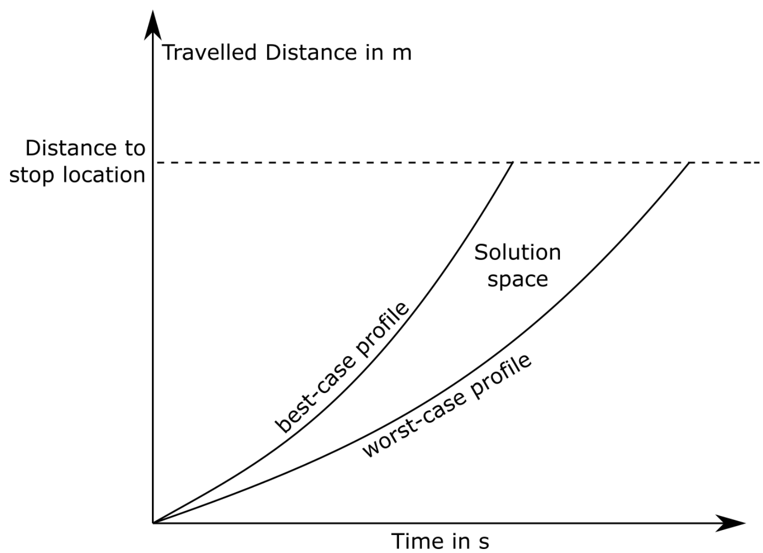
Throughout the approach towards an intersection, the selected TOSCo operating mode can change in case of changing external conditions (e.g., the traffic light changes its state), changing vehicle states (e.g., vehicle comes to stop) or leaving the solution space of the current operating mode (see Section 3.2). With the exception of the *Stopped* mode, a new speed profile is generated every time a new TOSCo operating mode is selected.

3.2 Speed Profiles

The following sections introduce to the concept underlying the computation of speed profiles. Section 3.2.1 details the concept of *best*- and *worst-case* profiles which are computed for any selected TOSCo mode. Section 3.2.2 provides the mathematical background for the speed profile computation.

3.2.1 Best- and Worst-case Profile

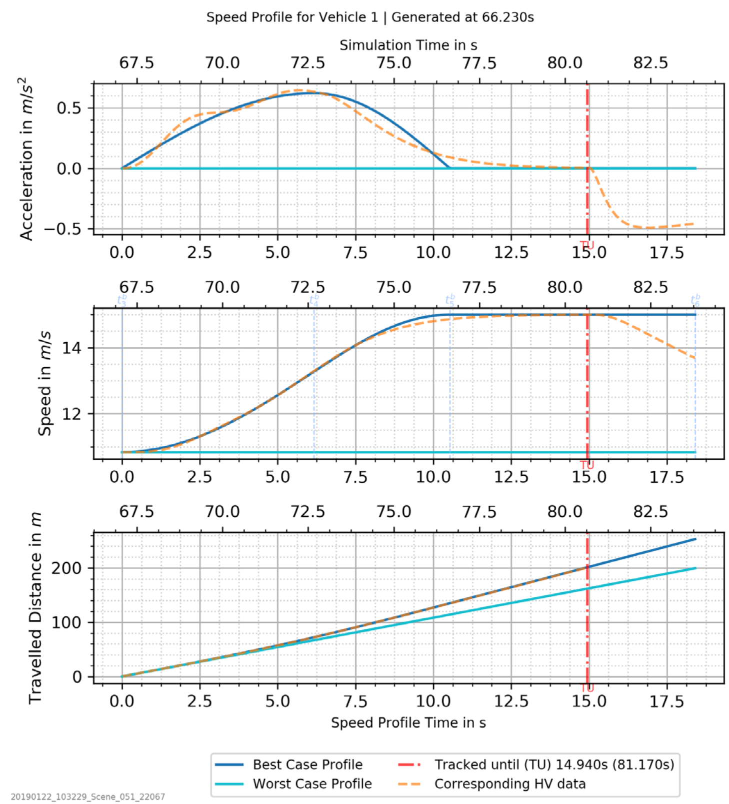
Whenever a TOSCo mode triggering the computation of speed profiles is entered (refer to Table 1), a set of speed profiles is computed, consisting of the *best*- and *worst-case* profile. It should be noted that a speed profile consists of an acceleration, speed and travelled distance profile over time. The *best-case* profile resembled a valid speed profile that enables a vehicle to cross the stop location as early as possible, i.e., as close to the beginning of the green window as possible without violating any speed limits. This corresponds to the optimization criterion of TOSCo to improve traffic efficiency by increasing the throughput at an intersection by means of getting as many vehicles across the stop location as possible. The corresponding *worst-case* profile represents a valid speed profile which enables a vehicle to pass the intersection at a green light as late as possible. The *best-case* speed profile is provided to the TOSCo longitudinal controller at all times, as detailed in [7]. If a vehicle cannot follow the *best-case* profile, for example due to a slower preceding vehicle, the speed profiles are maintained until the travelled distance drops below the minimum required travelled distance governed by the *worst-case* speed profile. Figure 6 generalizes this concept by representing the solution space created by the *best*- and *worst-case* speed profiles. Regardless of the profile followed limited by these two cases, the distance travelled must be equal to the distance to the stop location at the time the speed profile is created.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 6: Generalization of Best- and Worst-case Speed Profiles

The simulation result analyses presented in Chapter 4 will provide detailed a detailed representation of the computed speed profile, when necessary. Figure 7 depicts an exemplary computed speed profile for a Coordinated Speed Control – Speed Up Scenario. The three subplots represent the acceleration (top), corresponding speed (middle) and travelled distance (bottom) according to the computed speed profile. The *best-case* profile is provided in dark blue, the *worst-case* profile is provided in light blue. As outlined above, the *best-case* speed profile is provided to the TOSCo longitudinal controller at all times. The orange dashed lines represent the observed vehicle response to the controller output. At around 66 s into the simulation, a set of *best-* and *worst-case* speed profiles is computed. The *best-case* profile is characterized by a gradual acceleration from about 11 m/s to 15 m/s, whereas the *worst-case* profile results from not accelerating at all and maintaining the current speed. As long as the vehicle's observed travelled distance is between the allowed travelled distances between the *best-* and *worst-case* profiles depicted in the bottom diagram of Figure 7, a re-computation of the profiles is not required. The depicted profile is followed for about 15 s until the vehicle crosses the stop location.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 7: Exemplary Computed CSC Speed UP Profile

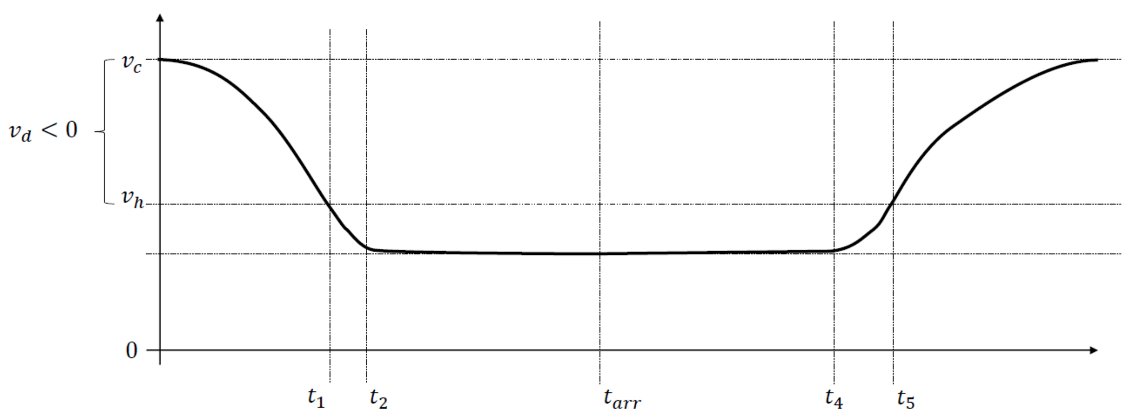
3.2.2 Profile Computation

The underlying computation method for any speed profile of the TOSCo algorithm is based on a piecewise trigonometric function [8]. The applicable TOSCo operating mode is selected as specified in [7].The optimization criterion is to select an arrival time t_{arr} such that the approaching vehicle does not pass the intersection while the traffic light is red while minimizing the applied acceleration / deceleration. After passing the stop location, a vehicle will reset its speed to the driver's set speed. Trigonometric linear functions are selected for the profile modelling due to their mathematical smoothness and tractability. Figure 7 depicts the six different timepieces for which individual acceleration functions represented in Equation 1 are integrated to represent the corresponding speed profiles of Equation 2. The symbols used throughout the derivation of the speed profiles are provided in Table 2.

Table 2: List of Symbols for the Speed Profile Computation

Symbol	Unit	Description
t_0	s	Generation time of Speed Profile
t_{arr}	s	Arrival time at stop location, departure time in case of CLAUNCH profile
t_1	s	Time at which computed Speed Profile intersects v_h for the first time
t_2	s	Time at which computed Speed Profile reaches the target speed
t_4	s	Time at which computed Speed Profile leaves the target speed
t_5	s	Time at which computed Speed Profile intersects v_h for the second time
d_0	m	Distance to stop bar at generation time of speed profiles in m
$jerk_{max}$	m/s^3	Maximum allowed jerk
a_{max}	m/s^2	Maximum acceleration
a_{min}	m/s^2	Minimum acceleration
v_c	m/s	Current speed of vehicle
v_h	m/s	Average speed of Speed Profile
v_d	m/s	Speed difference between average profile speed v_h and current speed v_c at generation time t_0
v_{limit}	m/s	Lane speed limit
m	–	Speed Profile Parameter
n	–	Speed Profile Parameter

Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 8: Piecewise Components of the TOSCo Speed Profiles (Speed Diagram Shown)

Table 3: Computation of Speed Profile Parameters

Operating Mode	v_h	n	m
CSC_UP or CSC_DWN	$v_h = d_0/t^{arr}$	$n = \min\left(\frac{min(\lvert a_{max}\rvert, \lvert d_{max}\rvert)}{\lvert v_d\rvert}, \sqrt{\frac{\lvert jerk_{max}\rvert}{\lvert v_d\rvert}}\right)$ check $n \geq \left(\frac{\pi}{2}-1\right)\cdot\frac{v_h}{d_0}$	$m = \frac{-\frac{\pi}{2}n - \sqrt{\left(\frac{\pi}{2}n\right)^2 - 4n^2\cdot\left[\left(\frac{\pi}{2}-1\right)-\frac{d_0}{v_h}\cdot n\right]}}{2\left[\left(\frac{\pi}{2}-1\right)-\frac{d_0}{v_h}\cdot n\right]}$
CSTOP	$v_h = v_c/2$	$n = \frac{v_h}{d_0}\cdot\pi = m$	$m = \frac{v_h}{d_0}\cdot\pi = n$
CLAUNCH or CREEP	$v_h = v^{limit}/2$	$n = m = \min\left(\frac{2a_{max}}{v_{limit}}, \sqrt{\frac{2\lvert jerk_{max}\rvert}{v_{limit}}}\right)$	$n = m = \min\left(\frac{2a_{max}}{v_{limit}}, \sqrt{\frac{2\lvert jerk_{max}\rvert}{v_{limit}}}\right)$

Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Table 4: Computation of Profile Interval Times

Profile time	Computation	
t_1	$\pi/2m$	
t_2	$\pi/2n + t_1$	
t_4	*CSC_UP or CSC_DWN*	*CSTOP, CLAUNCH or CREEP*
	$\frac{d_0}{v_h}+\frac{\pi}{2n}=\frac{d_0}{v_h}+t_2-t_1$	$t_{arr}+\pi/2n$
t_5	*CSC_UP or CSC_DWN*	*CSTOP, CLAUNCH or CREEP*
	$\frac{d_0}{v_h}+\frac{\pi}{2m}+\frac{\pi}{2n}=\frac{d_0}{v_h}+t_2$	$t_{arr}+\pi/2m+\pi/2n$

Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

The profile's average speed v_h and its parameters n and m are determined according to Table 3. The parameters thereby depend on the selected operating mode. With the interval timings as computed in Table 4, the piecewise defined acceleration profile is defined as in Figure 9

.

$$a_t = \begin{cases} v_d\cdot \mathrm{m}\cdot\sin(mt) & t\in[0,t_1) \\ \mathrm{v_d}\cdot\mathrm{m}\cdot\sin\left[n\cdot\left(t-t_2+\frac{\pi}{n}\right)\right] & t\in[t_1,t_2) \\ 0 & t\in[t_2,t_{arr}) \\ \mathrm{v_d}\cdot\mathrm{m}\cdot\sin\left[n\cdot\left(t-t_4+\frac{3\pi}{2n}\right)\right] & t\in[t_{arr},t_4) \\ v_d\cdot\mathrm{m}\cdot\sin(m\cdot(t-t_5)) & t\in[t_4,t_5) \\ 0 & t\in[t_5,+\infty) \end{cases}$$

Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 9: Expression for Acceleration Profile

The corresponding speed profile can be found by integrating the expression in Figure 9.

$$v_t = \int a_t\, dt = f(t|v_c, v_h) = \begin{cases} v_h - v_d \cdot \cos(mt) & t \in [0, t_1) \\ v_h - v_d \cdot \frac{m}{n} \cdot \cos\left[n \cdot \left(t + \frac{\pi}{n} - t_2\right)\right] & t \in [t_1, t_2) \\ v_h + v_d \cdot \frac{m}{n} & t \in [t_2, t_{arr}) \\ v_h - v_d \cdot \frac{m}{n} \cdot \cos\left[n \cdot \left(t + \frac{3\pi}{2n} - t_4\right)\right] & t \in [t_{arr}, t_4) \\ v_h - v_d \cdot \cos[m \cdot (t - t_5)] & t \in [t_4, t_5) \\ v_c & t \in [t_5, +\infty) \end{cases}$$

Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 10: Expression for Speed Profile

The corresponding distance traveled in Figure 11 can be computed by integrating Figure 10.

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$$d_t = \int_{t_s}^{t_e} f(t|v_c, v_h) dt = \begin{cases} \int_{t_s}^{t_e} v_h - v_d \cos(mt)\, dt = \\ = (t_e - t_s)v_h + \frac{v_d(\sin(mt_s) - \sin(mt_e))}{m} \quad t \in [0, t_1) \\ \int_{t_s}^{t_e} v_h - v_d \frac{m}{n} \cos\left[n\left(t + \frac{\pi}{n} - t_2\right)\right] dt = \\ = (t_e - t_s)v_h + \frac{mv_d(\sin(n(t_s - t_2) + \pi) - \sin(n(t_e - t_2) + \pi))}{n^2} \quad t \in [t_1, t_2) \\ \int_{t_s}^{t^e} v_h + v_d \frac{m}{n} dt = (t^e - t_s) \cdot \left(v_h + v_d \frac{m}{n}\right) \quad t \in [t_2, t_{arr}) \\ \int_{t_s}^{t_e} v_h - v_d \frac{m}{n} \cos\left[n\left(t + \frac{3\pi}{2n} - t_4\right)\right] dt = \\ = (t_e - t_s)v_h + \frac{mv_d\left(\sin\left(n(t_s - t_4) + \frac{3}{2}\pi\right) - \sin(n(t_e - t_4) + \frac{3}{2}\pi)\right)}{n^2} \quad t \in [t_{arr}, t_4) \\ \int_{t_s}^{t_e} v_h - v_d \cos[m \cdot (t - t_5)]\, dt = \\ = (t_e - t_s)v_h + \frac{v_d\left(\sin(m(t_s - t_5)) - \sin\left(m(t_e - t_5)\right)\right)}{m} \quad t \in [t_4, t_5) \\ \int_{t_s}^{t_e} v_c\, dt = (v_c t_e - v_c t_s) \quad t \in [t_5, +\infty) \end{cases}$$

Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 11: Expression for Distance Traveled

As a result, each Profile for a TOSCo mode P^{mode} consists of a set of three piecewise defined functions shown in Figure 12.

.

$$P^{mode} = \begin{cases} a_t \\ v_t \\ p_t \end{cases}$$

Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 12: Expression for TOSCo Mode

4 Simulation Results

The ability to simulate the vehicle-ready software implementation of the TOSCo system, using the simulation system outlined in Chapter 2, is key to economic and rapid development. Several iterations according to the workflow outlined in Section 2.1 are required to develop a system that can safely be tested in an actual vehicle environment. The following presents the analysis of the simulated TOSCo system behavior as a result of the final iteration cycle of the software development process [7]. Section 4.1 details the general simulation scenario setup and the analysis process employed in subsequent sections of this chapter. Sections 4.2 to 4.9 provide an in-depth analysis of key findings identified in each simulation scenario.

4.1 Methodology

Eight distinct simulation scenarios have been defined to assess the operations of the TOSCo algorithm, as outlined in Chapter 3. As outlined in Chapter 2, the purpose of these simulation scenarios is thereby not to determine the effectiveness of TOSCo on a macroscopic, traffic-efficiency related scale, but to ensure and test for specified behavior of the system in specific combinations of approach speeds, traffic light states and ambient traffic, such as queued vehicles at the intersection. Consequently, each scenario focuses on different aspects of the algorithm. Table 5 summarizes the defined simulation scenarios and provides a short description. Each following section then details the scenario and the corresponding findings.

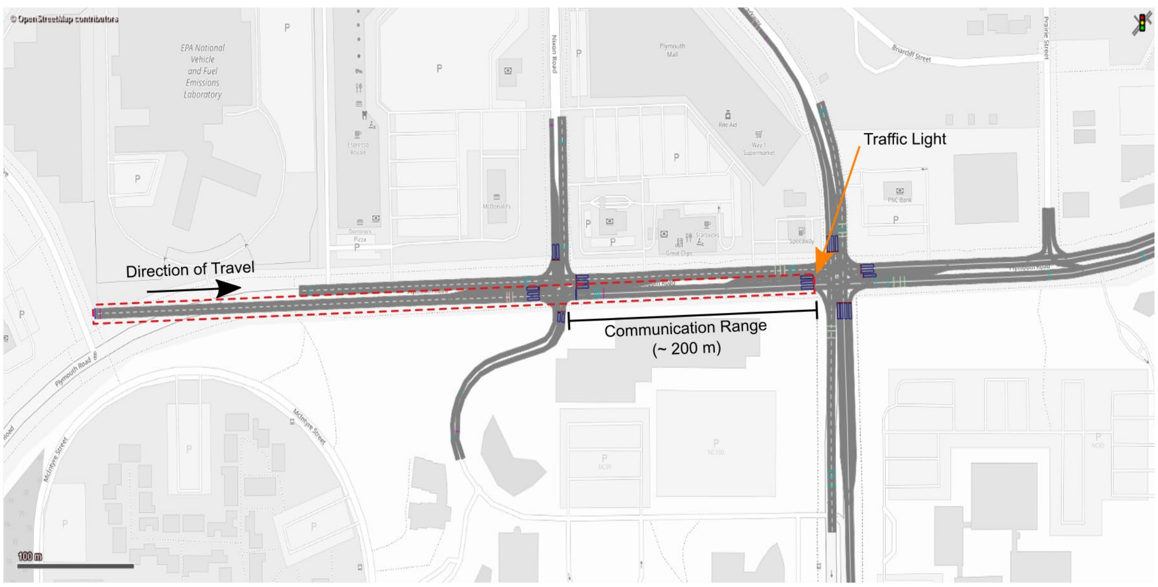
Table 5: Overview of Simulation Scenarios

Scenario Name	Section	Short Description and Purpose
Constant Speed Scenario	4.2	String of TOSCo-enabled vehicles is able to pass intersection without need for stopping or slowing down.
Speed-up Scenario	4.3	String of TOSCo-enabled vehicles has to speed up to pass intersection. String splits if not every vehicle is able to pass when speeding up.
Slow-down Scenario	4.4	String of TOSCo-enabled vehicles would arrive too early at stop location without slowing down during the approach.
Coordinated Stop and Launch Scenario	4.5	String of TOSCo-enabled vehicles has to come to a full stop. Upon green, all vehicles launch simultaneously.
Speed-up with Dissipating Queue at Intersection Scenario	4.6	String of TOSCo-enabled vehicles has to speed up to pass intersection at which a queue of non-equipped vehicles is discharging.
Slow-down with Dissipating Queue at Intersection Scenario	4.7	String of TOSCo-enabled vehicles would arrive too early at stop location without slowing down during the approach. String approaches a discharging queue at the intersection.
Coordinated Stop and Launch with Dissipating Queue at Intersection Scenario	4.8	String of TOSCo-enabled vehicles has to come to a full stop. Upon green, all vehicles launch simultaneously. TOSCo-enabled vehicles thereby come to a stop behind a string of non-equipped vehicles.

Scenario Name	Section	Short Description and Purpose
Creep at Intersection Scenario	4.9	String of TOSCo-enabled vehicles has to come to a full stop at intersection at which several non-equipped vehicles are waiting. Queue of waiting vehicles is decreased by the vehicle at the stop bar turning right on red. All waiting vehicles are then creeping forward to close the resulting gap.

Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

The scenarios and the Virtual Driving Environment are setup within the VISSIM simulation component, as outlined in Section 2.5. However, the underlying road network, consisting of approach-lanes, the traffic-light equipped intersection and infrastructure-component, is maintained for each scenario. Instead, the scenarios mainly differ in the introduction times of the vehicles in the scenario (such that these arrive at the intersection at different times, and, therefore, at different instances of the traffic-light schedule). The road network reflects the road topology at the intersection of Plymouth Road and Huron Parkway in Ann Arbor, Michigan, as depicted in Figure 13. All vehicles in the scenario are driving on the westbound approach before starting to receive[5] information from the infrastructure component about 200 m from the intersection equipped with the traffic light. As such, the road network represents an excerpt of the corridor employed by the simulations of the traffic-level simulations [1].



Source: Map data © OpenStreetMap contributors and available at https://www.openstreetmap.org

Figure 13: VISSIM Simulation Scenario

Vehicles in VISSIM are introduced with an introductory speed specific to each scenario. VISSIM thereby only allows vehicles to be introduced at a time gap of about 1 s. In some scenarios, however, the time gap will be varied, with a minimum allowed time gap setting of the TOSCo system of 0.6 s. Hence, to allow for vehicles in

[5] Inter-vehicle communications is not simulated explicitly. Instead, message reception is assumed to be perfect within the virtual communication range.

the simulation to create a stable string, in which the set time gap is maintained by each vehicle prior to entering RSU communication range and thus activating TOSCo, an approach lane of roughly 750 m is introduced in the scenario. The time vehicles travel along this approach lane can be interpreted as a warmup period.

Table 6: Global Simulation Parameters for all Vehicle-level Simulations

Number of Vehicles in TOSCo String	5
RSU Communication Range (m)	200
Length of Approach Lane to Stop Location (m)	950
Time gap between vehicles at introduction in Simulation (s)	1

Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Each scenario provides a myriad of parameters that can be changed to test for the resulting behavior of the TOSCo algorithm. As outlined in Table 5, various simulation scenarios thereby demonstrate specific aspects of the overall TOSCo operation. Therefore, only the parameters relevant to a specific scenario are altered rather than varying the same parameters for every scenario. Table 6 summarizes global parameters that are maintained for all simulation scenarios. Parameter settings specific to each scenario are detailed subsequently, resulting in 26 different simulation runs performed specifically for this report.

The following sections 4.2 to 4.9 follow the same structure to simplify the presentation of the analysis process. As such, each section can be read as a standalone part. Each section thereby presents findings for the different simulation scenarios outlined in Table 5. Due to the number of possible parameter variations, the analysis focuses on key findings rather than on presenting the results for each simulation run. Each detailed scenario will thereby provide three baseline diagrams depicting the monitored speed, acceleration and TOSCo state diagrams against the simulation time for all five vehicles within the TOSCo string. Descriptions and interpretations are provided for each diagram, highlighting the key findings. If required, additional diagram types may be provided to assist interpretation. The aforementioned three baseline diagrams for all simulation runs are presented in APPENDIX C.

4.2 Constant Speed Scenario

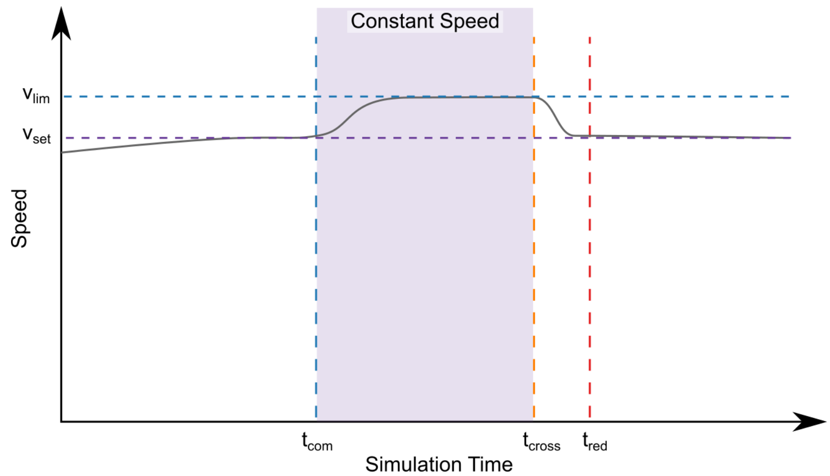
This section provides a description of the simulation results for vehicles travelling in *Coordinated Speed Control Constant (*CSC_CONST) towards an intersection. As detailed in the description of the TOSCo mode-selection [7], the system checks if cruising at the current speed will allow the vehicle to pass the intersection when the traffic light is about to turn red. If this is not a feasible option, the vehicle will accelerate to an appropriate higher speed, up until the posted speed limit, in order to traverse the intersection before the close of the green window.

4.2.1 Scenario Description and Parameters

The following section outlines the basic operation and expected behavior of TOSCo vehicles in this scenario along with a representation of parameter variations performed for this report.

4.2.1.1 Scenario Outline

The Constant Speed Scenario is set up in a way that all approaching TOSCo vehicles will be able to traverse the intersection before the end of the green phase. Figure 7 depicts the expected course of the simulation scenario and an exemplary speed diagram. Each vehicle is introduced in VISSIM at a speed close to the driver's set speed v_{set}. After entering the RSU communication range at t_{com}, the traffic light turns red at t_{red}. Whenever a vehicle enters the communication range at $t_{com,}$ and therefore receives SPaT-messages, the TOSCo system is activated as detailed in [7]. At that point in time in this scenario, each vehicle will accelerate to the speed limit until t_{cross}, when the vehicles cross the stop bar. After passing through the stop bar, the vehicles decelerate back to the initial set speed v_{set}.



t_{red}	Time at which traffic light turns red	t_{cross}	Time at which vehicle crosses stop bar
t_{com}	Time at which vehicles enters RSU communication range	v_{set}	Driver's set speed

Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 14: Idealized Vehicle Behavior for the Constant Speed Scenario

4.2.1.2 Parameter Variations

The purpose of this simulation scenario is to verify the intended behavior of the TOSCo system in CSC_CONST. The system thereby needs to be capable of handling different operating speeds when entering RSU communication range and time gap settings selected by the driver. Table 10 summarizes the parameter variations performed for the validation. Two different speed limits, reflecting the encountered speeds on the respective urban and rural corridors in Ann Arbor, Michigan and Conroe, Texas, are selected. For each lane speed limit, the driver's set speed of the lead vehicle of a TOSCo string is slightly below the following vehicle's set speed since VISSIM only allows introduction of vehicles with a time gap of about 1 s. For those scenarios in which a shorter time gap is selected, the vehicles behind the lead vehicle of the string need to be able to decrease their distance to the preceding vehicles to yield a time gap of less than 1 s – for which they need to drive faster than the lead vehicle.

For the 35 mph Lane Speed Limit case, different time gap settings are simulated to assess vehicle response and string behavior at four different inter-vehicle gaps. As each vehicle in a TOSCo string consecutively enters the RSU communication range, the time between two vehicles entering RSU communication range increases as well. For larger time gap settings, the preceding vehicle will already be optimizing its speed profile, hence affecting the following vehicle not yet under TOSCo control. Consequent analysis, therefore, has to assess the effect on the vehicle's behavior in case of different TOSCo activation states within a string. At the higher speed 55 mph case, only the extreme case of a 0.6 time gap setting was used.

Table 7: Simulation Parameters for the Constant Speed Scenario

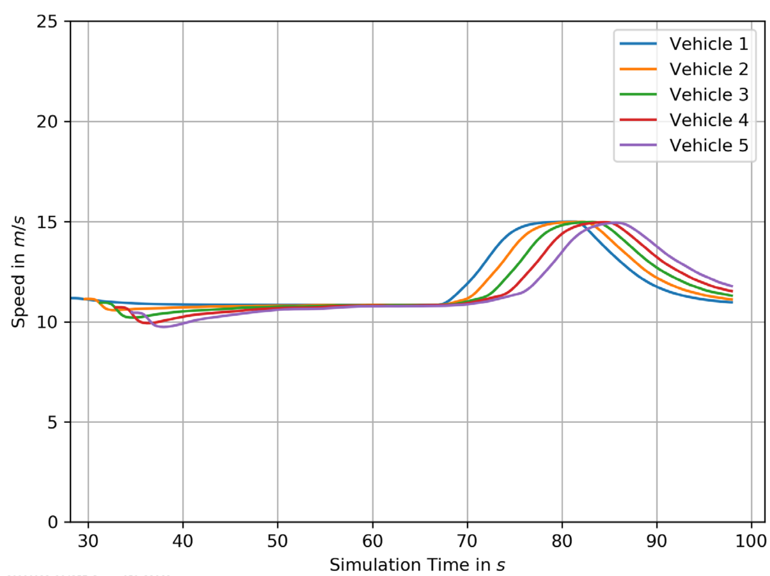
Lane Speed Limit (mph)	35			55
Lead Vehicle Driver's Set Speed (mph)	25			45
Following Vehicles Driver's Set Speed (mph)	32			55
Time Gap Settings (s)	0.6	1.0	1.5	0.6

Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

4.2.2 Analysis

The following analysis focuses on the results of the two extremes of the simulation parameters for this scenario: a time gap setting of 1.5 s on a 35 mph speed limit road and a time gap setting of 0.6 s on a 55 mph speed limit road. Diagrams for other parameter sets are listed in APPENDIX C.

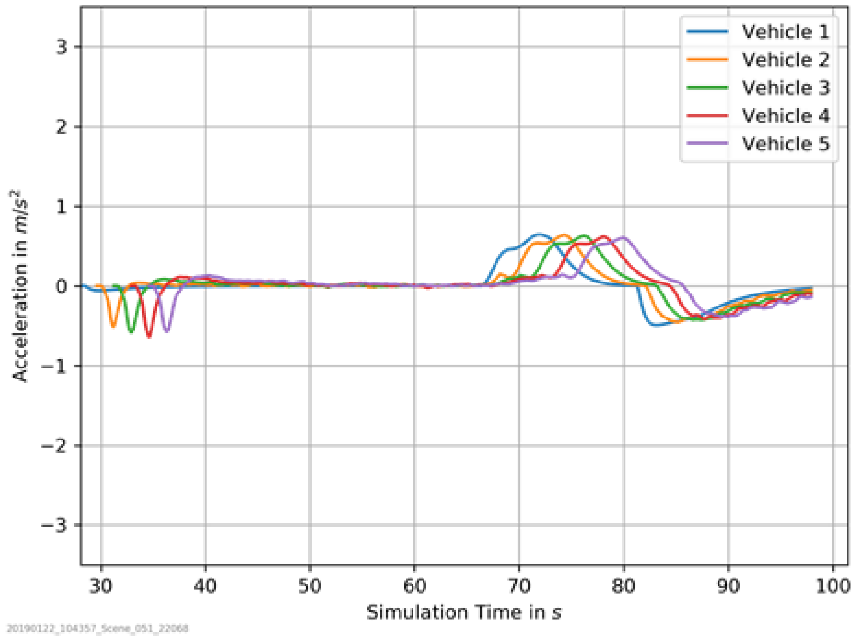
Figure 15 depicts the recorded vehicle speed for each of the five TOSCo vehicles approaching the intersection over the duration of the simulation for the 1.5 s time and a posted speed limit of 35 mph. Due to VISSIM only allowing vehicles to be introduced at a time gap of 1 s into the scenario, the first 68 seconds of simulation time are used to both introduce the vehicles at a proper time in order for the TOSCo vehicles to approach the intersection and establish the desired time gap of 1.5 s. At approximately 68 seconds, the first TOSCo-enabled vehicle enters the RSU communication range and accelerates to the posted speed limit of 35 mph. The following vehicles in the string similarly accelerate to the posted speed limit when they enter the RSU communication range. At approximately 82 seconds, the first vehicle crosses the stop bar and returns back to the initial set speed. The other TOSCo-enabled vehicles follow suit as they cross the stop bar.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 15: Constant Speed Scenario: Simulation Time vs. Speed for TOSCo-enabled Vehicles at 1.5 s Time Gap and 35 mph Speed Limit

Figure 16 depicts the recorded vehicle acceleration for each of the five TOSCo vehicles approaching the intersection over the duration of the simulation. At approximately 68 seconds simulation time, the first TOSCo-enabled vehicle enters the RSU communication range and accelerates according to the speed profile depicted in Figure 17.

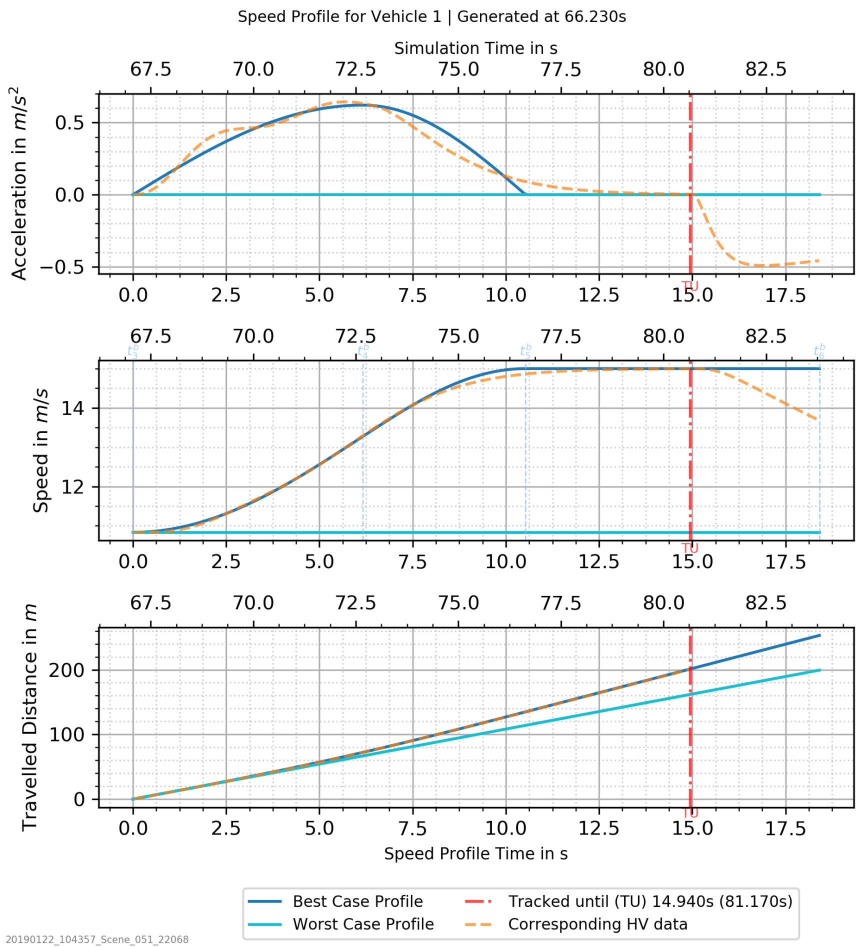


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 16: Constant Speed Scenario: Simulation Time vs. Acceleration for TOSCo-enabled Vehicles at 1.5 s Time Gap and 35 mph Speed Limit

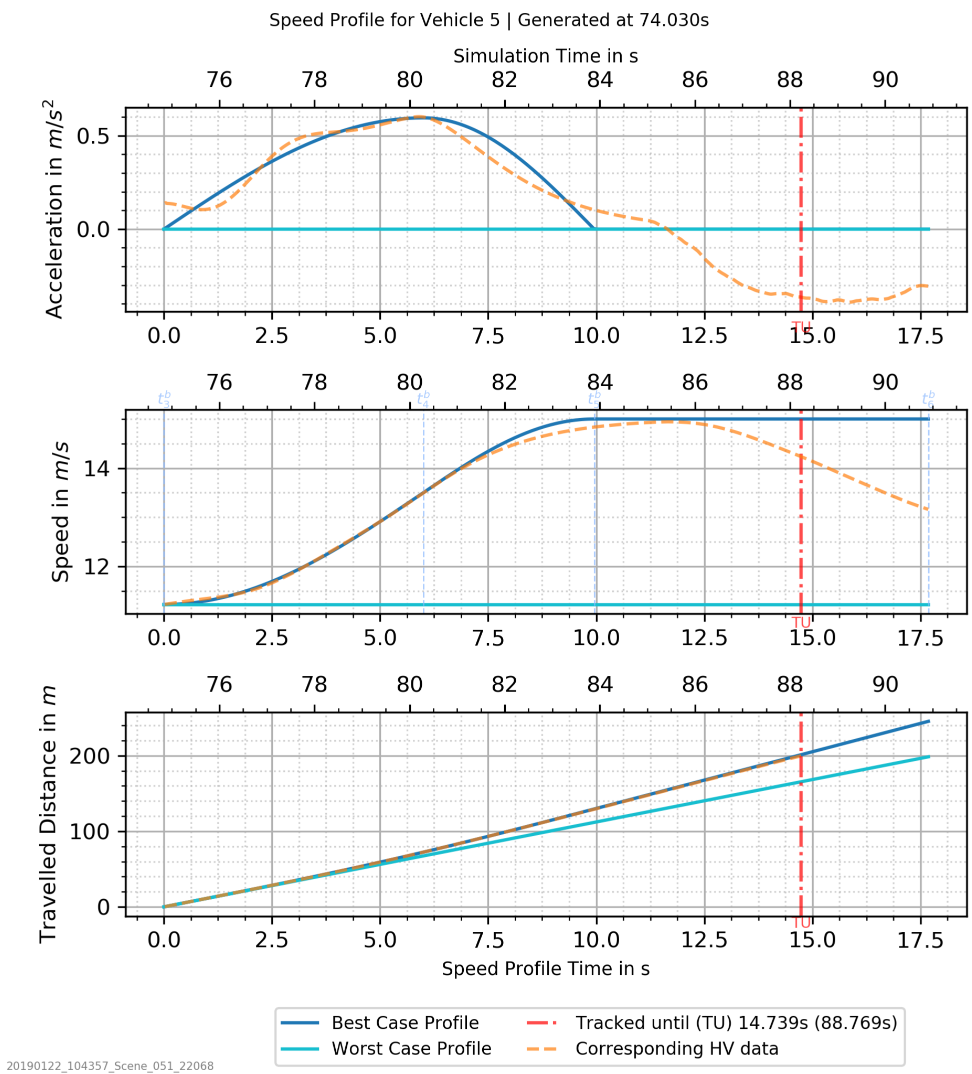
The following vehicles in the string similarly accelerate to the posted speed limit when they enter the RSU communication range. At approximately 82 seconds, the first vehicle crosses the stop bar and returns back to the initial set speed. The other TOSCo-enabled vehicles follow suit as they cross the stop bar. All vehicles correctly follow their respective speed profiles.

Figure 17 and Figure 18 depict the *best* and *worst case* speed profiles, described further in Section 3.2.1, along with the actual travelled speed that corresponds to the first and last vehicle in the TOSCo-enabled string, respectively. All vehicles calculate a *worst-case* speed profile, which describes the case in which the vehicle travels at constant speed towards the intersection, and a *best-case* speed profile, which allows the vehicle to arrive at the intersection as soon as possible. The CSC_CONST profiles are correctly calculated and represent the *worst-case* speed profile (see light-blue line in Figure 17). However, there also exists a *best-case* speed profile that allows the vehicle to reach the intersection as early as possible (see dark-blue line in Figure 17). All vehicles under this parameter setting are able to correctly travel at a speed within the solution space that is very near the *best-case* speed profile.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

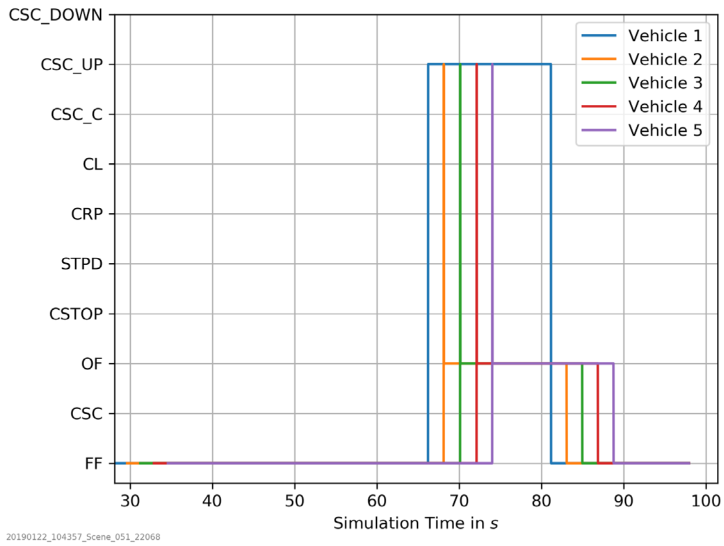
Figure 17: Constant Speed Scenario: Speed Profile for 1st TOSCo-enabled Vehicle at 1.5 s Time Gap and 35 mph Speed Limit



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 18: Constant Speed Scenario: Speed Profile for 5th TOSCo-enabled Vehicle at 1.5 s Time Gap and 35 mph Speed Limit

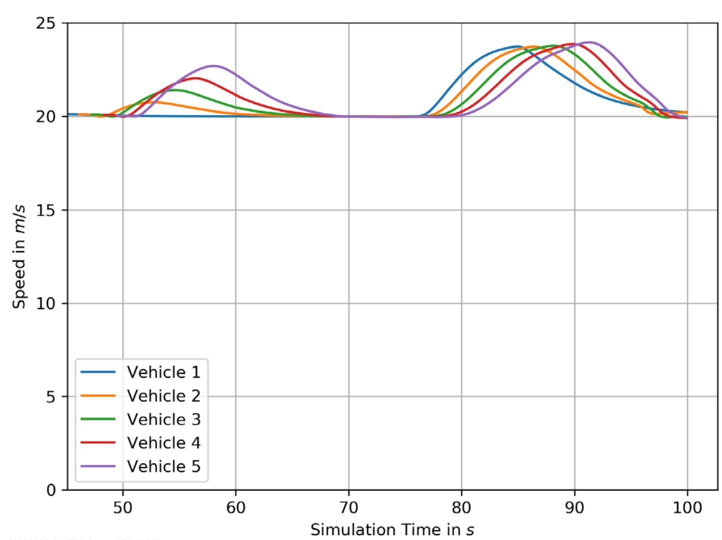
Figure 19 depicts the recorded vehicle operating modes for each of the five TOSCo vehicles approaching the intersection over the duration of the simulation. At approximately 68 seconds, the first TOSCo-enabled vehicle enters the RSU communication range and transitions from FF to CSC_UP. The following vehicles in the string similarly enter CSC_UP when they first enter the RSU communication range, but upon checking that they are a following vehicle, they transition to OF. At approximately 82 seconds, the first vehicle crosses the stop bar and returns back to FF. The other TOSCo-enabled vehicles remain in OF as they cross the stop bar.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 19: Constant Speed Scenario: Simulation Time vs. Operating-Modes for TOSCo-enabled Vehicles at 1.5 s Time Gap and 35 mph Speed Limit

Figure 20 depicts the recorded vehicle speed for each of the five TOSCo vehicles approaching the intersection over the duration of the simulation for a time gap setting of 0.6 s and 55 mph speed limit. At approximately 77 seconds, the first TOSCo-enabled vehicle enters the RSU communication range and accelerates to the posted speed limit of 55 mph as a result of the vehicles selecting the CSC_UP operating mode.

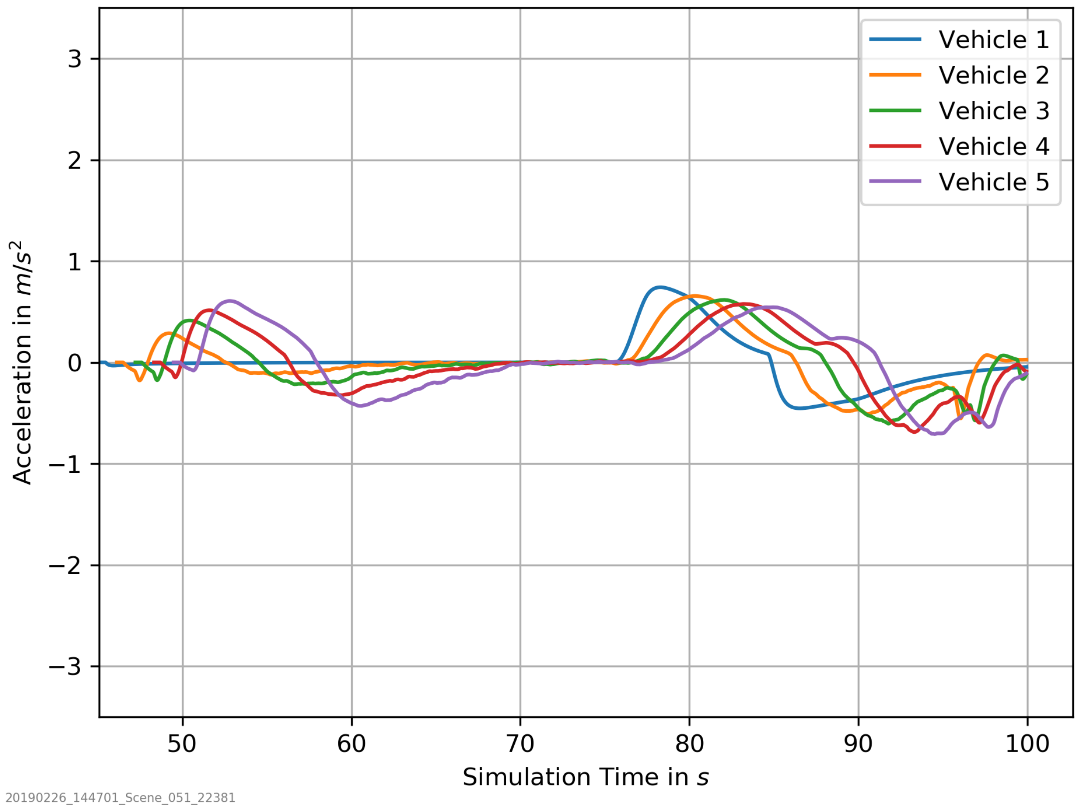


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 20: Constant Speed Scenario: Simulation Time vs. Speed for TOSCo-enabled Vehicles at 0.6 s Time Gap and 55 mph Speed Limit

The following vehicles in the string similarly accelerate to the posted speed limit when they enter the RSU communication range. At approximately 84 seconds, the first vehicle crosses the stop bar and returns back to the initial set speed. The other TOSCo-enabled vehicles follow suit as they cross the stop bar.

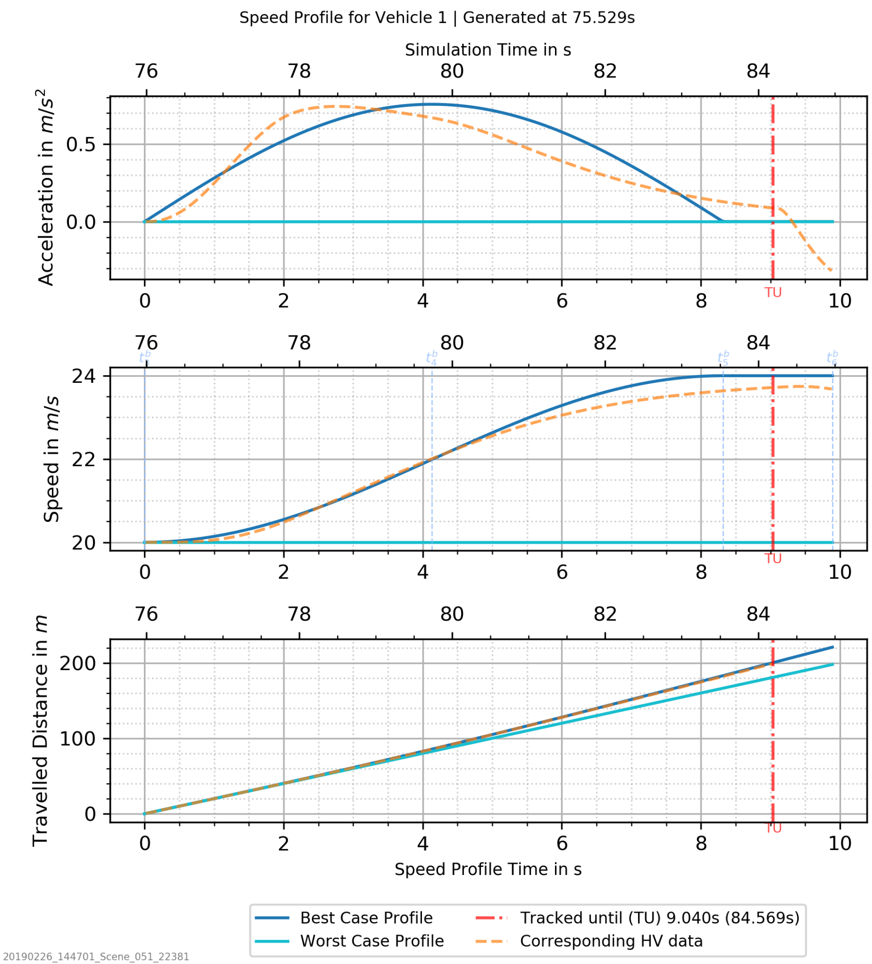
Figure 21 depicts the recorded vehicle acceleration for each of the five TOSCo vehicles approaching the intersection over the duration of the simulation. At approximately 77 seconds, the first TOSCo-enabled vehicle enters the RSU communication range and accelerates according to the speed profile depicted in Figure 21. The following vehicles in the string similarly accelerate to the posted speed limit when they enter the RSU communication range. At approximately 84 seconds, the first vehicle crosses the stop bar and returns back to the initial set speed. The other TOSCo-enabled vehicles follow suit as they cross the stop bar.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

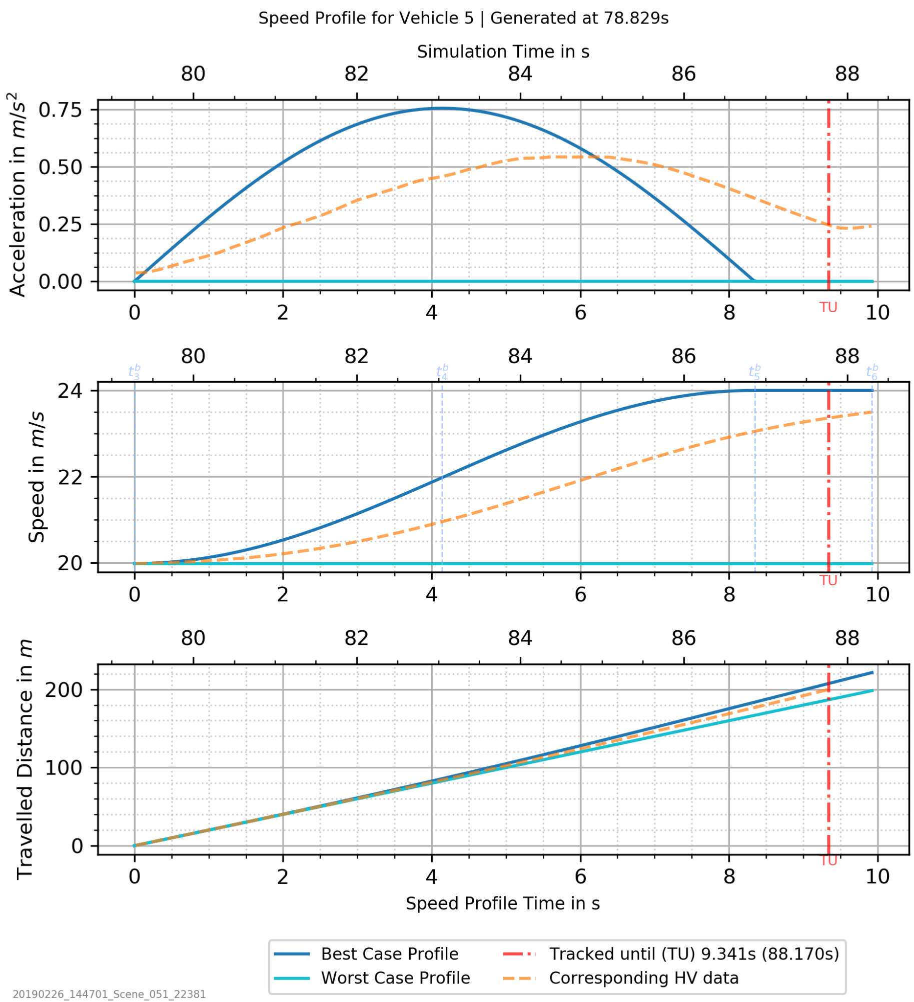
Figure 21: Constant Speed Scenario: Simulation Time vs. Acceleration for TOSCo-enabled Vehicles at 0.6 s Time Gap and 55 mph Speed Limit

Figure 22 and Figure 23 depict the *best-* and *worst-case* speed profiles, described further in Section 3.2.1, along with the actual speed profiles that correspond to the first and last vehicle in the TOSCo-enabled string, respectively. All vehicles correctly choose a speed profile that is within the solution space in between the best and *worst-case* profile boundary conditions. As each vehicle calculates the same *best-case* speed profiles, the vehicle's actual speed (see orange dashed lines in Figure 22 and Figure 23) deviates further away from the *best-case* profile progressively down the string because of CACC operations.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

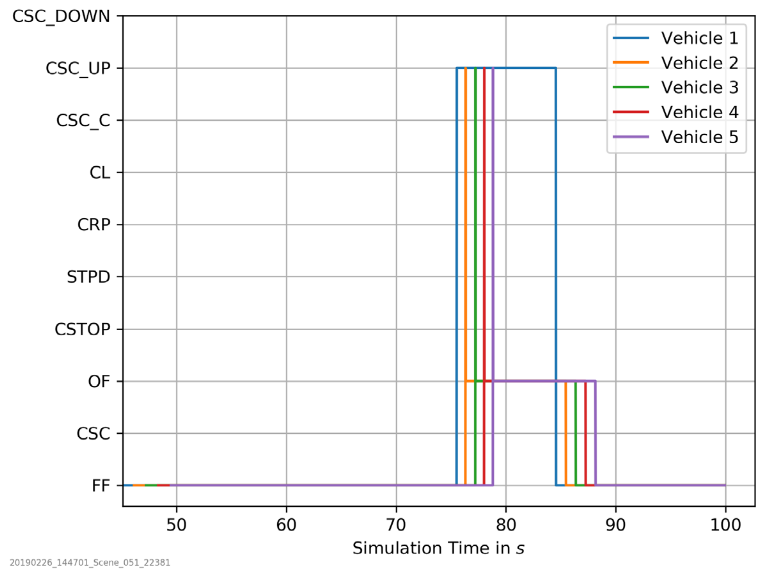
Figure 22: Constant Speed Scenario: Speed Profile for 1st TOSCo-enabled Vehicle at 0.6 s Time Gap and 55 mph Speed Limit



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 23: Constant Speed Scenario: Speed Profile for 5th TOSCo-enabled Vehicles at 0.6 s Time Gap and 55 mph Speed Limit

Figure 24 depicts the recorded vehicle operating modes for each of the five TOSCo vehicles approaching the intersection over the duration of the simulation. At approximately 77 seconds, the first TOSCo-enabled vehicle enters the RSU communication range and transitions from FF to CSC_UP. The following vehicles in the string similarly enter CSC_UP when they first enter the RSU communication range, but upon checking that they are a following vehicle, they transition to OF. At approximately 84 seconds, the first vehicle crosses the stop bar and returns back to FF. The other TOSCo-enabled vehicles remain in Optimize Flow (OF) as they cross the stop bar.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 24: Constant Speed Scenario: Simulation Time vs. Operating-Modes for TOSCo-enabled Vehicles at 0.6 s Time Gap and 55 mph Speed Limit

4.2.3 Scenario Summary

The Constant Speed Scenario successfully demonstrates that the developed TOSCo system is able to create a *worst-case* (constant speed) profile, a *best-case* (CSC_UP profile), and is able to successfully select the appropriate profile and transition to CSC_UP. This works for different time gaps and speed levels. With mild parameter settings, vehicles select a speed profile close to the *best-case* speed profile. With shorter time gap settings and on roadways with higher speeds, chosen speed profiles deviate from the *best case* profile progressively down the string, but still remain well within the solution space created by the *best-* and *worst-case* profiles.

4.3 Speed-up Scenario

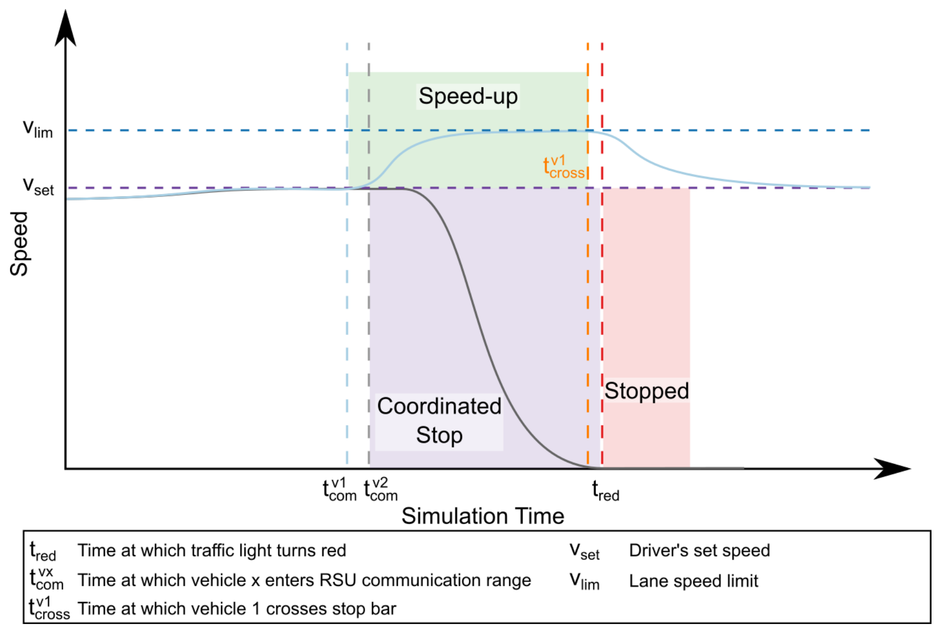
In this scenario, a TOSCo-equipped individual vehicle or string of multiple vehicles is traveling along a TOSCo-equipped corridor at a speed of less than the posted speed limit. The scenario is setup in a way that allows the vehicles to pass the intersection on a green traffic light by increasing their speed up to the speed limit.

4.3.1 Scenario Description and Parameters

The following two paragraphs outline the basic operation and expected behavior of TOSCo vehicles in this scenario along with a representation of parameter variations performed for this report.

4.3.1.1 Scenario Outline

The speed-up scenario is set up in a way that approaching TOSCo vehicles will speed up to pass the intersection. Figure 25 depicts the expected course of the simulation scenario and an exemplary speed diagram. Each vehicle is introduced in VISSIM at a speed close to the driver's set speed $\mathrm{v}_{\mathrm{set}}$. After vehicle 1 enters RSU communication range at. $\mathrm{t}_{\mathrm{com}}^{\mathrm{v1}}$, the TOSCo system is activated in vehicle 1 and decides to pass the intersection by accelerating to the lane speed limit $\mathrm{v_{lim}}$. Once the vehicle crosses the intersection at $\mathrm{t_{cross}^{v1}}$, vehicle 1 decelerates to the driver's set speed $\mathrm{v_{set}}$. The scenario is also setup in a way that for some parameter settings, the string of TOSCo-equipped vehicles will have to split up, as not all approaching vehicles will have the chance to pass the intersection in the current cycle of the traffic light. When vehicle 2 enters the RSU communication range at $\mathrm{t_{com}^{v2}}$, it decides to stop before the stop bar because it cannot pass the intersection before the time at which the signal turns red at $\mathrm{t_{red}}$. As a result, it selects the Coordinated Stop operating mode. For the time vehicle 2 follows the preceding vehicle within the solution space calculated by this mode, it switches to the OF operating mode. Upon stopping, it switches to the Stopped mode.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 25: Idealized Vehicle Behavior for the Speed-up Scenario

4.3.1.2 Parameter Variations

The purpose of this simulation scenario is to validate the intended behavior of the TOSCo system in case vehicles speed up to pass the intersection and to split up the string, if necessary. The system thereby needs to be capable of handling different operating speeds when entering RSU communication range. Table 8 summarizes the parameter variations performed for the validation. Two different speed limits, reflecting the encountered speeds on the respective urban and rural corridors in Ann Arbor, Michigan and Conroe, Texas, are selected to study the system behavior in different speed ranges. To allow for different string states before entering RSU communication range, the lead vehicle driver's set speed is varied. For each lane speed limit, the driver's set speed of the lead vehicle of a TOSCo string is slightly below the following vehicle's set speed since VISSIM only allows introduction of vehicles with a time gap of about 1 s. For the lower speed limit, the different lead vehicle driver's set speeds are selected to cause a difference in the time to arrival at the intersection to vary vehicle string behavior.

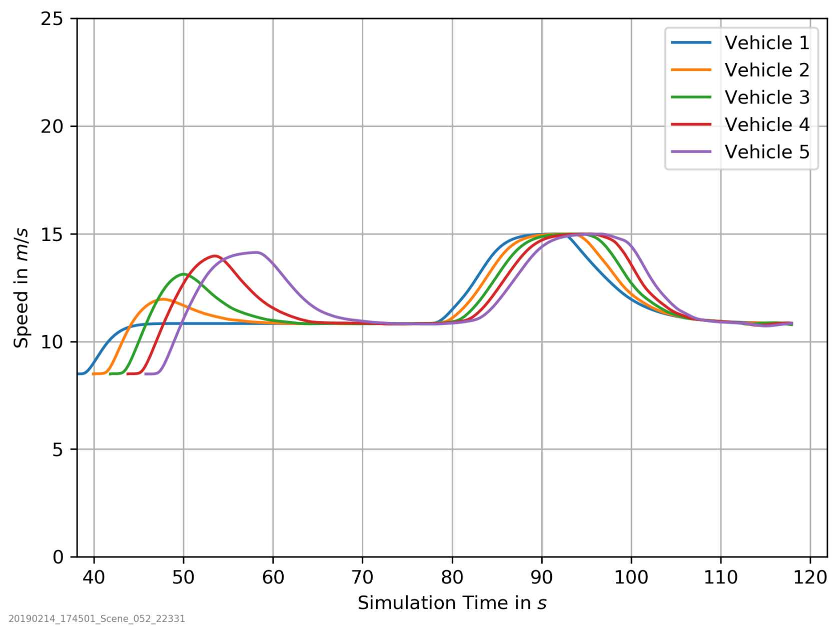
Table 8: Simulation Parameters for the Speed-up Scenario

Lane Speed Limit (mph)	35		55
Lead Vehicle Driver's Set Speed (mph)	19	25	45
Following Vehicles Driver's Set Speed (mph)	32	32	55
Time Gap Settings (s)	0.6		

Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

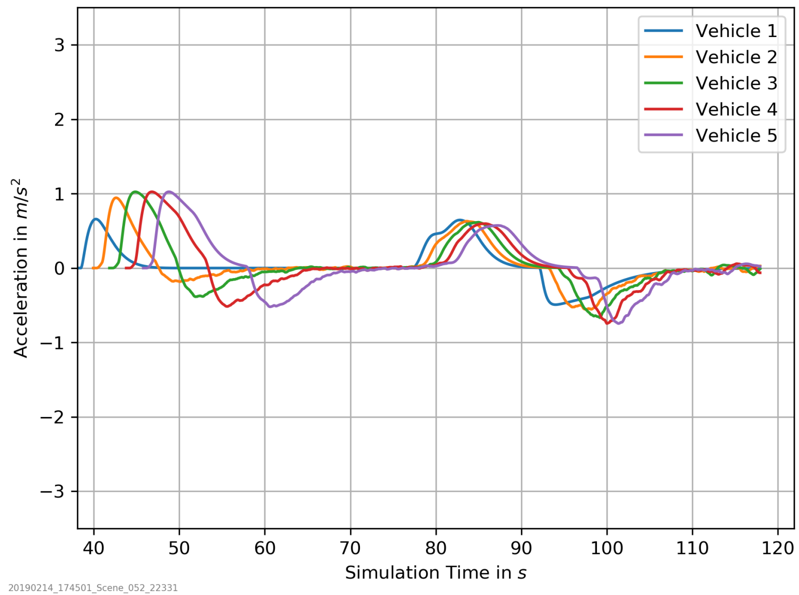
4.3.2 Analysis

The first part of the analysis focuses on the results of the lower lane speed limit case in which the lead vehicle driver's set speed is 25 mph. Figure 26 depicts the recorded vehicle speed for each of the five TOSCo vehicles approaching the intersection over the duration of the simulation. At around 70 s simulation runtime, the string of TOSCo-enabled vehicles has stabilized and established a time gap of about 0.6 s. Around 80 s simulation runtime, all vehicles start to accelerate as the TOSCo system on each vehicle decides that the vehicle is able to pass the intersection within the current green window. The associated comfortable acceleration process is depicted in Figure 27, observed acceleration levels are within 1 m/s^2.



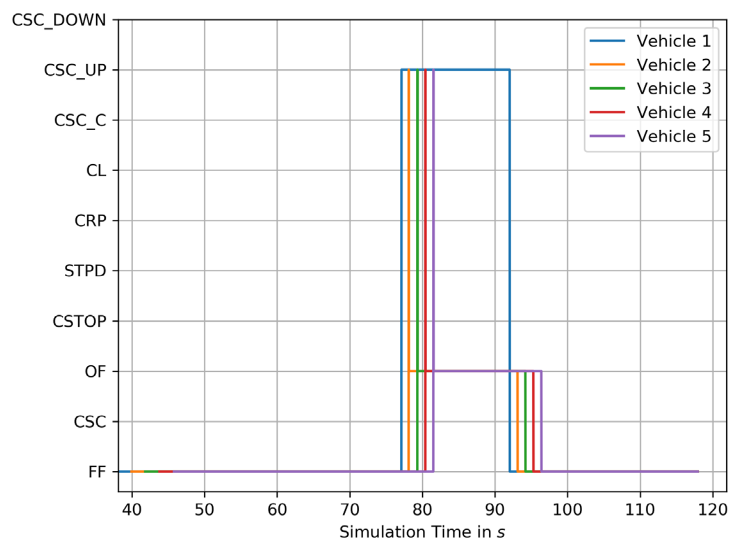
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 26: Speed-up Scenario: Simulation Time vs. Speed for TOSCo-enabled Vehicles at 25 mph Lead Vehicle Driver's Set Speed, 0.6 s Time Gap and 35 mph Speed Limit



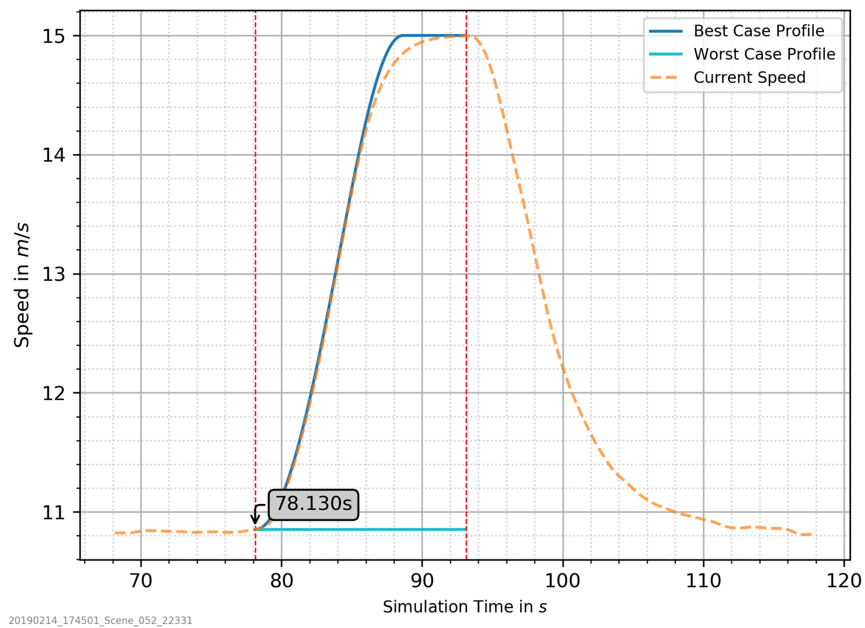
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 27: Coordinated Stop and Launch Scenario: Simulation Time vs. Acceleration for TOSCo-enabled Vehicles at 25 mph Lead Vehicle Driver's Set Speed, 0.6 s Time Gap and 35 mph Speed Limit



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 28: Speed-up Scenario: Simulation Time vs. Operating Modes for TOSCo-enabled Vehicles at 25 mph Lead Vehicle Driver's Set Speed, 0.6 s Time Gap and 35 mph Speed Limit

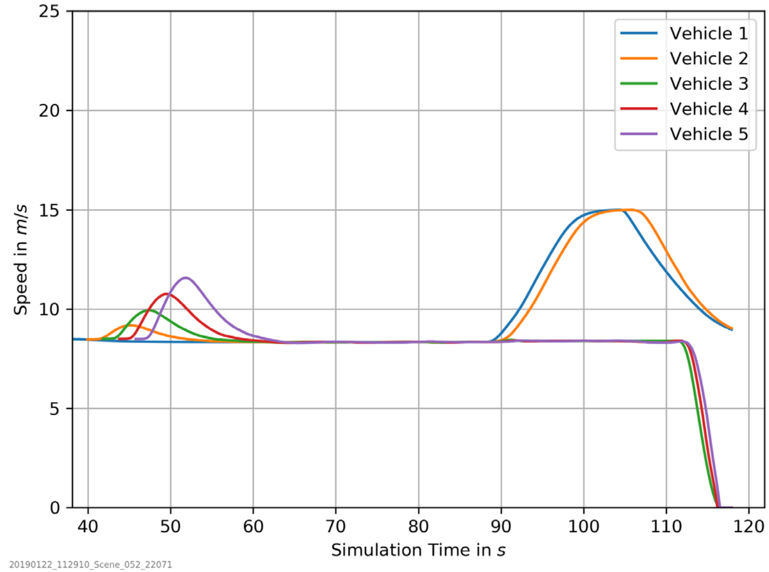


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 29: Speed-up Scenario: Simulation Time vs. Computed Speed Profiles for Vehicle 2 for TOSCo-enabled Vehicles at 25 mph Lead Vehicle Driver's Set Speed, 0.6 s Time Gap and 35 mph Speed Limit

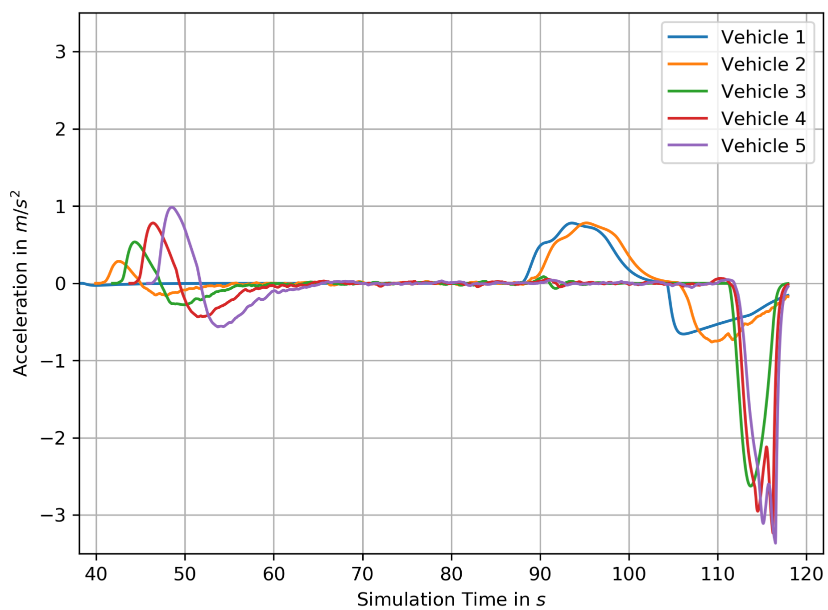
As a result of the decision to speed up, all vehicles select the CSC_UP operating mode. Vehicles 2 - 5 immediately switch to the OF operating mode as a result of a preceding vehicle operating within the solution space as outlined in Chapter 3 and depicted in Figure 28.

Next, the analysis focuses on the results of the lower lane speed limit setup, in which the lead vehicle driver's set speed is 19 mph. Figure 30 depicts the recorded vehicle speed for each of the five TOSCo vehicles approaching the intersection over the duration of the simulation. At around 60 s simulation runtime, a stable vehicle string has been established with a time gap maintained between the vehicles of about 0.6 s. Around 90 s simulation runtime, when entering RSU communication range, vehicles 1 and 2 start to accelerate. Vehicles 3-5, on the other hand, maintain their speed and then slow down to stop as they determined that they will not be able to pass the intersection on green. During this speed change, vehicles 1 and 2 recorded acceleration is within the limits of ± 1 m/s^2. Deceleration levels for vehicles 3 - 5, on the other hand, reaches the deceleration limit of -3 m/s^2, as depicted in Figure 31. This is the result of the CACC system stopping the vehicles and the behavior of the longitudinal controller at low speeds. This behavior is an artifact of the simulation environment and has to be parameterized when testing in a vehicle environment. The corresponding TOSCo operating modes are depicted in Figure 32. Once the speed profiles corresponding to the selected modes are computed, vehicles 2 - 4 switch to the *OF* operating mode as they have a TOSCo-enabled vehicle in front and are able to operate within the solution space computed by their respective operating mode. Figure 33 depicts the computed speed profiles of vehicle 3. It can be inferred that the vehicle had to re-compute the initial profile generated at around 90 s again at around 106 s when the traffic light switches to red and hence a change in external conditions occurred. Although these re-computations may occur, it will be up to the vehicle HMI to detect those re-computations. To avoid confusion of the driver, in case the re-computation is not associated to a change in the selected TOSCo operating mode, re-computations should not be shown to the driver.



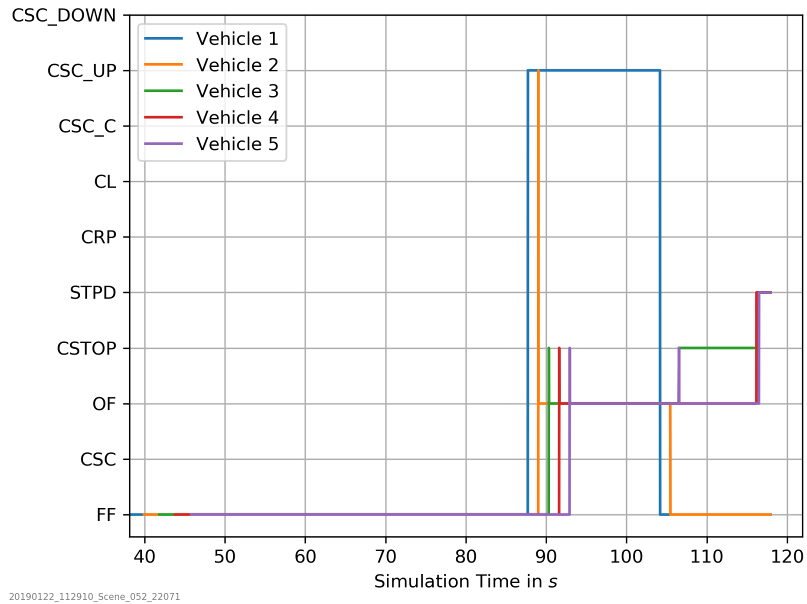
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 30: Speed-up Scenario: Simulation Time vs. Speed for TOSCo-enabled Vehicles at 19 mph Lead Vehicle Driver's Set Speed, 0.6 s Time Gap and 35 mph Speed Limit



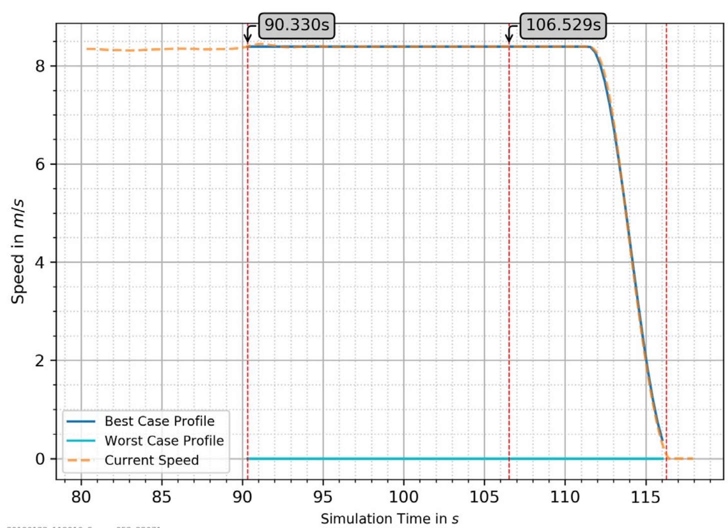
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 31: Coordinated Stop and Launch Scenario: Simulation Time vs. Acceleration for TOSCo-enabled Vehicles at 19 mph Lead Vehicle Driver's Set Speed, 0.6 s Time Gap and 35 mph Speed Limit



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

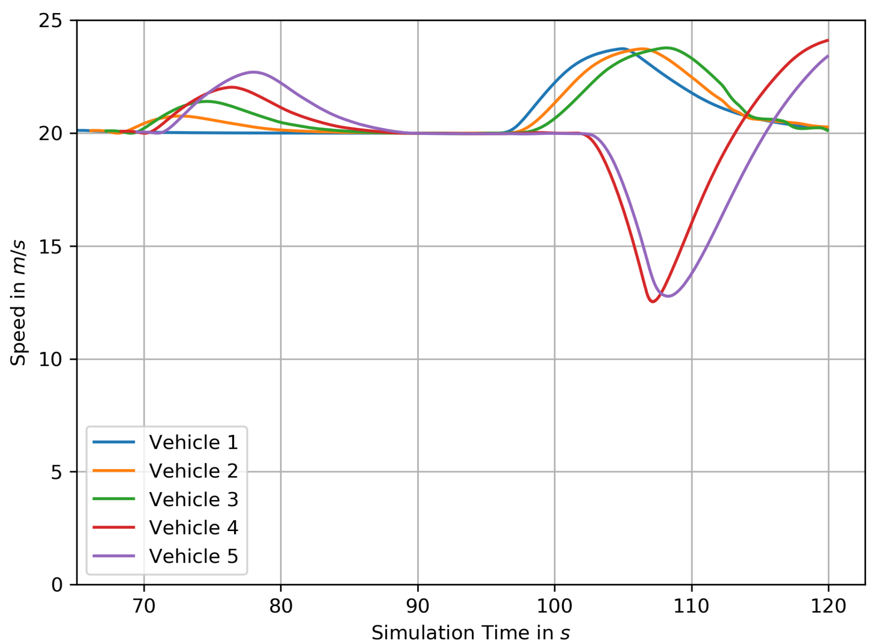
Figure 32: Speed-up Scenario: Simulation Time vs. Operating-Modes for TOSCo-enabled Vehicles at 19 mph Lead Vehicle Driver's Set Speed, 0.6 s Time Gap and 35 mph Speed Limit



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

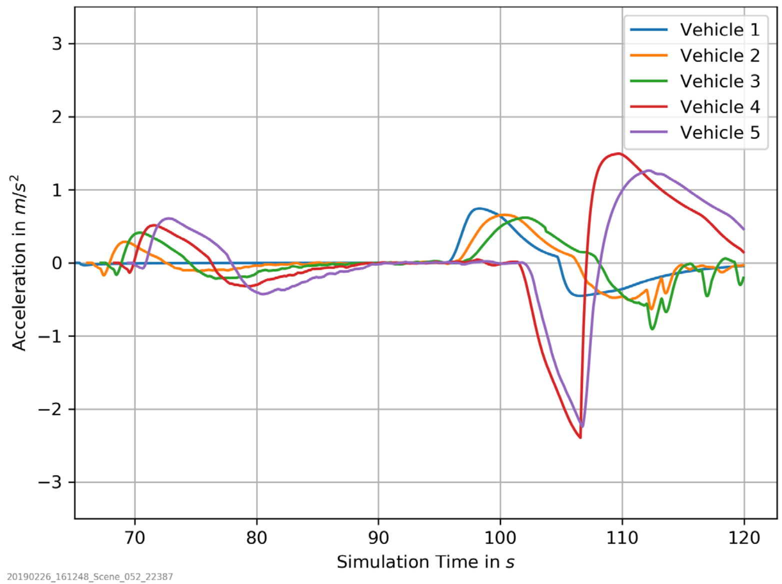
Figure 33: Speed-up Scenario: Simulation Time vs. Computed Speed Profiles for Vehicle 3 for TOSCo-enabled Vehicles at 25 mph Lead Vehicle Driver's Set Speed, 0.6 s Time Gap and 35 mph Speed Limit

Finally, the analysis focuses on the results of the higher lane speed limit case. Figure 34 depicts the recorded vehicle speed for each of the five TOSCo vehicles approaching the intersection. At around 90 s simulation runtime, a stable string has established at a time gap of about 0.6 s. Around 90 s simulation runtime, vehicles 1 - 3 decide to speed up to pass the intersection, whereas vehicles 4 and 5 decide to stop. However, while decelerating, vehicles 4 and 5 start acceleration at around 105 s simulation runtime, especially in vehicle 4. The acceleration changes from around -2.3 m/s^2 to 1.5 m/s^2 in about 2 seconds as in Figure 35 and this could be uncomfortable for both driver and passengers. At this timing, vehicles 4 and 5 change their operating mode from *CSTOP* to *OF*, as reflected in Figure 36. This causes these two vehicles to pass the intersection on a red signal which is not the intended behavior. Figure 37 shows the computed *CSTOP* speed profile for vehicle 4. At 98.030 s simulation runtime, the TOSCo system computes the speed profile that allows the vehicle to come to a full stop before the intersection at the stop bar. However, when the signal turns red at 103.629 s, a change in external condition occurs, causing vehicle 4 to re-compute its speed profile. Rather than adapting a new *CSTOP*-profile, as would be expected, the vehicle switches to *Free Flow* (FF) Mode instead. Figure 38 depicts that a re-computation is triggered for vehicle 4 at 103.629 s in simulation time. However, no valid profile could be determined that allows the vehicle to come to stop at the stop location. This is a result of an insufficient specification of the speed profiles as defined in Chapter 3. Whenever a change in external conditions occurs, a re-computation of a vehicle's speed profile needs to be triggered since, in case of actuated traffic signals, the green window might have changed. The definitions of the profiles in Chapter 3, however, do not take initial accelerations of a vehicle into account. As can be inferred from Figure 35, at the time the re-computation occurs at 103.629 s, the vehicle is currently decelerating at about -2 m/s^2. A speed profile generated at that point in time according to the definitions in Chapter 3, however, would not take this initial acceleration into account. As a result, there can be no valid speed profile computed that does not violate the space-time constraint. Consequently, the vehicles select the *FF* operating mode, resulting in a passing of the vehicles on red.



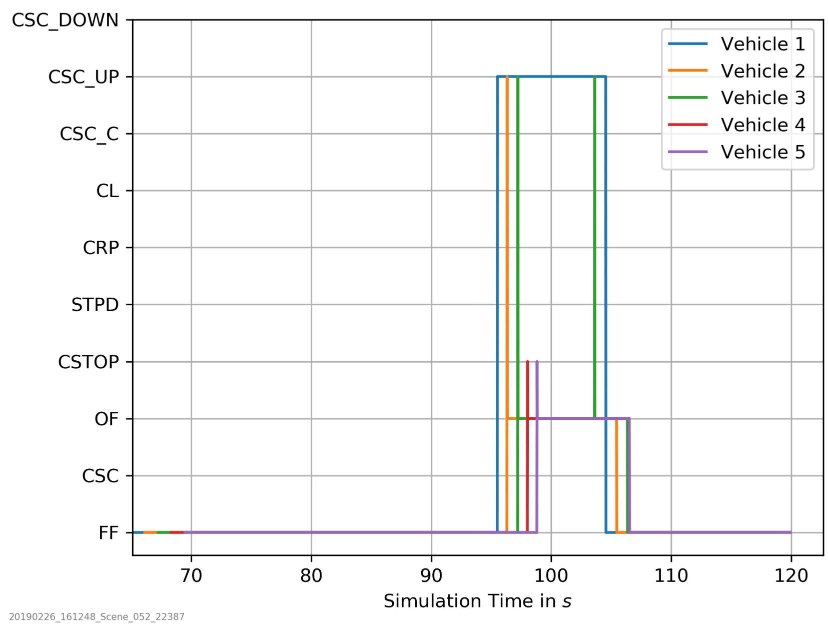
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 34: Speed-up Scenario: Simulation Time vs. Speed for TOSCo-enabled Vehicles at 45 mph Lead Vehicle Driver's Set Speed, 0.6 s Time Gap and 55 mph Speed Limit



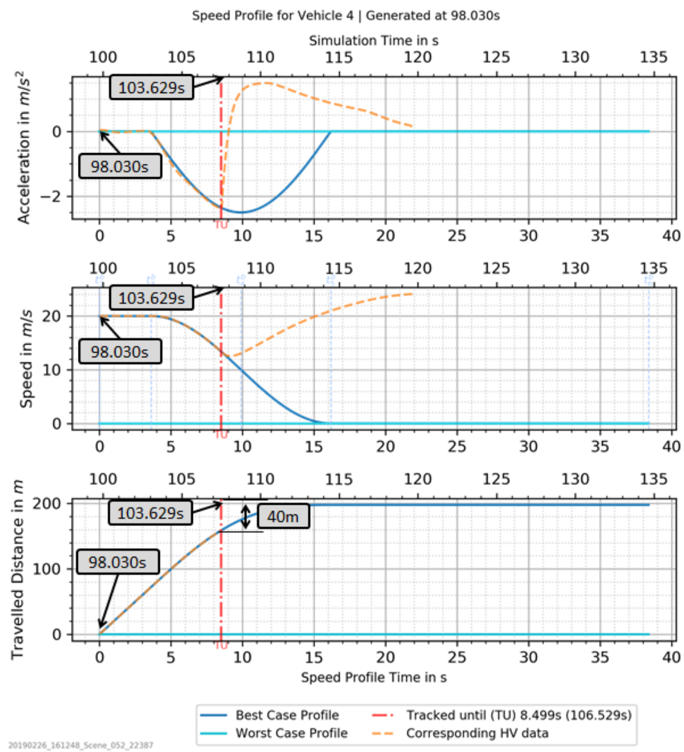
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 35: Coordinated Stop and Launch Scenario: Simulation Time vs. Acceleration for TOSCo-enabled Vehicles at 45 mph Lead Vehicle Driver's Set Speed, 0.6 s Time Gap and 55 mph Speed Limit



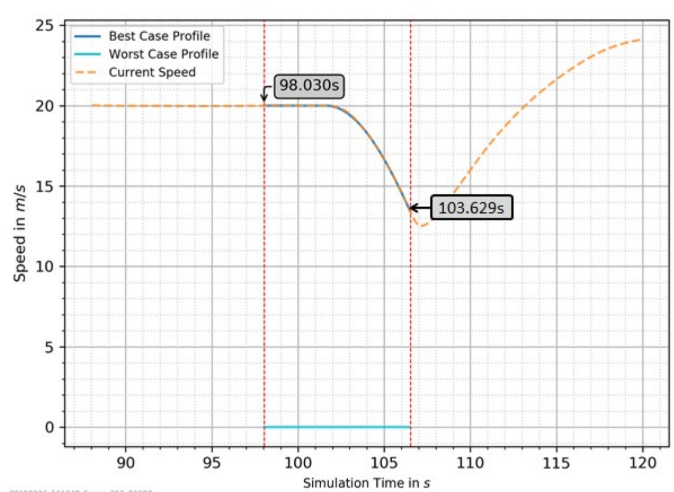
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 36: Speed-up Scenario: Simulation Time vs. Operating-Modes for TOSCo-enabled Vehicles at 45 mph Lead Vehicle Driver's Set Speed, 0.6 s Time Gap and 55 mph Speed Limit



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 37: Speed-up Scenario: Computed Coordinated Stop Speed Profile for Vehicle 4 at 45 mph Lead Vehicle Driver's Set Speed, 0.6 s Time Gap and 55 mph Speed Limit at 98.030 s Simulation Time



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 38: Speed-up Scenario: Simulation Time vs. Computed Speed Profile for Vehicle 4 at 45 mph Lead Vehicle Driver's Set Speed, 0.6 s Time Gap and 55 mph Speed Limit

4.3.3 Scenario Summary

The Speed Up Scenario successfully demonstrates that the developed TOSCo system is not only able to speed up vehicles in a string to pass the intersection but also to split up the vehicle string when it detects situations in which not all of the member of vehicle string can pass the intersection in the current green window. However, it was also observed that in case of re-computations occurring while a vehicle is already decelerating, the current speed profile definitions are insufficient, as initial accelerations are not considered.

Consequently, the following work items have been identified for future work:

- The insufficiency in the speed profile definitions should be revised to take initial acceleration into account. Certain acceleration levels can also be held constant for a longer duration, thus increasing the possible solution space for an approaching vehicle.
- The behavior of the longitudinal vehicle controller at low speeds (close to standstill) needs to be revisited for the implementation in an actual vehicle. The harsh acceleration levels exceeding -3 m/s^2 close to standstill are specific to the simulation environment.

4.4 Slow-down Scenario

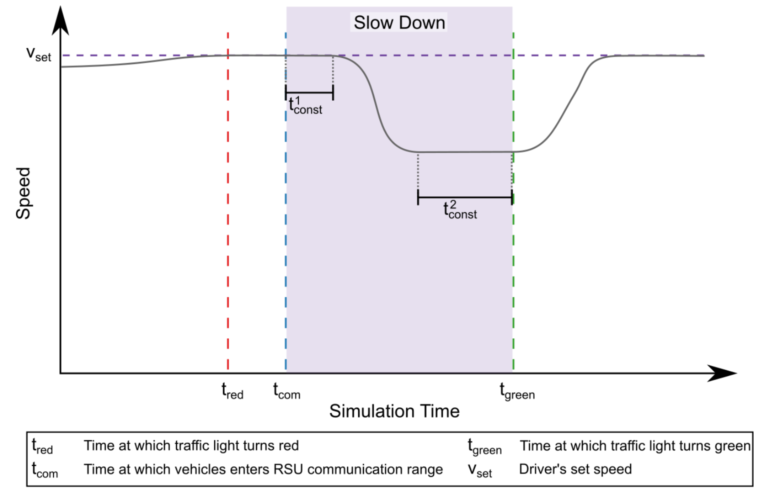
In situations when approaching vehicles might not be able to reach the green window to pass the intersection by maintaining their current speed or by increasing their speed, vehicles instead can choose to slow down to reach the green window to avoid stopping at the stop bar. For reasons of comfort and efficiency, this mode is preferred over a coming to a full stop. As detailed in the description of the TOSCo mode-selection [7], the system checks if maintaining or increasing the vehicle's current speed is an option that will allow the vehicle to pass the intersection when the traffic light is about to turn green. However, if this is not a feasible option, the vehicle will slow down to a speed that allows it to reach the green window without stopping at the stop bar. In case of multiple TOSCo vehicles driving behind each other approaching the intersection (a TOSCo string), the lead vehicle (Vehicle 1) operates in a *coordinated speed control slow down* (CSC_DOWN) operating mode, while the remaining vehicles in the string ideally operate in OF Mode until they reach the green window.

4.4.1 Scenario Description and Parameters

The following two paragraphs outline the basic operation and expected behavior of TOSCo vehicles in the current implementation of this scenario along with a representation of parameter variations performed for this report.

4.4.1.1 Scenario Outline

The Slow-down Scenario is set up in a way that approaching TOSCo vehicles will have to slow down from their current speed to a new target speed. Figure 39 depicts the expected course of the simulation scenario and an exemplary speed diagram. Each vehicle is introduced in VISSIM at a speed close to the driver's set speed $\mathrm{v_{set}}$. The traffic light turns red at $\mathrm{t_{red}}$ before the vehicles enter the RSU communication range at $\mathrm{t_{com}}$. Whenever a vehicle enters the communication range at $\mathrm{t_{com}}$ and, therefore, receives MAP and SPaT-messages, the TOSCo system is activated. At that point in time in this scenario, each vehicle will determine that it has to slow down to a new target speed before it reaches the stop bar location.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 39: Idealized Vehicle Behavior for the Slow-down Scenario

In the implementation of this scenario, two time durations t^1_{const} and t^2_{const} are computed as illustrated in Figure 39. During t^1_{const} , the vehicle keeps its current set speed until it has to start decelerating to a new predetermined target speed to reach t^2_{const} , which the vehicle maintains until it reaches the stop bar. Throughout this period, the vehicle will be in *Slow Down* operating mode.

4.4.1.2 Parameter Variations

The purpose of this simulation scenario is to validate the intended behavior of the TOSCo system in case vehicles need to slow down to reach the green window. The system thereby needs to be capable of handling different operating speeds when entering RSU communication range. Table 9 summarizes the parameter variations performed for the validation. Two different speed limits, reflecting the encountered speeds on the respective urban and rural corridors in Ann Arbor, Michigan and Conroe, Texas, are selected. In the implementation of this scenario, the minimum cruising speed or target speed is chosen to be approximately 70% of the lane speed limit. Since VISSIM only allows introduction of vehicles with a time gap of about 1 s, the driver's set speed of the lead vehicle of a TOSCo string is slightly below the following vehicle's set speed so the following vehicles of the string need to be able to decrease their distance to the preceding vehicles to yield a time gap of less than 1 s – for which they need to drive faster than the lead vehicle.

Table 9: Simulation Parameters for the Slow-down Scenario

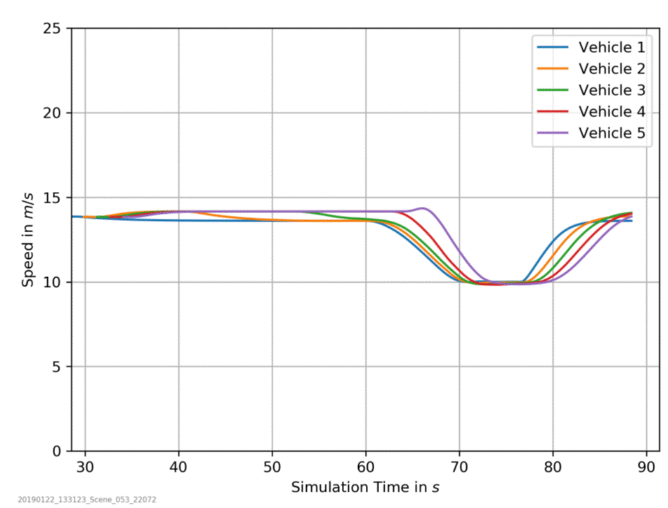
Lane Speed Limit (mph)	35	55
Lead Vehicle Driver's Set Speed (mph)	31	45
Following Vehicles Driver's Set Speed (mph)	32	55
Time Gap Settings (s)	0.6	
Minimum Cruising Speed or Target Speed (mph) [70 % of the speed limit]	24	38

Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

4.4.2 Analysis

The following analysis focuses on the results of the two cases of the simulation parameters for this scenario: A speed limit of a 35 mph road and speed limit of a 55 mph road.

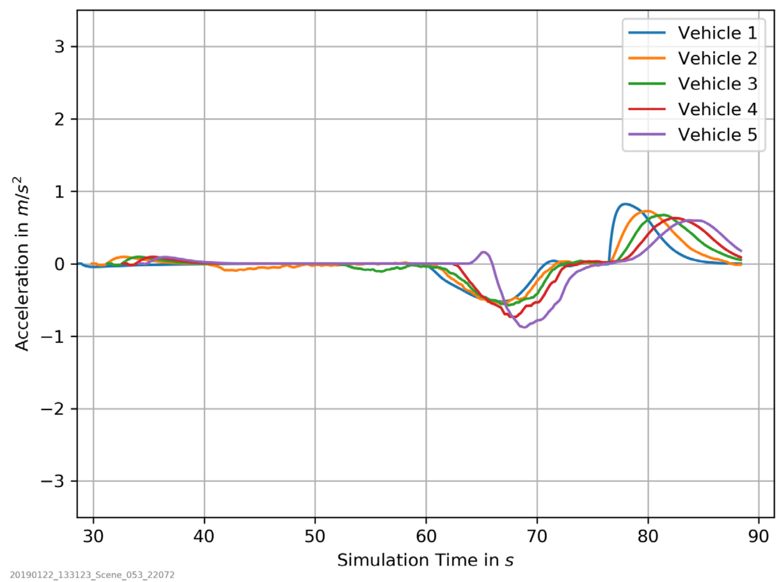
Figure 40 depicts the recorded vehicle speed for each of the five TOSCo vehicles approaching the intersection over the duration of the simulation. Up until around 60 s simulation runtime, only vehicles 2-3 have caught up with vehicle 1 and established a time gap of about 0.6 s. Due to VISSIM only allowing vehicles to be introduced at a time gap of 1 s, the first 60 seconds in this simulation run are used to establish the desired time gap of 0.6 s. Since vehicles 4-5 have not established a time gap of 0.6 s yet, vehicle 4 maintains its speed whereas vehicle 5 increases its speed to achieve the set time gap. This behavior is intended in this particular setup, to analyze the behavior of the TOSCo system in case a non-stabilized string is entering RSU communication range.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

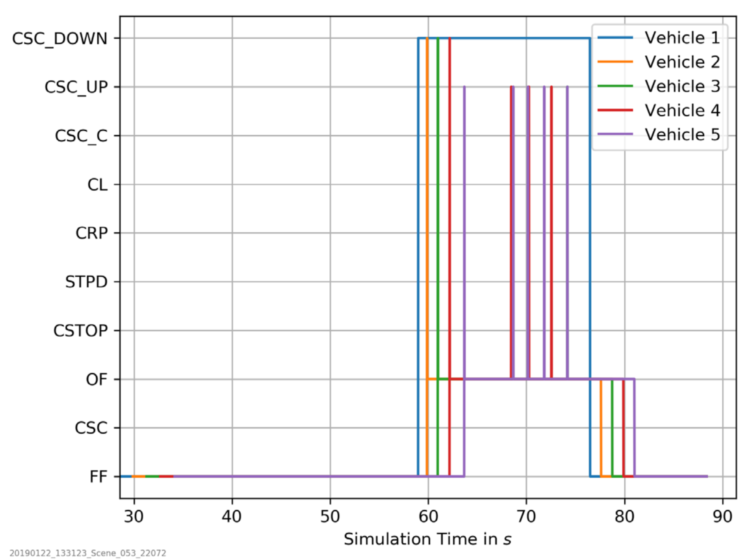
Figure 40: Slow-down Scenario: Simulation Time vs. Speed for TOSCo-enabled Vehicles at 35 mph Speed Limit

As depicted in Figure 42, around 59 s simulation time, the first vehicle starts to receive messages from the RSU, triggering the TOSCo mode selection to select an operating mode, alongside the computation of a valid speed profile. Whenever a vehicle enters the RSU communication range, as is intended for this scenario setup, the *Slow Down* Operating Mode is entered by each vehicle Figure 44. In *Slow Down* operating mode, each vehicle computes a speed profile consisting a time duration ($t^2{}_{\text{const}}$ in Figure 35) for which a predetermined target speed will be maintained until the stop bar. Upon entering the RSU communication range, vehicles 1-4 enter the *Slow Down* operating Mode because they cannot reach the green window by maintaining their current set speed, however, vehicle 5 enters the *Speed Up* Operating Mode but soon switches to *OF* due to the presence of the preceding vehicles preventing it from following its own computed speed profile. Each following vehicle has therefore determined its desired operating mode if it was the lead vehicle but then selects the *OF* Mode as long as it operates within its computed solution space of the originally selected desired operating mode. The recurring re-computations of speed profiles for vehicles 4 and 5 in Figure 42 are a result of these vehicles being pushed out of the solution space due to the behavior of the preceding vehicles. Whereas vehicle 4 did select the *Slow Down* Operating Mode at around 62 s, it then decides to select a *Speed Up* Operating Mode at around 68 s, as the approach conditions have changed at the time of re-computation.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

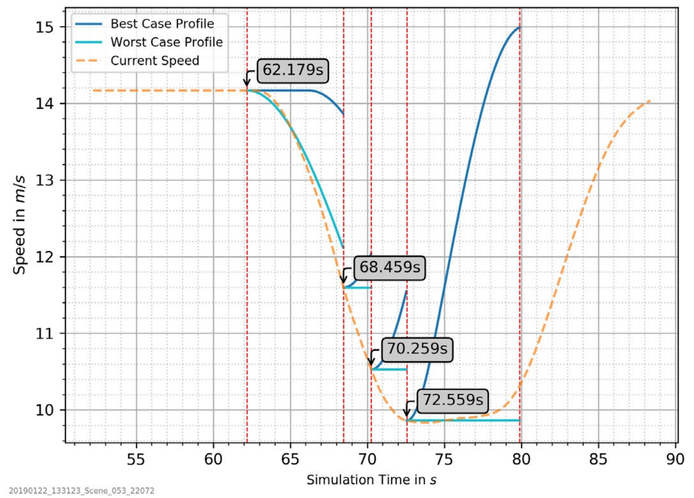
Figure 41: Slow-down Scenario: Simulation Time vs. Acceleration for TOSCo-enabled Vehicles at 35 mph Speed Limit



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 42: Slow-down Scenario: Simulation Time vs. Operating-Modes for TOSCo-enabled Vehicles at 35 mph Speed Limit

To further explain this, the computed speed profiles for vehicles 4 and 5 are plotted in Figure 43 and Figure 44, respectively. Vehicle 4, upon entering the RSU communication range at around 62 s enters into the *Slow Down* Operating Mode as per its new computed *best*- and *worst-case* speed profiles. Vehicle 4 follows its new computed speed profile until about 68 s time mark upon which it leaves the solution space for its current speed profile and another speed profile is computed. According to this new speed profile, at this time in simulation, vehicle 4 could ideally speed up to reach its green window but is hindered by the presence of the preceding vehicle, and hence again enters the OF Operating Mode due to its CACC operation to follow the preceding vehicle [3].



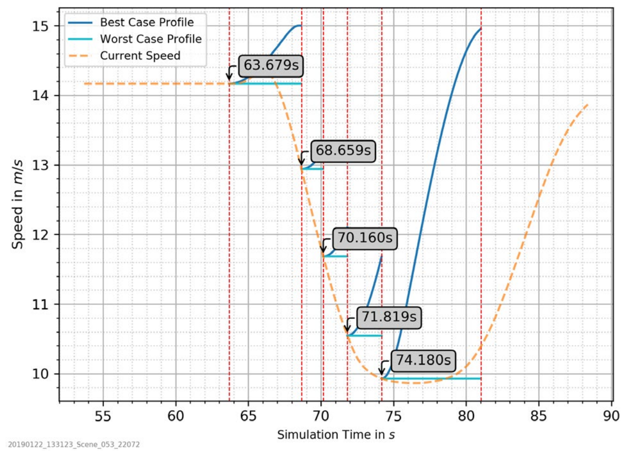
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 43: Slow-down Scenario: Simulation Time vs. Computed Speed Profiles for Vehicle 4 at 35 mph Speed Limit

Taking Figure 44 into account, Vehicle 5 enters the DSRC communication range at about 63 s into the simulation and computes a speed profile which allows it to enter the *Speed Up* operating mode. Ideally, vehicle 5 would have reached the green window in the absence of the preceding vehicles by following its new computed speed profile but is forced to soon enter the *OF* Operating Mode due to its CACC operation. Several other speed computations for vehicle 4 and vehicle 5 are computed because of this reason thus causing the corresponding operating mode changes in Figure 42.

Taking Figure 41 into account, vehicles 1-3 gradually start decelerating after the 60 s simulation time, vehicle 4 starts decelerating around 63 s, while vehicle 5 accelerates around 65 s but soon decelerates due to the presence of the other vehicles in front.

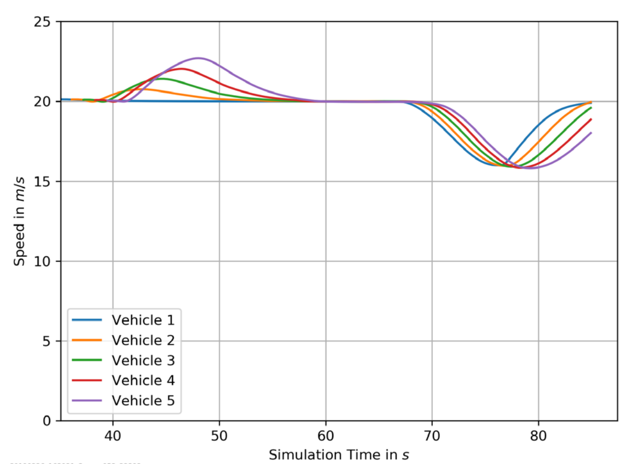
Vehicle responses for the speed limit of 55 mph road and time gap setting of 0.6 s are presented in Figure 45, Figure 46, and Figure 47. While the overall observed behavior is very similar to that of 35 mph speed limit, it should be noted that a stable string has now already been established when the vehicles are entering RSU communication range due to the increased speed difference between the lead vehicle (45 mph) and the following vehicles (55 mph). Between 40 s and 60 s simulation time, each vehicle accelerates and is able to maintain the set time gap of 0.6 s. Furthermore, upon entering the communication range at around 66 s simulation time, each vehicle slows down either to try to achieve its predetermined target speed (16 m/s) due to its computed speed profile or because of its CACC operation in the presence of a preceding vehicle. However, the vehicles reach the green window as soon as the target speed is achieved. This is a result of the short approach to the intersection (200 m) and the increased set speed of the vehicles.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

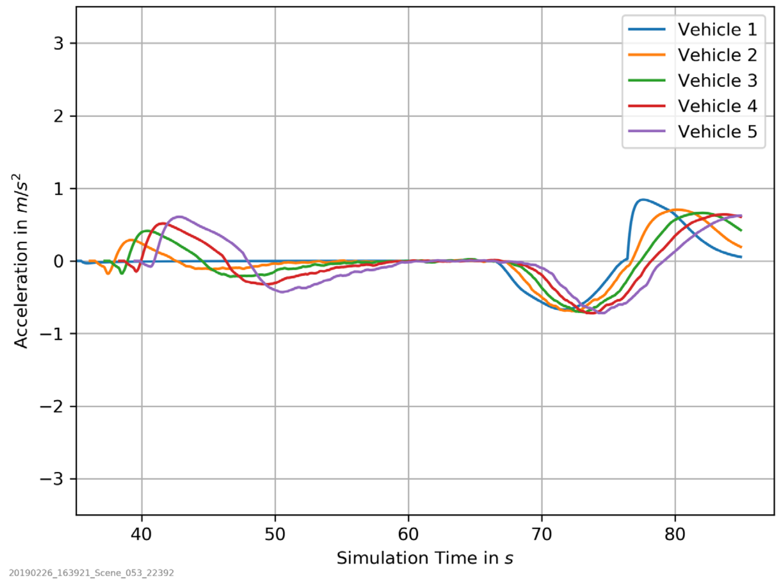
Figure 44: Slow-down Scenario: Simulation Time vs. Computed Speed Profiles for Vehicle 5 at 35 mph Speed Limit

The target speed in the current implementation of the *Slow Down* Scenario is a predetermined value and is set to be approximately 70% of the lane speed limit (10 m/s for 35 mph and 16 m/s for 55 mph). This predetermined target speed value prevents vehicles from choosing a more appropriate speed to arrive at the green window and, therefore, the following vehicles are forced to follow the preceding vehicles due to their CACC operation instead of following their computed speed profile.



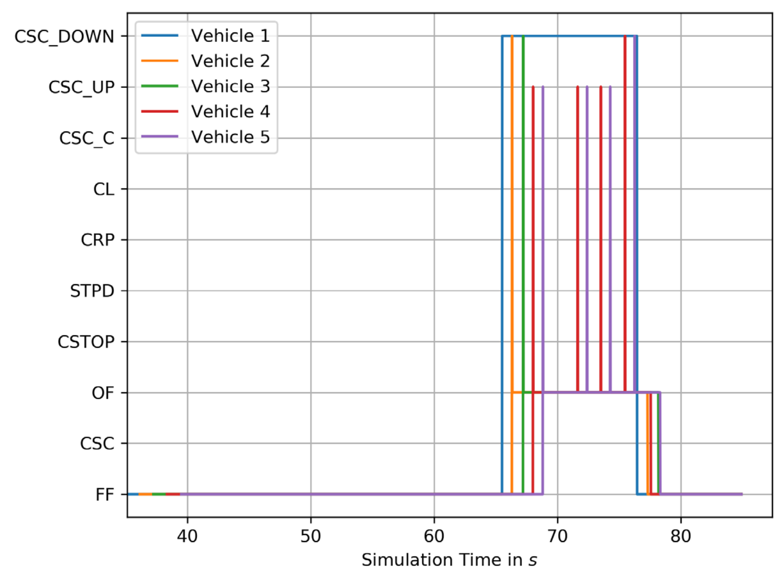
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 45: Slow-down Scenario: Simulation Time vs. Speed for TOSCo-enabled Vehicles at 55 mph Speed Limit



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 46: Slow-down Scenario: Simulation Time vs. Acceleration for TOSCo-enabled Vehicles at 55 mph Speed Limit



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 47: Slow-down Scenario: Simulation Time vs. Operating-Modes for TOSCo-enabled Vehicles at 55 mph Speed Limit

4.4.3 Scenario Summary

The Slow-down Scenario successfully demonstrates that the developed TOSCo system is able to detect situations when it is not feasible for a vehicle or string of vehicles to either maintain its current speed or speed up to pass through an intersection. Instead, the vehicles choose a predetermined target speed (about 70% of the speed limit) and are able to pass through the intersection without coming to a full stop. Two different situations for the slow down scenarios were analyzed to accommodate a 35 mph and 55 mph speed limits with a time gap setting of 0.6 s.

Identified open work item:

- Computed speed profiles calculate a predetermined target speed and a time duration for which that target speed is maintained to reach the green window. This limits vehicle's capability to decelerate earlier and choose a more appropriate target speed allowing it to arrive at the stop bar at a high possible speed. Instead, a vehicle's target speed when slowing down should be computed dynamically, based on the current distance and timing constraints as opposed to slowing down to a predetermined target speed.

4.5 Coordinated Stop and Launch Scenario

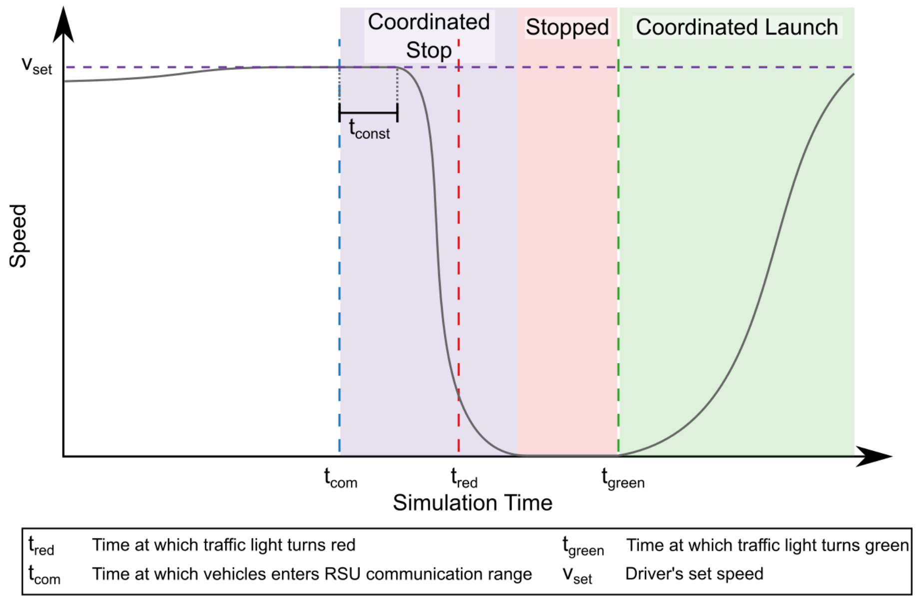
Although preferable from environmental-, traffic-efficiency- and comfort-aspects, approaching vehicles might not always have the option to decrease their current speed enough to pass the intersection without coming to a full stop. As detailed in the description of the TOSCo mode-selection [7], the system checks if reducing the vehicle's speed up to the minimum cruising speed is an option that will allow the vehicle to pass the intersection when the traffic light is about to turn green. However, if this is not a feasible option, the vehicle will come to a full stop to at the reported stop location. In case of multiple TOSCo vehicles waiting behind each other at the traffic light (a TOSCo string), the vehicles will perform a coordinated, simultaneous launch when the traffic light switches to green to increase throughput at the intersection.

4.5.1 Scenario Description and Parameters

The following two paragraphs outline the basic operation and expected behavior of TOSCo vehicles in this scenario along with a representation of parameter variations performed for this report.

4.5.1.1 Scenario Outline

The Coordinated Stop and Launch Scenario is set up in a way that approaching TOSCo vehicles will have to come to a full stop. Figure 48 depicts the expected course of the simulation scenario and an exemplary speed diagram. Each vehicle is introduced in VISSIM at a speed close to the driver's set speed $\mathrm{v}_{\mathrm{set}}$. After entering RSU communication range at $\mathrm{t}_{\mathrm{com}}$, the traffic light turns red at $\mathrm{t}_{\mathrm{red}}$. Whenever a vehicle enters the communication range at $\mathrm{t}_{\mathrm{com}}$ and, therefore, receives SPaT messages, the TOSCo system is activated as detailed in [7]. At that point in time in this scenario, each vehicle will determine that it has to come to a full stop in front of the traffic light.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 48: Idealized Vehicle Behavior for the Coordinated Stop and Launch Scenario

Depending on the current speed and remaining distance to the received stop location, it may not be advisable[6] to start decelerating immediately. Instead, the computed speed profile may include a duration t_{const}, in which the vehicle keeps its current speed until it has to start decelerating to come to a full stop at the stop location. Throughout this period, the vehicle will be in *Coordinated Stop* Mode. As soon as the vehicle's speed is below the standstill speed threshold, it enters the *Stopped* Mode until the traffic light turns green[7]. Upon start of the green window at t_{green}, each vehicle enters *Coordinated Launch* and computes a corresponding speed profile. During this phase (and within system limits), each vehicle in a string of TOSCo vehicles will pick up speed at the same point in time to increase throughput at the intersection.

4.5.1.2 Parameter Variations

The purpose of this Simulation Scenario is to validate the intended behavior of the TOSCo system in case vehicles need to come to a full stop. The system thereby needs to be capable of handling different operating speeds when entering RSU communication range and time gap settings selected by the driver. Table 10 summarizes the parameter variations performed for the validation. Two different speed limits, reflecting the encountered speeds on the respective urban and rural corridors in Ann Arbor, Michigan and Conroe, Texas, are selected. For each lane speed limit, the driver's set speed of the lead vehicle of a TOSCo string is slightly below the following vehicle's set speed since VISSIM only allows introduction of vehicles with a time gap of about 1 s. For those scenarios, in which a shorter time gap is selected, the vehicles behind the lead vehicle of

[6] Decelerating early or over a long period may seem unfeasible to other traffic participants and the driver of the TOSCo system.

[7] Driver clearance for consecutive launch when the traffic light turns green is not implemented in the simulation but shall be included in an in-vehicle implementation.

the string need to be able to decrease their distance to the preceding vehicles to yield a time gap of less than 1s, for which they need to drive faster than the lead vehicle.

For each speed limit, different time gap settings are simulated to assess vehicle response and string behavior at for different inter-vehicle gaps. As each vehicle in a TOSCo string enters the RSU communication range consecutively, the time between two vehicles entering RSU communication range increases as well. Especially for larger time gap settings, the preceding vehicle will already be optimizing its speed profile, thereby affecting the following vehicle not yet under TOSCo control. Consequent analysis, therefore, has to assess the effect on the vehicle’s behavior in case of different TOSCo activation states within a string.

Table 10: Simulation Parameters for the Coordinated Stop and Launch Scenario

Lane Speed Limit (mph)	35			55		
Lead Vehicle Driver’s Set Speed (mph)	31			45		
Following Vehicles Driver’s Set Speed (mph)	32			55		
Time gap Settings (s)	0.6	1.0	1.5	0.6	1.0	1.5

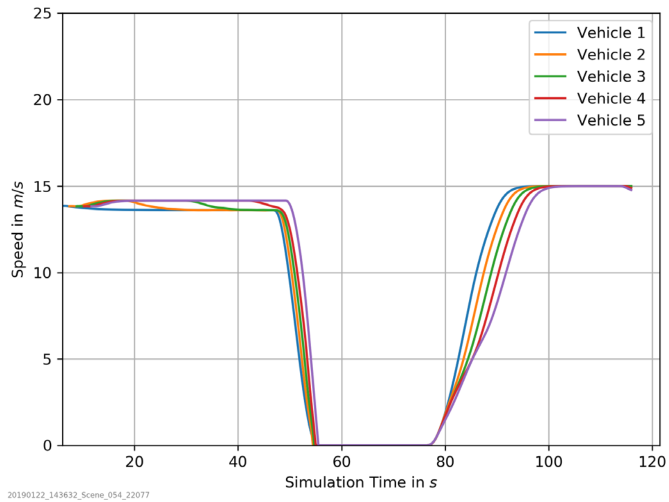
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

4.5.2 Analysis

The following analysis focuses on the results of the two extremes of the simulation parameters for this scenario which are a time gap setting of 0.6 s on a 35 mph speed limit road and a time gap setting of 1.5 s on a 55 mph speed limit road.

Figure 49 depicts the recorded vehicle speed for each of the five TOSCo vehicles approaching the intersection over the duration of the simulation. Up until around 45 s simulation runtime, only vehicles 2-3 have caught up with vehicle 1 and established a time gap of about 0.6 s. Due to VISSIM only allowing vehicles to be introduced at a time gap of 1 s into the scenario, the first 45 seconds are used to establish the desired time gap of 0.6 s. Vehicles 4 and 5 have not established a time gap of 0.6 s yet. This is due to the short approach to the intersection which is insufficient to establish a stable string.

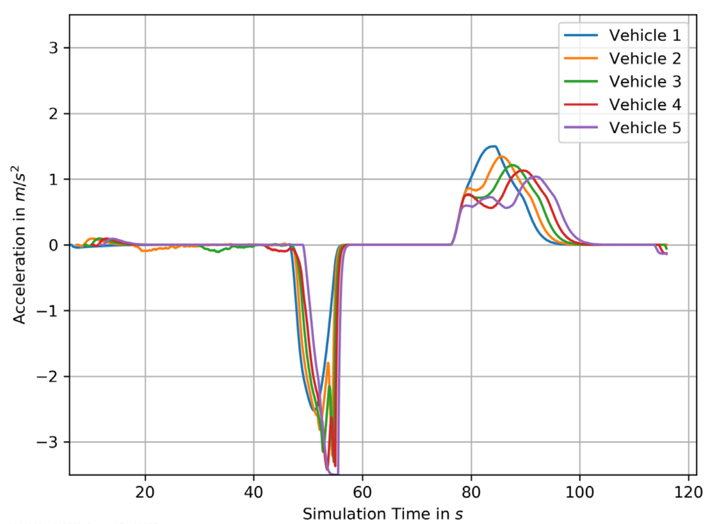
As depicted in Figure 51, around 38 s simulation time, the first vehicle starts to receive messages from the RSU, triggering the TOSCo mode selection to select an operating mode, alongside the computation of a valid speed profile. Whenever a vehicle enters the RSU communication range, as is intended for this scenario setup, the CSTOP operating mode is entered by each vehicle. In case the preceding vehicle operates within the solution space resulting from the computed *best*- and *worst-case* speed profile (see Chapter 3 and [7]), it then switches to the OF operating mode in the next operating cycle until either a new mode applies or the currently followed speed profile is no longer within the solution space. Between 38 s to about 55 s, all vehicles are following a speed profile complying with the CSTOP operating mode to eventually bring the vehicles to a full stop before entering the STOPPED operating mode. Deceleration to standstill, however, is not initiated until about 50 s into the simulation, as by the time the CSTOP profile was generated at around 38 s, immediate deceleration would have been unfeasible. Instead, current vehicle speed is maintained by all vehicles until a vehicle has to start decelerating to come to a full stop at the stop location (refer to t_{const} in Figure 48).



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

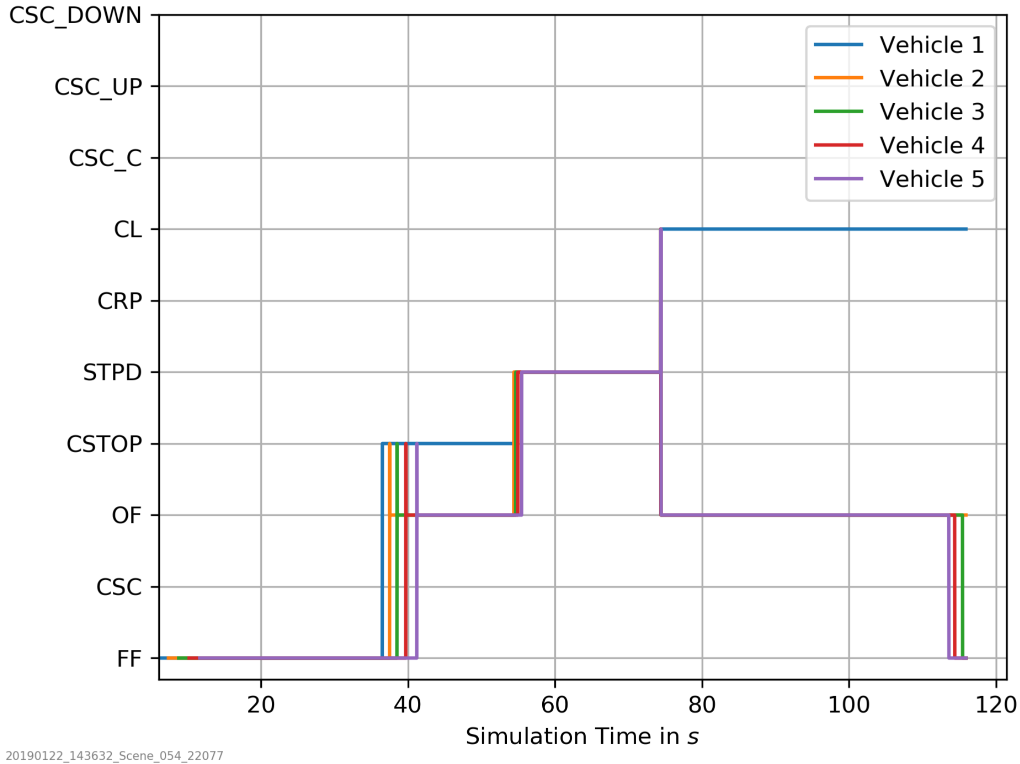
Figure 49: Coordinated Stop and Launch Scenario: Simulation Time vs. Speed for TOSCo-enabled Vehicles at 0.6 s Time Gap and 35 mph Speed Limit

Taking Figure 50 into account, the negative acceleration level is built up gradually according to the computed speed profile, with CACC control yielding harsher deceleration levels for the following vehicles. The observed acceleration levels exceeding -3 m/s^2 are a result of the existence of the non-stable string when the first vehicle starts its deceleration process.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

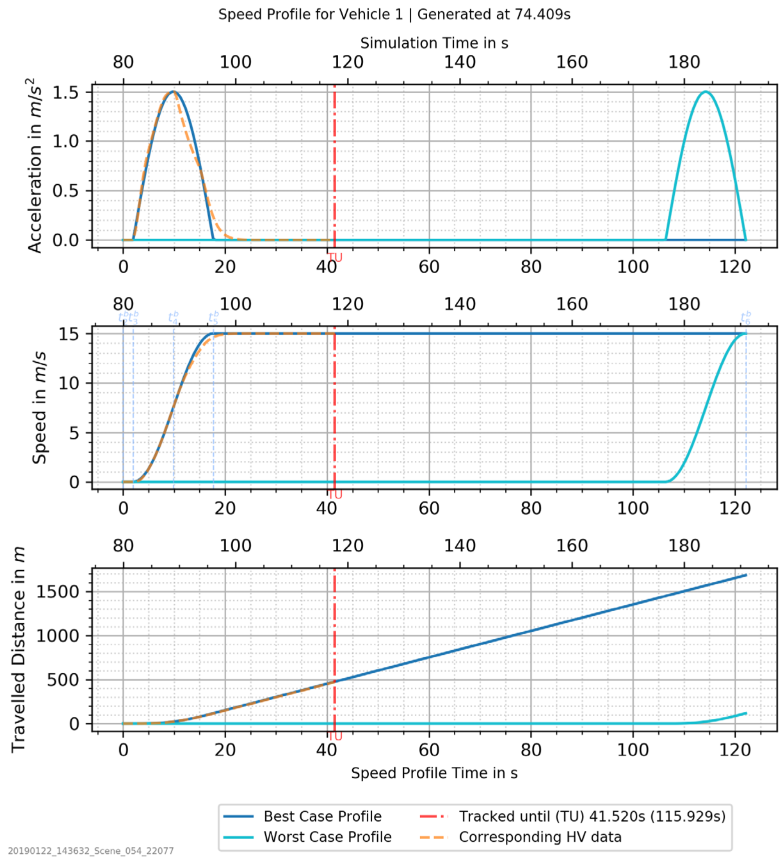
Figure 50: Coordinated Stop and Launch Scenario: Simulation Time vs. Acceleration for TOSCo-enabled Vehicles at 0.6 s Time Gap and 35 mph Speed Limit



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 51: Coordinated Stop and Launch Scenario: Simulation Time vs. Operating-Modes for TOSCo-enabled Vehicles at 0.6 s Time Gap and 35 mph Speed Limit

From about 55 s, all vehicles remain in STOPPED operating mode until the traffic light turns green at around 75 s. At that instance, every vehicle switches to the CL operating mode, triggering the computation of a Coordinated Launch Speed Profile as depicted in Figure 52. Upon entering the CL operating mode, each vehicle signalizes its pending launch by broadcasting a *CL-Flag* as part of the next transmitted BSM. Each vehicle in the string computes the same speed profile as depicted in Figure 52 which is then fed to the TOSCo Longitudinal Controller and starts to move simultaneously, as shown in Figure 49 between 75 s and 78 s. During this timeframe, the distance between the vehicles is maintained constant, followed by a gradual switch to a time gap based distance control after around 80 s. Although maintaining a positive accelerating level after 80 s, each vehicle within the string consecutively decreases its acceleration level slightly, in order to increase the distance to the preceding vehicle until the desired time gap of 0.6 s is established. All vehicles accelerate up to driver’s set speed of the lead vehicle.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

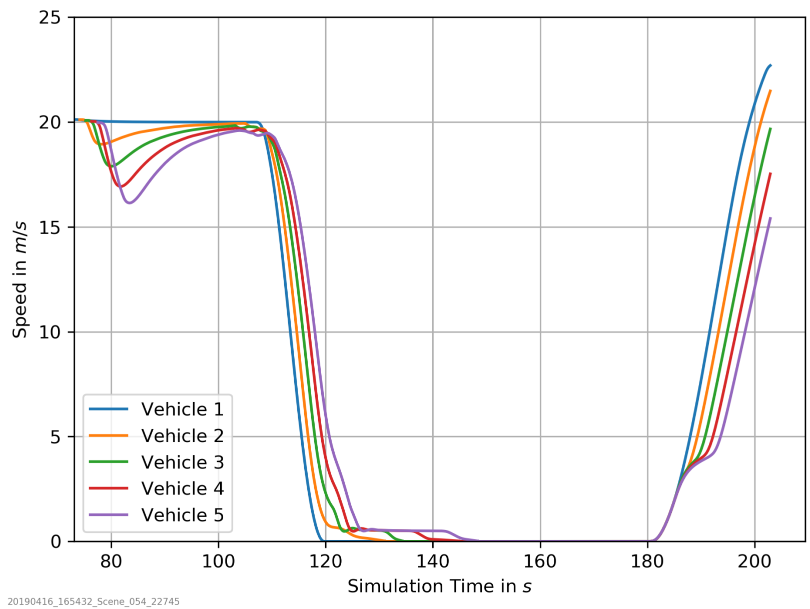
Figure 52: Coordinated Stop and Launch Scenario: Computed Coordinated Launch Speed Profile for Vehicle 1 for 0.6 s Time Gap and 35 mph Speed Limit

Vehicle responses for the remaining time gap settings of 1.0 s and 1.5 s at a speed limit of 35 mph are depicted in APPENDIX C. While the overall observed behavior is very similar, it should be noted that since a stable string is now established when the vehicles are entering RSU communication range, the observed maximum acceleration levels during the CSTOP operating mode phase between 45 s and 60 s in Figure 104 decrease for each vehicle along the string as a result of CACC operations. Additionally, while still positive, acceleration levels are decreased during the CL phase for each vehicle as a result of switching from a constant distance to a time gap based distance control. The increased time gap of 1.0 s also results in a larger inter-vehicle gap at standstill. Consequently, increasing the distance to the preceding vehicle when switching to the time gap based control occurs at higher speeds (refer to Figure 103) when compared to the shorter time gap of 0.6 s (refer to Figure 49).

For a time gap setting of 1.5 s, the vehicle behavior only partially complies with the theoretical scenario description outlined in Section4.5.1.1. While vehicles 1 to 3 demonstrate a similar behavior to the previously described time gap settings, vehicles 4 and 5 are not coming to a full stop as a result of the controller attempting to create a larger inter-vehicle distance at standstill and, consequently, an adapted approach strategy at lower speeds, as depicted in Figure 106. Consequently, these vehicles are not at a full stop when entering CL operating mode. Since the computed speed profiles always assume no initial acceleration when generated, the resulting acceleration behavior is rendered implausible (Figure 107).

When increasing the speed limit of the approach lane to 55 mph and increasing the driver's set speed to the valued listed in Table 10, the TOSCo system is still able to operate as intended. APPENDIX C lists the corresponding speed, acceleration and TOSCo mode diagrams for time gap settings of 0.6 s and 1.0 s.

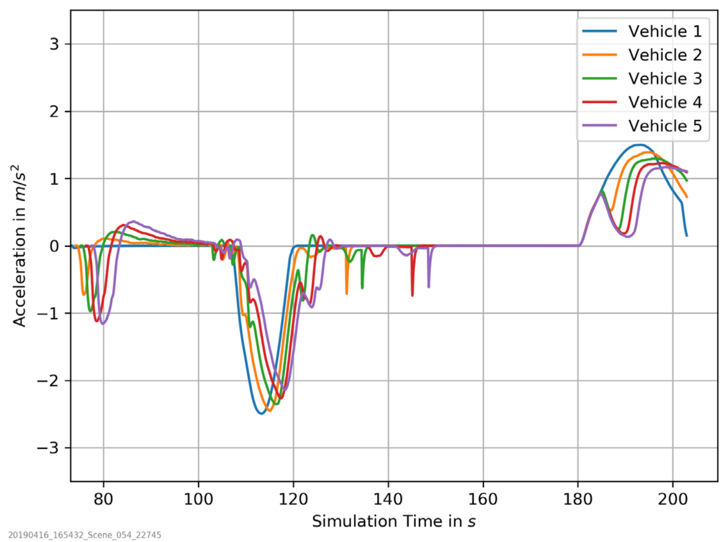
Figure 53 depicts the speed diagram at a time gap setting of 1.5 s with a higher allowed lane speed of 55 mph for all vehicles of the TOSCo string. As the vehicles are still introduced in VISSIM at a time gap of 1 s, vehicles 2 - 5 initially decelerate to establish a time gap of 1.5 s between the vehicles.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

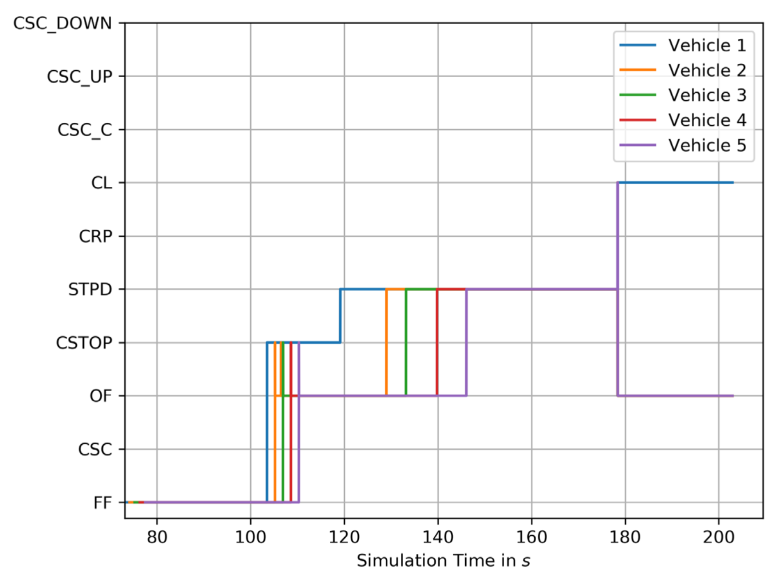
Figure 53: Coordinated Stop and Launch Scenario: Simulation Time vs. Speed for TOSCo enabled Vehicles at 1.5 s Time Gap and 55 mph Speed Limit

Due to the higher approach speed but otherwise unchanged scenario parameters, all vehicles come to a full stop at the in front of the traffic light opposed to the behavior explained above for a time gap setting of 1.5 s at a 35 mph speed limit.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 54: Coordinated Stop and Launch Scenario: Simulation Time vs. Acceleration for TOSCo-enabled Vehicles at 1.5 s Time Gap and 55 mph Speed Limit



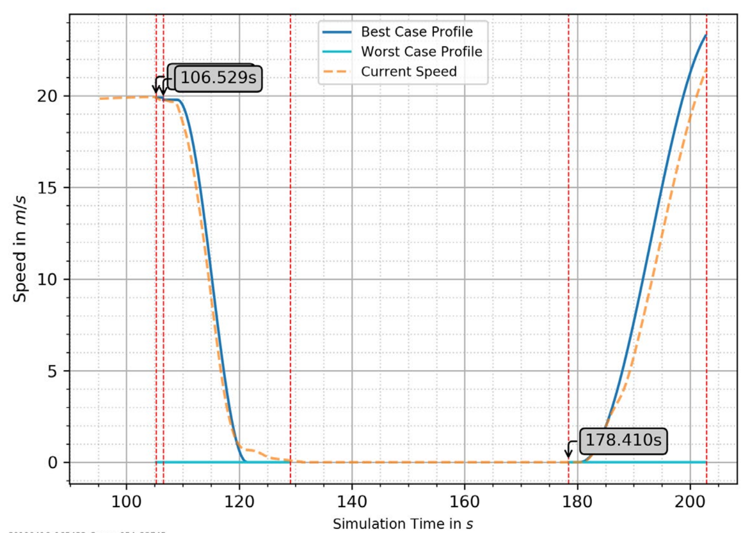
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 55: Coordinated Stop and Launch Scenario: Simulation Time vs. Operating-Modes for TOSCo-enabled Vehicles at 1.5 s Time Gap and 55 mph Speed Limit

Throughout the CL operating mode duration (refer to Figure 55), vehicle acceleration is now congruent, with consecutive deceleration levels dropping to almost 0 m/s^2 when switching from distance- to time gap-based control, as depicted in Figure 54 between 180 to 190 s.

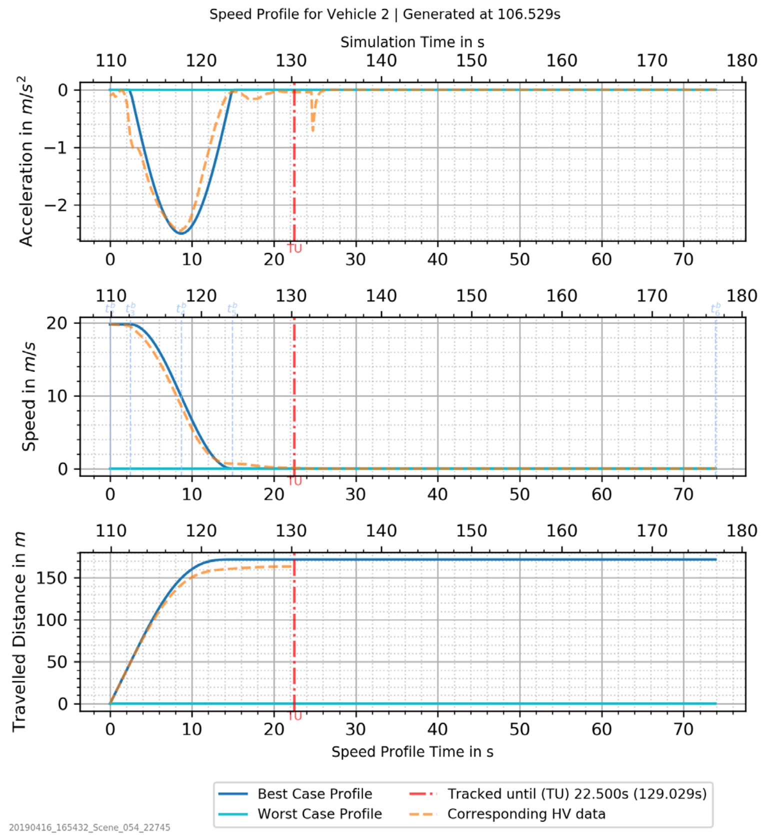
As a result of the unchanged communication range of 200 m compared to the previously described lower speed limit scenario, vehicles have a reduced timeframe available to operate the TOSCo optimization. As a result, the duration of t_{const} is reduced to about 3.2 s compared to 10 s for the lower speed approach. Hence, ensuring a sufficient communication range to propagate TOSCo relevant infrastructure messages (MAP and SPaT) well in advance by adequately mounted antennas (e.g., directional antennas, multiple antennas along the approach) is key to operating TOSCo.

For any vehicle approaching the traffic light in this scenario (regardless of the configured speed limit), vehicles will receive the change of the traffic light from yellow to red. According to the TOSCo system specification, this corresponds to a change of external conditions (see [7]) and hence a re-computation of the underlying speed profile. Figure 56 depicts vehicle 2's current speed and the corresponding valid *best-* and *worst-case* CSTOP speed profiles. The fist CSTOP profile is computed at 104.23 s simulation time as a result of receiving the first set met messages from the RSU required for TOSCo optimization while the traffic light is already yellow. At 106.529 s, the traffic light switches from yellow to red and the "green window" is updated accordingly. This corresponds to a change in external conditions, causing a re-computation of the applicable speed profiles. Figure 56 depicts the re-computed speed profile at 106.529 s in more detail. In contrast to the high-speed setup of the Speed-up Scenario described in Section 4.3, the issue of not taking initial acceleration into account, when re-computing a speed profile is not an impediment in this situation, as the coordinated stop speed profile includes a phase of constant speed which is maintained until the vehicle is left with the required distance to come to a full stop from the constant cruising speed. Hence, when the speed profile is re-computed at 106.529 s, when the traffic light changes, the current vehicle acceleration reads about –0.02 m/s^2 , as depicted in Figure 57. Even in the new profile the initial vehicle speed is maintained for another two seconds before decelerating. If, however, the traffic light information had been updated while already decelerating, a similar situation as described in high-speed setup of the Speed-up Scenario (Section 4.3) would have occurred and the vehicle would have passed the intersection on a green light as a result of initial accelerations not being taken into account.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 56: Coordinated Stop and Launch Scenario: Simulation Time vs. Computed Speed Profiles for Vehicle 2 for 1.5 s Time Gap and 55 mph Lane Speed Limit



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 57: Coordinated Stop and Launch Scenario: Second Computed CSTOP Profile for Vehicle 2 for 1.5 s Time Gap and 55 mph Lane Speed Limit

4.5.3 Scenario Summary

The Coordinated Stop and Launch Scenario successfully demonstrates that the developed TOSCo system is able to detect situations in which more optimal approach strategies are limited and bringing the vehicle to a full stop at the stop location is more feasible as opposed to slowing down only. This works for different time gap and speed levels. When the traffic light switches to green, the TOSCo system improves throughput at the intersection by performing a coordinated launch which causes all TOSCo-enabled vehicles to pick up speed simultaneously.

Identified open work items:

- Computed speed profiles always assume no initial acceleration. This results in discrepancies between the current vehicle behavior and the controller input, expressed and control deviations, resulting in implausible vehicle behavior at the expense of driving comfort.
- For any constellations in which the stopping duration is very short, not all vehicles within a string might come to a full stop. The current specification impedes the operation of the Coordinated

Launch operating mode in case a vehicle receives a CL-flag from a preceding vehicle but is not yet at standstill.

- Communication ranges with the RSU need to be adapted to the speed limit. Whereas this scenario assumed a fixed communication range of 200 m regardless of the vehicle speed, earlier information increases the solution space of a TOSCo vehicle. This can be achieved by using directional antennas or mounting additional antennas along the approach lane at some distance from the intersection.

4.6 Speed-up with Dissipating Queue at Intersection Scenario

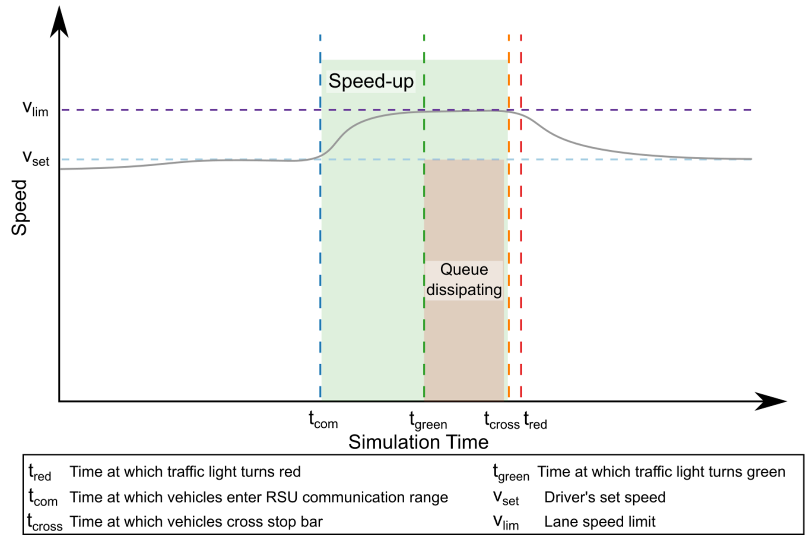
In this scenario, a TOSCo-equipped individual or string of multiple vehicles is traveling along a TOSCo-equipped corridor at a speed lower than the posted speed limit. While approaching the intersection, a dissipating queue of other, non-TOSCo vehicles is present at the stop location. The scenario is setup in a way that allows vehicles to speed up at the intersection, although of a queue of vehicles currently leaving the intersection.

4.6.1 Scenario Description and Parameters

The following two paragraphs outline the basic operation and expected behavior of TOSCo vehicles in this scenario along with a representation of parameter variations performed for this report.

4.6.1.1 Scenario Outline

This scenario is very similar to the scenario outlined in Chapter 4.3. In this scenario, however, a dissipating queue of non-TOSCo vehicles is introduced at the intersection. Figure 58 depicts the expected course of the simulation scenario and an exemplary speed diagram. Each vehicle is introduced in VISSIM at a speed close to the driver's set speed v_{set}. After the vehicle entering RSU communication range at t_{com} , the TOSCo system is activated and it decides to pass the intersection by accelerating towards the lane's speed limit v_{lim}. Once a vehicle crosses the intersection at t_{cross}, the vehicle decelerates to the driver's set speed v_{set}. In this scenario, the target stop location is changed from the stop bar to the back of queue. This updated stop location is provided by the TOSCo infrastructure component, as outlined in Chapter 2 and the TOSCo System Specification [7]. In case of the absence of a queue, the green signal duration time (green window) is simply calculated between t_{green} and t_{red}, but in this scenario, the actual green window is reduced due to the presence of a queue of other vehicles at the stop bar.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 58: Idealized Vehicle Behavior for the Speed-up with Dissipating Queue at Intersection Scenario

4.6.1.2 Parameter Variations

The purpose of this simulation scenario is to validate the intended behavior of the TOSCo system in case of vehicles speeding up to pass the intersection even if the queue affects its target stop location and actual green signal duration times. The system thereby needs to be tested in situations of different queue movements. Table 11 summarizes the parameter variations performed for the validation. Two different vehicle introduction times are set to alter the point in time the lead vehicle encounters the back of queue. Introduction time of Vehicle 1 is based on simulation runtime.

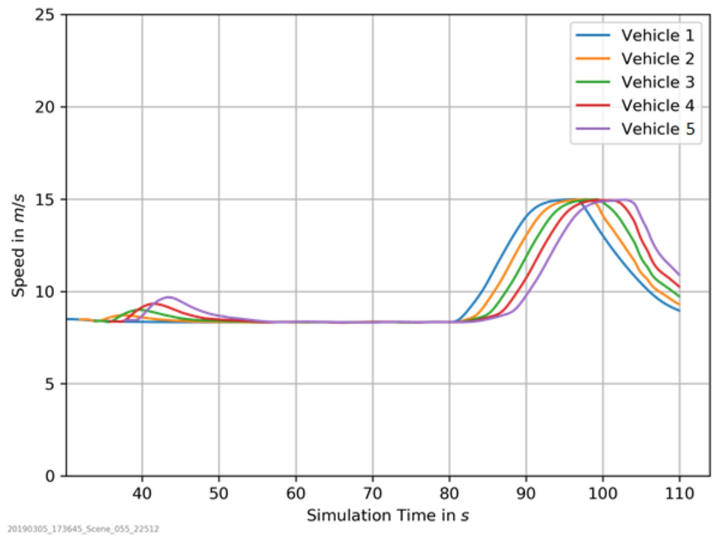
Table 11: Simulation Parameters for the Speed-up with Dissipating Queue at Intersection Scenario

Lane Speed Limit (mph)	35	
Lead Vehicle Driver's Set Speed (mph)	19	
Following Vehicles Driver's Set Speed (mph)	32	
Time Gap Settings (s)	0.6	
Vehicle 1 Introduction Time (s)	27	30

Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

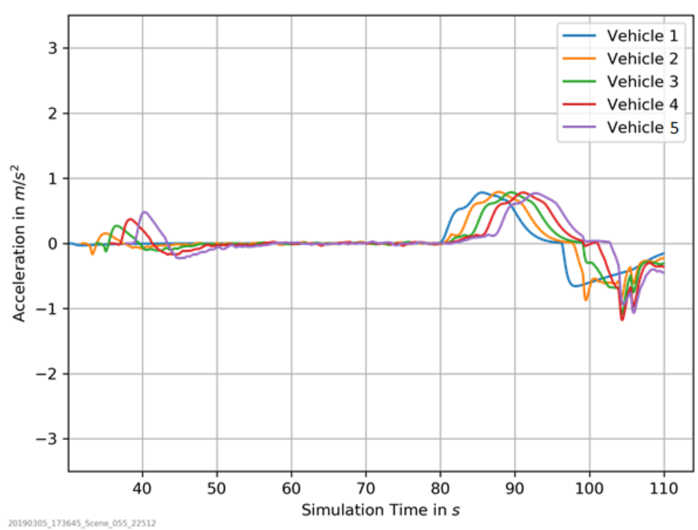
4.6.2 Analysis

Figure 59 depicts the recorded vehicle speed for each of the five TOSCo vehicles approaching the intersection over the duration of the simulation for the introduction time of Vehicle 1 at 30 s. At around 55 s simulation runtime, a stable vehicle string with a time gap of about 0.6 s has been established. Around 80 s simulation runtime, all the vehicles start to accelerate, as a result of the vehicles entering RSU communication range. The general vehicle behavior for acceleration (Figure 60) and TOSCo operating mode (Figure 61) in this setup is identical to the Speed-up Scenario as described in Section 4.3.



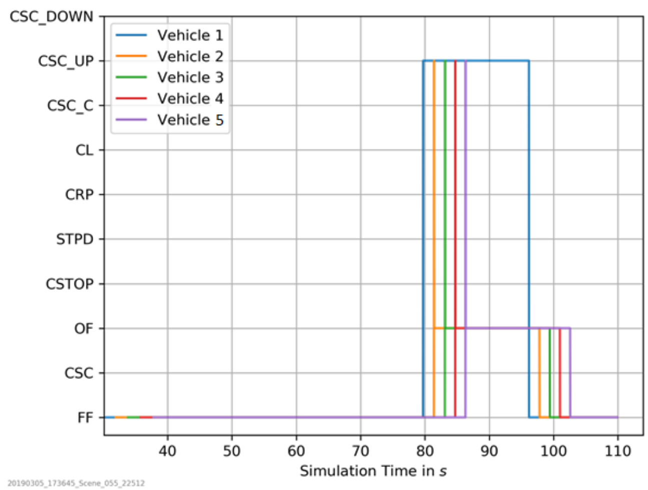
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 59: Speed-up with Dissipating Queue at Intersection Scenario: Simulation Time vs. Speed for TOSCo-enabled Vehicles for Vehicle 1 Introduction Time 30 s



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

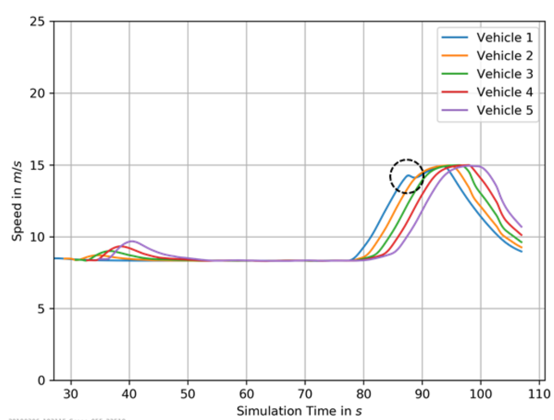
Figure 60: Coordinated Stop and Launch Scenario: Simulation Time vs. Acceleration for TOSCo-enabled Vehicles for Vehicle 1 Introduction Time 30 s



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

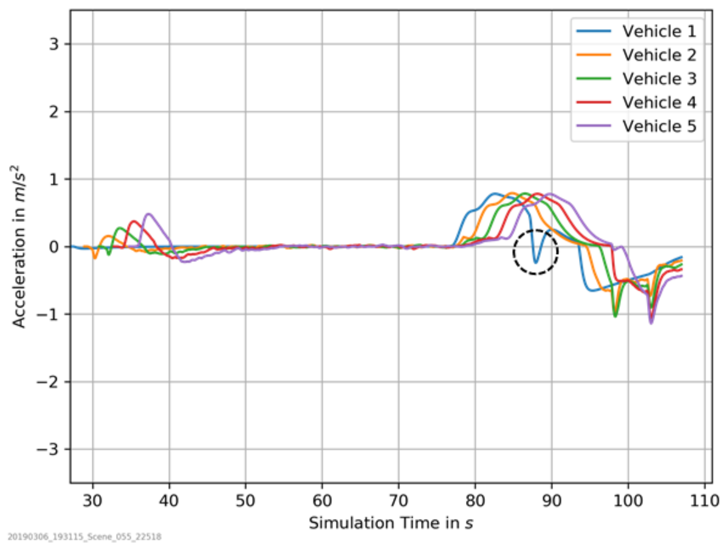
Figure 61: Speed-up with Dissipating Queue at Intersection Scenario: Simulation Time vs. Operating Modes for TOSCo-enabled Vehicles for Vehicle 1 Introduction Time 30 s

Next, the analysis focuses on the scenario in which Vehicle 1 is introduced at a simulation time of 27 s, to encounter the end of the queue earlier. Figure 62 depicts the recorded vehicle speed for each of the five TOSCo vehicles approaching the intersection. At around 50 s simulation runtime, a stable vehicle string with a time gap setting of about 0.6 s has been established. Around 80 s simulation runtime, vehicle 1 starts to accelerate as a result of selecting the CSC_UP operating mode. Around 87 s in simulation runtime, however, a slight decrease in the speed of vehicle 1 can be observed, as depicted in Figure 62 (see circled area). The associated acceleration level is highlighted in Figure 63, a moderate acceleration of -0.3 m/s^2 is recorded. In this particular setup, the presence of the queue, therefore, has little impact on the behavior of the other vehicles in the string. Figure 64 depicts the corresponding operating modes, which is almost identical to the previously described scenario.



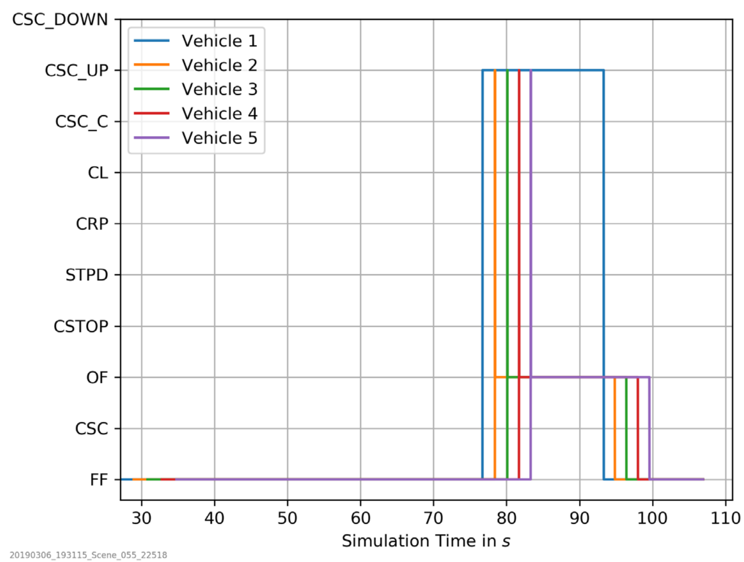
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 62: Speed-up with Dissipating Queue at Intersection Scenario: Simulation Time vs. Speed for TOSCo-enabled Vehicles for Vehicle 1 Introduction Time 27s



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 63: Coordinated Stop and Launch Scenario: Simulation Time vs. Acceleration for TOSCo-enabled Vehicles for Vehicle 1 Introduction Time 27s



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 64: Speed-up with Dissipating Queue at Intersection Scenario: Simulation Time vs. Operating-Modes for TOSCo-enabled Vehicles for Vehicle 1 Introduction Time 27s

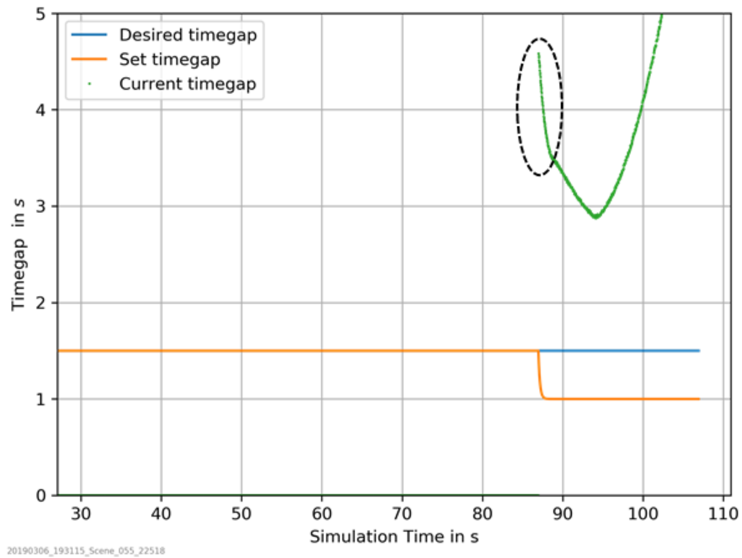
Figure 65 depicts the situation of the Simulation Scenario at the moment vehicle 1 (first yellow vehicle, TOSCo-enabled) detects the end of the queue. At this moment, vehicle 1 is approaching the intersection while accelerating. As a result of the detection of the end of queue, the CACC controller in vehicle 1 detects a large gradient in the computed time gap to the preceding vehicle, as depicted in the circled area in Figure 66.

Consequently, CACC operations causes the vehicle to deviate from the selected operating mode's corresponding *best-case* speed profile, as depicted in Figure 67 at around 87 s simulation time.

Yellow vehicle = TOSCo-enabled, Red vehicle = DSRC only

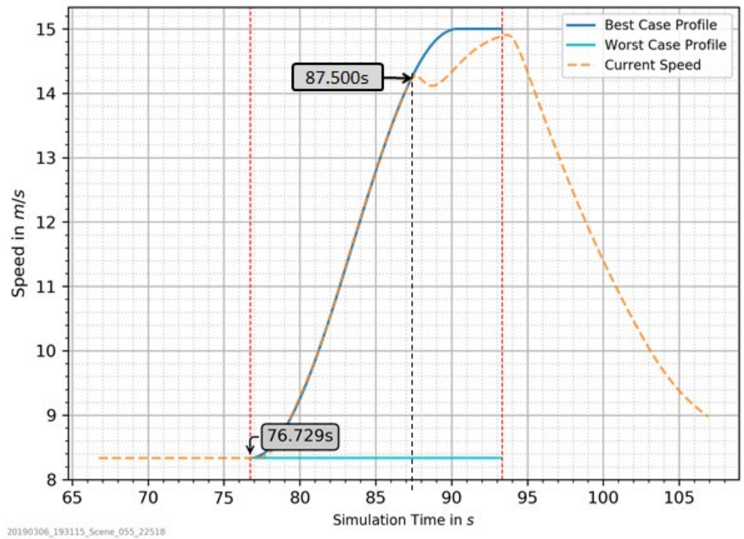
Source: Imagery ©2019 Google. Map Data ©2019 Google and Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 65: Speed-up with Dissipating Queue at Intersection Scenario: Vehicle Location Comparison between Vehicle 1 Introduction Time 27 s



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 66: Speed-up with Dissipating Queue at Intersection Scenario: Simulation Time vs. Time Gap for Vehicle 1 for Vehicle 1 Introduction Time 27s



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 67: Speed-up with Dissipating Queue at Intersection Scenario: Simulation Time vs. Computed Speed Profiles for Vehicle 1 Introduction Time 27s

4.6.3 Scenario Summary

Speed-up with Dissipating Queue at Intersection Scenario successfully demonstrates that the developed TOSCo system is able to operate in case of a queue present at the intersection. It is also shown that in case a queue is detected, the underlying CACC system can control the vehicle to deviate from its computed best-case trajectory. No further follow-up work items have been identified.

4.7 Slow-down with Dissipating Queue at Intersection Scenario

In situations when approaching vehicles might not be able to reach the green window in the presence of a dissipating queue at the intersection by maintaining their current speed or by increasing their speed, vehicles instead can choose to slow down to reach the green window without stopping at the end of the queue. The system checks if maintaining or increasing the vehicle's current speed is an option that will allow the vehicle to reach the green window. However, if this is not a feasible option, the vehicle will slow down to a speed that allows it to reach the green window without stopping at the end of the queue. In case of multiple TOSCo vehicles driving behind each other approaching the queue, the lead vehicle (vehicle 1) operates in *a coordinated speed control slow down* operating mode, while the remaining vehicles in the string ideally operate in *optimize follow* mode until they reach the green window. This scenario resembles the scenario described in Section 4.4, with the addition of a dissipating queue at the stop bar present, when the first TOSCo-enabled vehicle enters the RSU communication range.

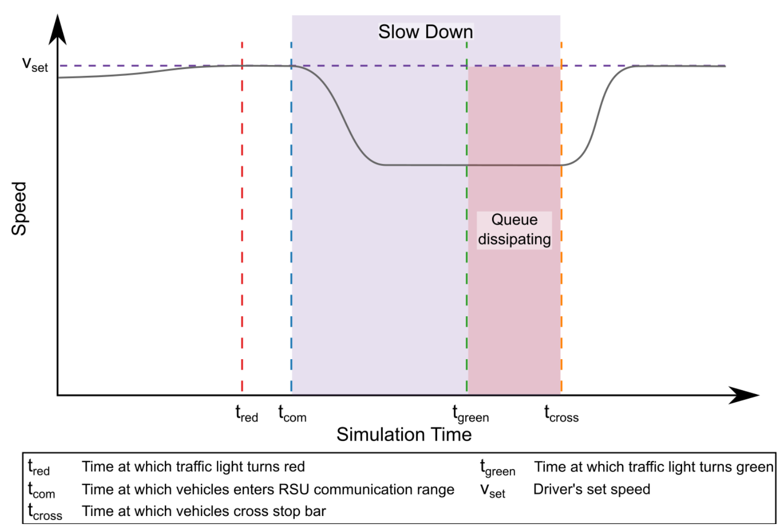
4.7.1 Scenario Description and Parameters

The following two paragraphs outline the basic operation and expected behavior of TOSCo vehicles in the current implementation of this scenario along with a representation of parameter variations performed for this report.

4.7.1.1 Scenario Outline

The Slow-down with Dissipating Queue at Intersection Scenario is set up in similar way to the Slow-down scenario (Section 4.4) but with a dissipating queue at the intersection. Non-TOSCo (but DSRC-enabled) vehicles stop at an intersection to generate a queue, resulting in a delayed green window for the TOSCo approaching vehicles. These DSRC-only vehicles then start clearing the intersection when the traffic light switched to green and the TOSCo vehicles are just entering the RSU communication range so that the lead vehicle has to slow down to reach the green window without stopping at the end of the dissipating queue. Figure 68 depicts the expected course of the simulation scenario and an exemplary speed diagram. Each TOSCo vehicle is introduced in VISSIM at a speed close to the driver's set speed v_{set}. The traffic light turns red at t_{red} before the TOSCo vehicles enter the RSU communication range at t_{com}. The scenario setup causes the vehicles to select the *Coordinated Speed Control Slow Down (CSC_DOWN)*. While the TOSCo vehicles are approaching the intersection, the traffic light turns green at t_{green}. At the same time, the DSRC-only vehicles waiting at the stop location start to move, the queue dissipates. Hence, this scenario targets the analysis of the TOSCo-system in presence of a queue, while operating in *CSC_DOWN* mode.

In the implementation of this scenario, vehicles enter the *Slow Down* operating mode upon entering the RSU communication range. In *Slow Down* Operating Mode the lead vehicle computes a predetermined target speed and a time duration for which the target speed will be maintained. After crossing the stop location, the normal CACC operation is maintained, causing the vehicles to speed up to the driver's set speed.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 68: Idealized Vehicle Behavior for the Slow-down with Dissipating Queue at Intersection Scenario

4.7.1.2 Parameter Variation

The purpose of this simulation scenario is to validate the intended behavior of the TOSCo system in case of vehicles having to slow down in the presence of a dissipating queue at the intersection. The system thereby needs to be capable of handling different approach states and queue dissipation rates when entering the RSU communication range. Table 12 summarizes the parameter variations performed for the validation. The introduction time of the first vehicle is varied as listed, resulting in different conditions, when encountering the dissipating queue. Since VISSIM only allows introduction of vehicles with a time gap of about 1 s (every other TOSCo-enabled vehicle is introduced a second after the previous vehicle), the driver's set speed of the lead vehicle of a TOSCo string is slightly below the following vehicle's set speed so that the following vehicles of the string are able to decrease their distance to the preceding vehicles to yield a time gap of less than 1s for which they need to drive faster than the lead vehicle.

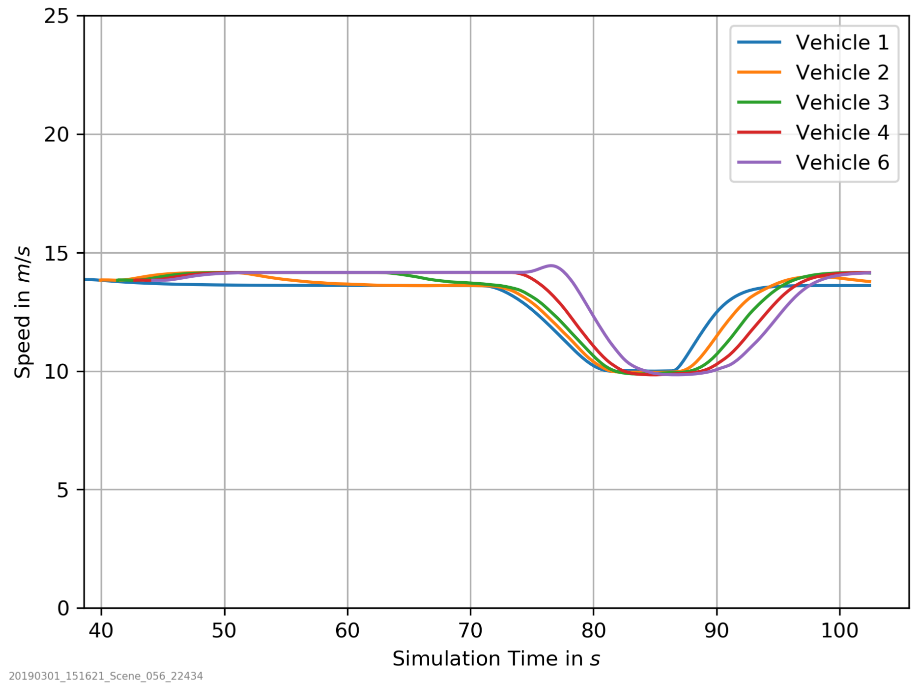
Table 12: Simulation Parameters for the Slow-down with Dissipating Queue at Intersection Scenario

Lane Speed Limit (mph)	35	
Lead Vehicle Driver's Set Speed (mph)	31	
Following Vehicles Driver's Set Speed (mph)	32	
Time gap Settings (s)	0.6	
Minimum Cruising Speed or Target Speed (% of the speed limit)	70%	
Introduction Time of Vehicle 1 (simulation time in s)	32	39

Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

4.7.2 Analysis

In the simplest setup, an approaching string of vehicles does not need to adapt to the queue present at the stop location at all. Figure 69 resembles the same slow-down behavior as described in Section 4.4, although the approaching vehicle string is influenced by a queue at the stop location.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 69: Slow-down with Dissipating Queue at Intersection Scenario: Simulation Time vs. Speed for TOSCo-enabled Vehicles at 0.6 s Time Gap at Vehicle 1 Introduction Time of 39 s

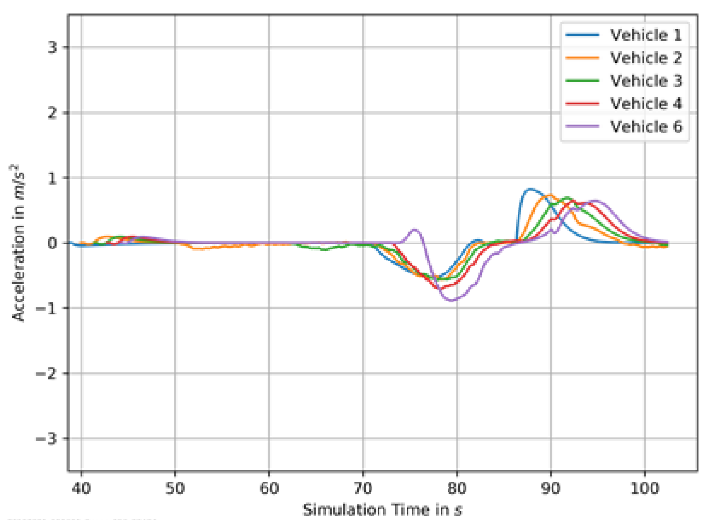
(a) Traffic scenario just before the traffic light turns green at 80 s

(b) Traffic scenario about four seconds after the traffic light turned green

Yellow vehicle = TOSCo-enabled, Red vehicle = DSRC only

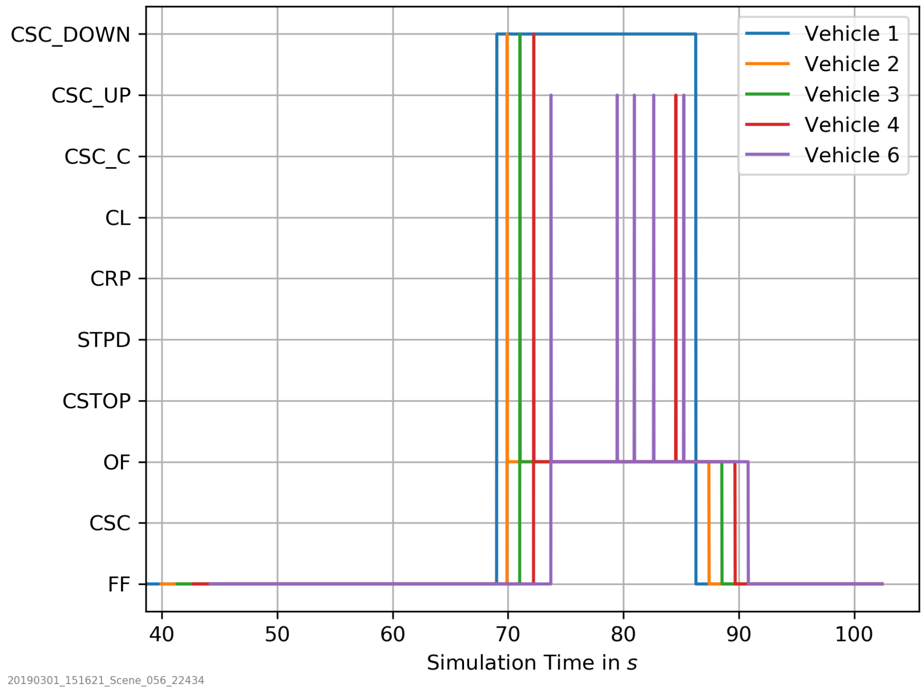
Source: Map data © 2018 Google and Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 70: Slow-down with Dissipating Queue at Intersection Scenario: Traffic Scenarios Screenshots for Vehicle 1 Introduction Time of 39 s



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

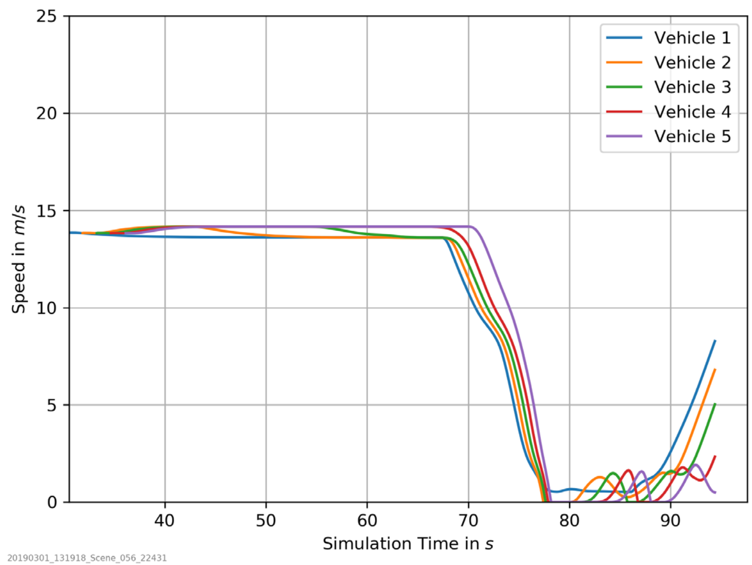
Figure 71: Slow-down with Dissipating Queue at Intersection Scenario: Simulation Time vs. Acceleration for TOSCo-enabled Vehicles at 0.6 s Time Gap at Vehicle 1 Introduction Time of 39 s



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

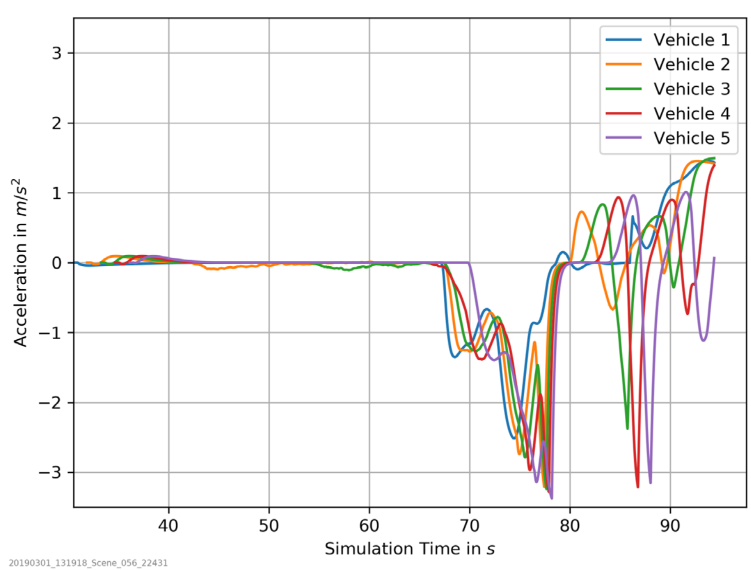
Figure 72: Slow-down with Dissipating Queue at Intersection Scenario: Simulation Time vs. TOSCo Operating Mode for TOSCo-enabled Vehicles at 0.6 s Time Gap at Vehicle 1 Introduction Time of 39 s

Figure 70 depicts the corresponding scenario at different points in time, just before the traffic light turns green (a) and about four seconds after (b). In conjunction with the speed diagram in Figure 69, and by comparing it with the behavior for the corresponding scenario without a queue present in Figure 40, it is apparent that for this scenario setup the vehicles are not influenced by the presence of a queue at the stop location. A re-computation of the corresponding speed profiles is not required as the traffic light is already green when the first set of profiles is generated. This results in similar acceleration (Figure 71) and TOSCo-operating mode diagrams (Figure 72) compared to the scenario detailed in Section 4.4.



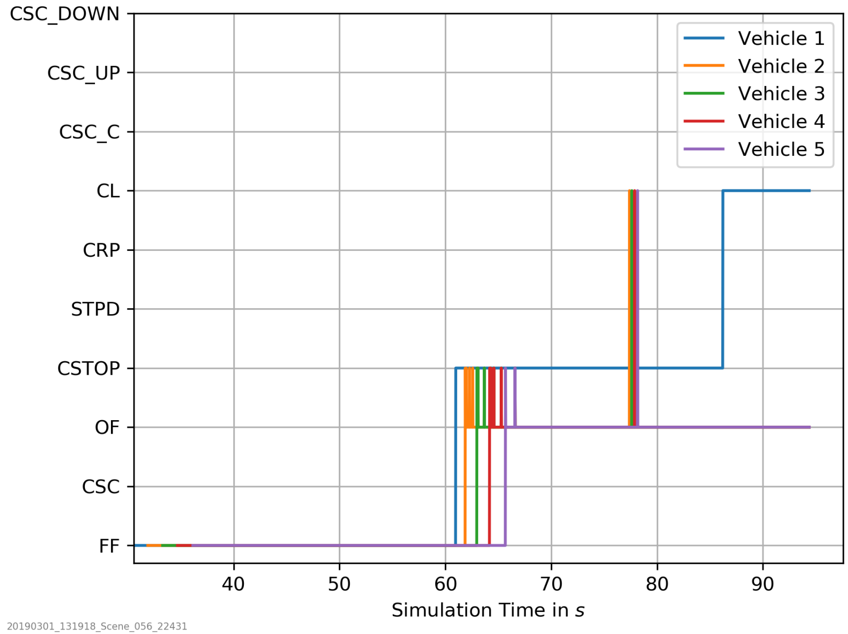
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 73: Slow-down with Dissipating Queue at Intersection Scenario: Simulation Time vs. Speed for TOSCo-enabled Vehicles at 0.6 s Time Gap at Vehicle 1 Introduction Time of 32 s



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 74: Slow-down with Dissipating Queue at Intersection Scenario: Simulation Time vs. Acceleration for TOSCo-enabled Vehicles at 0.6 s Time Gap at Vehicle 1 Introduction Time of 32 s

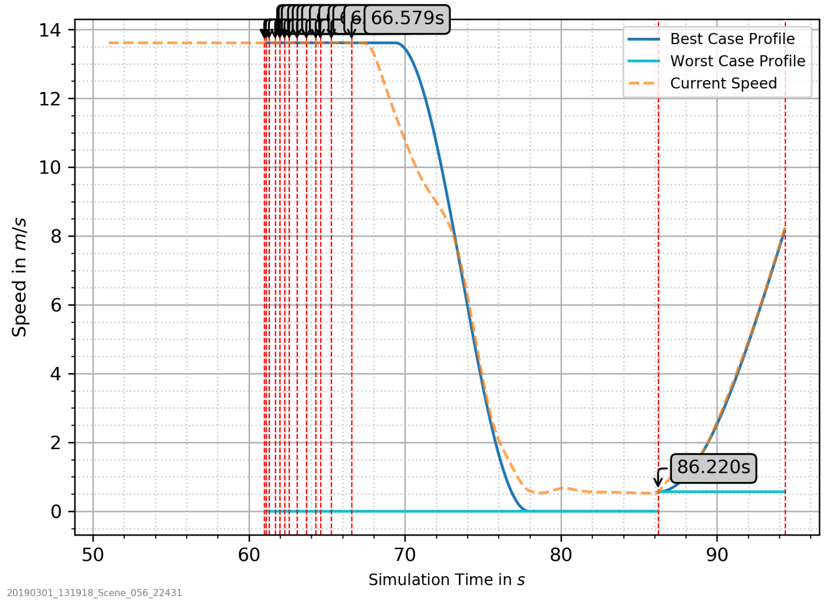


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 75: Slow-down with Dissipating Queue at Intersection Scenario: Simulation Time vs. TOSCo Operating Mode for TOSCo-enabled Vehicles at 0.6 s Time Gap at Vehicle 1 Introduction Time of 32 s

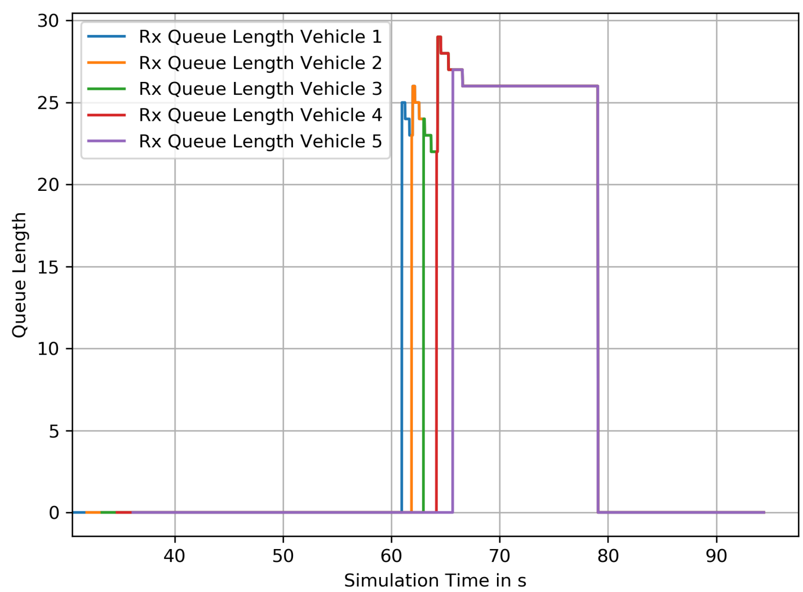
When changing the introduction time of the first vehicle so that the string arrives earlier at the intersection as compared to the previous scenario, the queue is perceived as stationary for a longer time, hence causing the vehicles to enter the *coordinated stop* mode as opposed to *slow down*. Figure 73 depicts the corresponding observed vehicle speeds in this scenario while the corresponding operating modes are shown in Figure 75. As soon as the RSU communication range is entered, several re-computations of the speed profiles occur.

While approaching the stopped queue and coming closer to a stop themselves, the TOSCo vehicles are toggling between the CSTOP and OF mode. This is a result of the infrastructure component cyclically updating the green window and the queue length, as shown in Figure 77. Upon receiving an updated green window information, the speed profiles are re-computed, as detailed in [7]. Cyclic regeneration of profiles can be observed in Figure 76, in which a re-computation occurs for every vertical red line. When the queue of DSRC-only vehicles is stationary after about 66 s, no further re-computations are required.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 76: Slow-down with Dissipating Queue at Intersection Scenario: Simulation Time vs. Computed Speed Profiles for Vehicle 1 for 0.6 s Time Gap and Vehicle 1 Introduction Time of 32 s



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 77: Slow-down with Dissipating Queue at Intersection Scenario: Simulation Time vs. Reported Queue Length for TOSCo-enabled Vehicles at 0.6 s Time Gap at Vehicle 1 Introduction Time of 39 s

(a) Traffic scenario at around 62 s, queue is building up

(b) Traffic scenario when the traffic light just turned green, queue stationary

Yellow vehicle = TOSCo-enabled, Red vehicle = DSRC only

Source: Map data © 2018 Google and Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 78: Slow-down with Dissipating Queue at Intersection Scenario: Traffic Scenarios Screenshots for Vehicle 1 Introduction Time of 32 s

While approaching the intersection, between around 61 s to around 66 s, the queue length is cyclically updated (see Figure 77) as a result of the last DSRC-only vehicle (red) creeping towards the end of the queue, as depicted in Figure 78 (a). A few seconds later, at around 75 s, when the traffic light turns green (Figure 78 (b)), the queue starts to dissipate. Vehicle 1, however, continues to creep towards the end of the queue at around 79 s. Note that the TOSCo Creep Mode is not entered as the vehicle is still operating within its solution space of the computed CSTOP profile and no trigger occurs to re-compute a profile when a queue of preceding vehicle disperses has been defined in the TOSCo Mode Selection [7]. While vehicle 1 is creeping towards the end of the queue, the CACC system of the following vehicles brings those to a full stop instead. As soon as the following vehicle's speed drops below the standstill speed threshold (-0.1 m/s), the CLAUNCH profile is computed, as indicated in Figure 75 at around 77 s. CACC operations also becomes apparent in Figure 74, in which maximum deceleration levels of -3 m/s^2 are exceeded.

As stated above, vehicle 1 is still creeping forward although its following vehicles already entered CLAUNCH at around 77 s as a result of their speed dropping below the standstill-speed threshold. This is an unintended behavior since all vehicles, including the first one, should speed up once the queue dissipates. The reason for this behavior, however, is the specification of the mode selection [7], in which a transition to a *coordinated launch* operating mode is only allowed once a vehicle's speed drops below the standstill speed threshold of 0.1 m/s, which is not the case for vehicle 1 until around 86 s (see also Figure 76 for more details) which coincides with the point in time its currently followed CSTOP profile ends.

4.7.3 Scenario Summary

This scenario is targeted at demonstrating that the TOSCo-system is capable of operating when approaching a queue of vehicles in front of the traffic light. For this analysis, different arrival times of the TOSCo-string at the end of the queue have been simulated.

The following work-item was identified:

- In case a queue brings a vehicle to a complete stop (i.e., the resulting green window because of a queue present at a stop location is decreased), traffic conditions may arise in which the lead TOSCo vehicle creeps towards the end of the queue before attempting to stop. If in this scenario, while creeping towards the end of the queue, the last queued vehicle starts to accelerate at a time at which the first TOSCo-vehicle has not yet reached the minimum speed threshold required to enter a *coordinated launch* mode, or any other appropriate mode, undefined system behavior results. Even though the TOSCo-system is able to detect that the preceding vehicle is departing (and a speed up may be possible), the system remains in the current mode as a corresponding re-computation transition has not been defined in the TOSCo Mode Selection [7]. Consequently, follow-up work has to define mechanisms that allows approaching vehicles to speed up (or change the selected TOSCo operating mode) in case of a preceding vehicle departing, hence changing the conditions for the resulting solution space.

4.8 Coordinated Stop and Launch with Dissipating Queue at Intersection Scenario

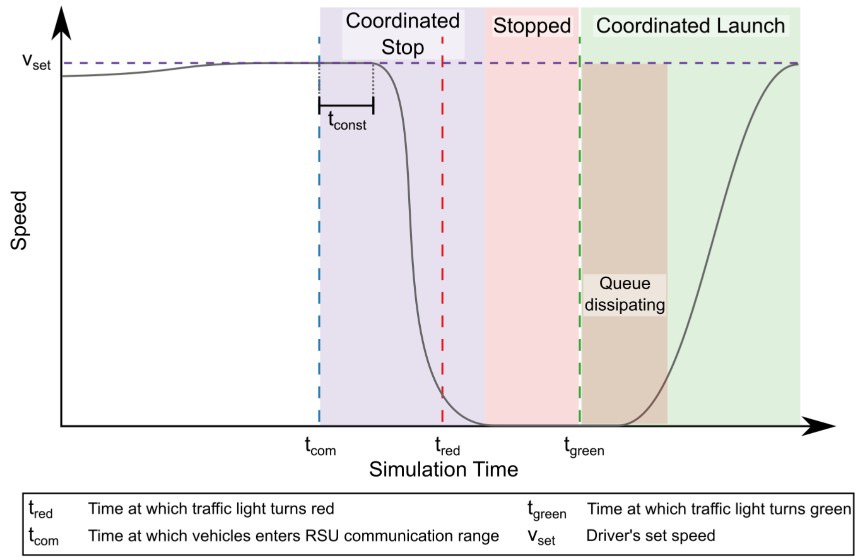
TOSCo-equipped vehicles are traveling along a TOSCo-equipped corridor as defined in Section 4.5. In addition to the scenario description outlined in Section 4.5, a queue of DSRC-only vehicles is present, thereby changing the stop location compared to the reference scenario. As before, TOSCo-equipped vehicles perform a coordinated launch when the queue dissipates.

4.8.1 Scenario Summary and Parameters

The following sections summarize the basic operation and expected the behavior of TOSCo-vehicles in this scenario.

4.8.1.1 Scenario Outline

Figure 79 depicts the expected course of the simulation scenario and an exemplary speed diagram. Each TOSCO vehicle is introduced in VISSIM at the speed close to the driver’s set speed (v_{set}). A string of DSRC vehicles is introduced to create a queue at the intersection. After the TOSCo-equipped vehicles enter RSU communication range at t_{com}, they receive SPAT-messages and the TOSCo system is able to transition from FREE_FLOW to an applicable operating mode, as detailed in [7]. In this scenario, the TOSCo vehicles select the CSTOP operating mode after comparing the current green window with the time of arrival. The computed CSTOP speed profile includes a duration of t_{const} to maintain the vehicle’s current speed until the point that they are required to decelerate to come to a full stop. During CSTOP, when the vehicle’s speed is below the standstill speed threshold, the vehicle enters the STOPPED mode. When the traffic light turns green at t_{green}, the queue dissipates and the TOSCo vehicles select the CLAUNCH operating mode.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 79: Idealized Vehicle Behavior for the Coordinated Stop and Launch with Dissipating Queue at Intersection Scenario

4.8.1.2 Parameter Variation

The purpose of this simulation scenario is to validate the intended behavior of the TOSCo system in case vehicles need to come to a full stop behind the end of a queue. The scenario is identical to the Coordinated Stop and Launch scenario with stopped DSRC-equipped vehicles at the intersection when the TOSCo-equipped vehicles arrive. In order to assess the influence of a queue presence at the stop location, this scenario is simulated with only one set of parameters, as outlined in Table 13.

Table 13: Simulation Parameters for the Coordinated Stop and Launch with Dissipating Queue at Intersection Scenario

Lane Speed Limit (mph)	35
Lead Vehicle Driver’s Set Speed (mph)	31
Following Vehicles Driver’s Set Speed (mph)	32
Time gap Setting (s)	0.6

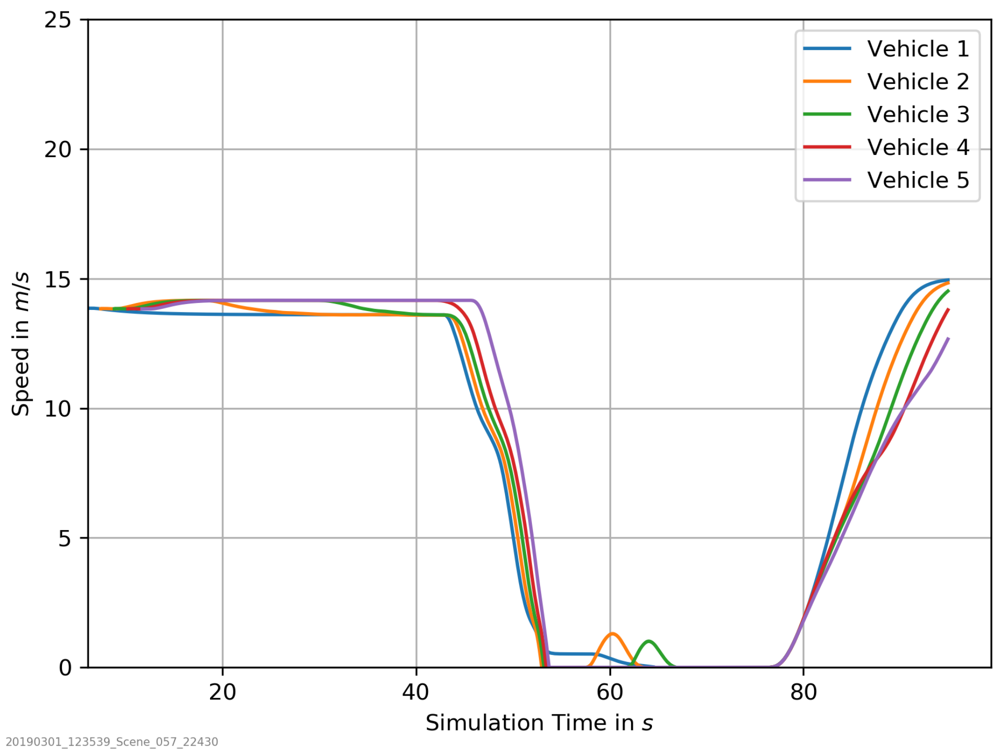
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

4.8.2 Analysis

As depicted in Figure 80, the TOSCo vehicles are entering the RSU communication range at around 37 s. At this point in time, a stable string has not yet been established due to VISSIM only allowing vehicles to be introduced at a time gap of 1 s. The TOSCo vehicles enter the CSTOP operating mode at around 40 s, as depicted in Figure 82. The first TOSCo vehicle’s deceleration at around 45 s results in the time gaps of vehicles 4 and 5 to further decrease. As shown at around 43 s in Figure 83, the detected queue length is constant as a result of the queue of DSRC vehicles coming to a full stop. As the TOSCO vehicles are still approaching the now stationary queue, the rate of change of the time gap between the first TOSCo vehicle and the end of the queue rapidly increases, causing the underlying CACC-system to decelerate appropriately. This effect propagates down the string and can be observed in Figure 80 at around 43 s.

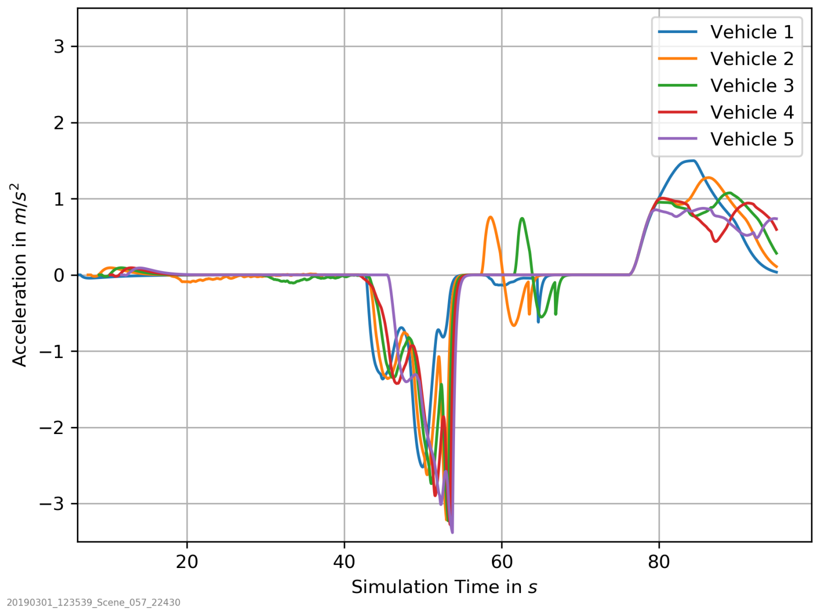
All but the first TOSCo vehicle come to a full stop at around 57 s. Due to CACC operations, the first TOSCo vehicle creeps towards the end of the queue without entering the TOSCO CREEP operating mode as the vehicle's actual speed is still within the applicable solution space of the previously selected CSTOP operating mode. Vehicle 1 comes to a full stop at around 62 s when the minimum distance to a preceding target is reached. While vehicle 1 creeps towards the end of the queue, its distance from the already stopped TOSCo vehicle 2 increases. When vehicle 2's minimum distance to the preceding object (first TOSCo vehicle) exceeds the minimum standstill distance threshold at around 59 s, vehicle 2 is able to also creep forward by selecting the CREEP operating mode, as depicted in Figure 82. The same effect is present in vehicle 3 at around 60 s simulation time. For vehicles 4 and 5, this threshold is never reached as the distance between each TOSCO vehicle progressively decreases down the string. The latter is a result of all vehicles attempting to follow identical computed *best-case* speed profiles. However, CACC operation overrides the requested TOSCO acceleration, causing the vehicles to decelerate by progressively harsher amounts, as depicted in Figure 81.

At around 78 s, when the green window starts as a result of the traffic light switching to green, the TOSCo vehicles perform a coordinated launch maneuver, as detailed in Section 4.5.



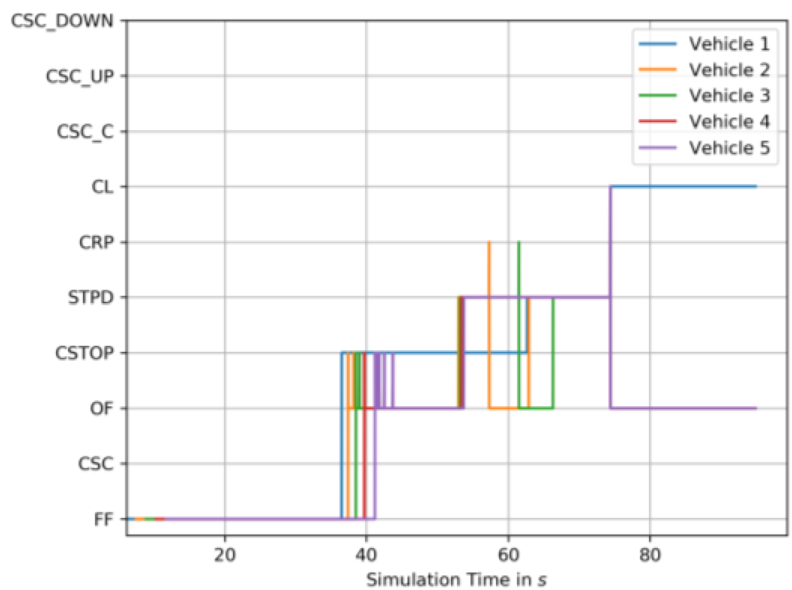
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 80: Coordinated Stop and Launch with Dissipating Queue at Intersection Scenario: Simulation Time vs. Speed for TOSCo-enabled Vehicles at 35 mph Speed Limit



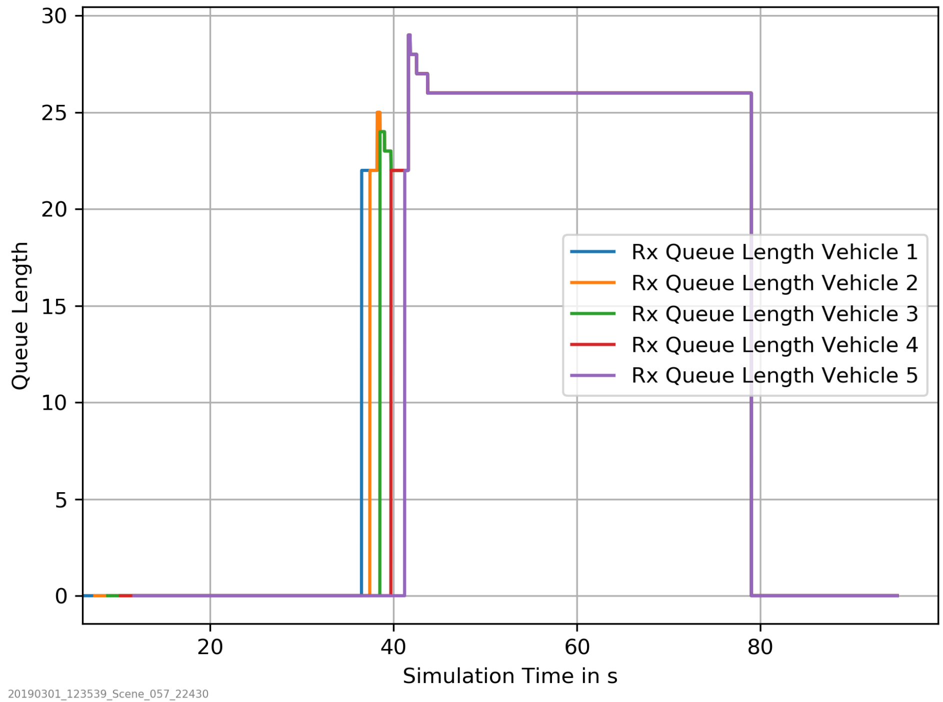
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 81: Coordinated Stop and Launch with Dissipating Queue at Intersection Scenario: Simulation Time vs. Acceleration for TOSCo-enabled Vehicles at 35 mph Speed Limit



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 82: Coordinated Stop and Launch with Dissipating Queue at Intersection Scenario: Simulation Time vs. Operating-Modes for TOSCo-enabled Vehicles at 35 mph Speed Limit



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 83: Coordinated Stop and Launch with Dissipating Queue at Intersection Scenario: Simulation Time vs. Reported Queue Length for TOSCo-enabled Vehicles at 0.6s Time Gap

4.8.3 Scenario Summary

This scenario demonstrates the TOSCo system's ability to come to a full stop behind a stopped queue of non-TOSCo vehicles. It is shown that CACC-operations may cause vehicles to deviate from their computed corresponding *best-case* speed profiles while approaching the end of the queue.

4.9 Creep at Intersection Scenario

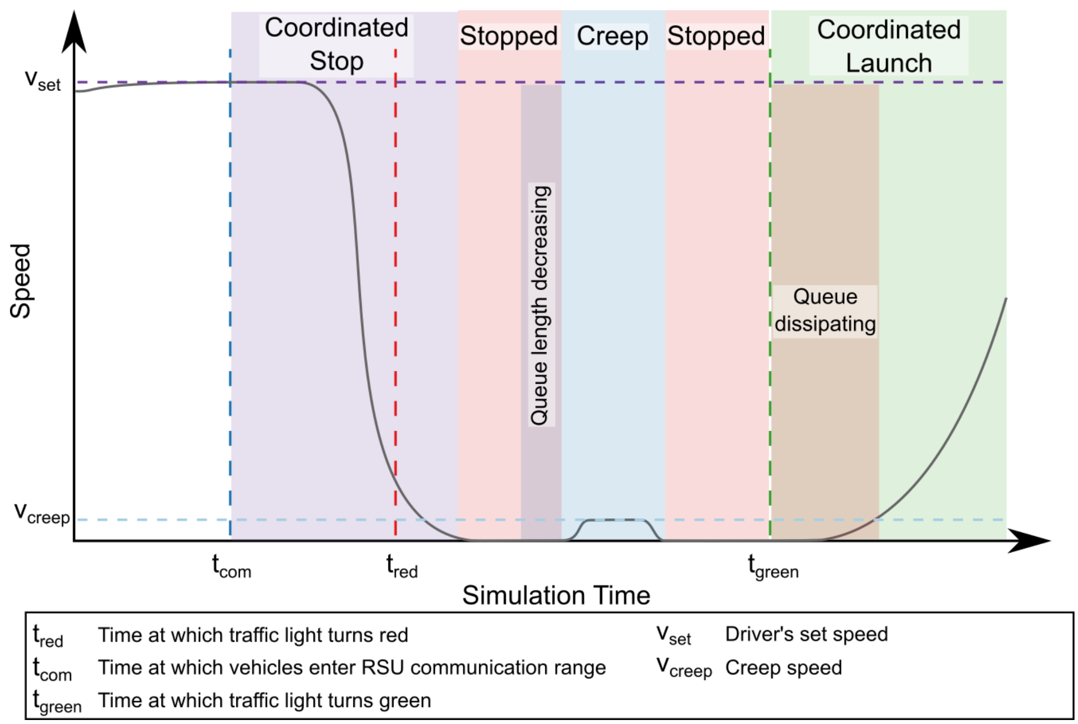
This section provides a description of the simulation results for vehicles travelling in CREEP towards an intersection. As detailed in the description of the TOSCo mode selection [7], while the vehicle is in the STOPPED mode and the preceding queue partially or fully dissipates, the vehicle creeps forward to close the distance gap between itself and its current target stop location in order to optimize the use of the roadway for large amounts of traffic.

4.9.1 Scenario Description and Parameters

The following section outlines the basic operation and expected behavior of TOSCo vehicles in this scenario along with a representation of parameter variations performed for this report.

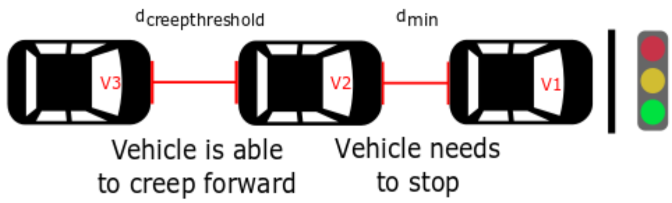
4.9.1.1 Scenario Outline

The Creep at Intersection Scenario is set up in a way that approaching TOSCo vehicles will have to come to a full stop. Figure 84 depicts the expected course of the simulation scenario and an exemplary speed diagram. Each vehicle is introduced in VISSIM at a speed close to the driver's set speed v_{set}, and a string of DSRC-equipped vehicles is introduced in order to generate a queue at the intersection. After entering RSU communication range at t_{com}, the traffic light turns red at t_{red}. Whenever a vehicle enters the communication range at t_{com} and, therefore, receives SPaT-messages, the TOSCo system is activated as detailed in [7]. At that point in time in this scenario, each vehicle will determine that it has to come to a full stop in front of the existing queue. All vehicles enter CSTOP and enter STOPPED behind their respective stopping distances. Afterwards, one of the DSRC-equipped vehicles makes a right turn on red, decreasing the queue length. The other DSRC-equipped vehicles move forward as controlled by VISSIM's internal driver model, and the TOSCo-enabled vehicles consecutively enter CREEP once each vehicle's distance to its immediate target increases beyond a threshold, $d_{creepthreshold}$.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 84: Idealized Vehicle Behavior for the Creep at Intersection Scenario



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 85: Relative Vehicle Distances for the Creep at Intersection Scenario

When in CREEP, each TOSCo vehicle speeds up to v_{creep} in order to move to its current target stop location, as each vehicle reaches within its minimum stopping distance, d_{min}, the vehicles return to STOPPED. At t_{green}, the DSRC-equipped queue accelerates and all TOSCo vehicles enter CLAUNCH. Figure 85 depicts vehicle v1 at the stop bar, with two vehicles behind; vehicle v3 is separated by distance $d_{creepthreshold}$ from its preceding vehicle. Once the separation between vehicle v3 and v2 exceeds $d_{creepthreshold}$, the vehicle v3 will be able to enter the CREEP operating mode. vehicle v2 is a distance d_{min} from its preceding vehicle; while vehicle v2 is in motion and the distance to its target v1 drops below the minimum stopping distance, d_{min}, vehicle v2 needs to come to a stop.

4.9.1.2 Parameter Variations

The purpose of this simulation scenario is to verify the intended behavior of the TOSCo system in the CREEP mode. The system thereby needs to be capable of maintaining distance gap control while the vehicle moves to its new target stop location. Table 14 summarizes the parameter variations performed for the validation. Two different sets of distance gaps $d_{creepthreshold}$ and d_{min} are selected in order to test TOSCo's CREEP mode functionality at different distance gaps. For each set of distance gaps, the scenario was run at various time gap settings.

Table 14: Simulation Parameters for the Creep at Intersection Scenario

$\mathbf{d_{creepthreshold}}$ (m)	10 [8]			7 [9]		
$\mathbf{d_{min}}$(m)	5			3.5		
Time gap Settings (s)	0.6	1.0	1.5	0.6	1.0	1.5

Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

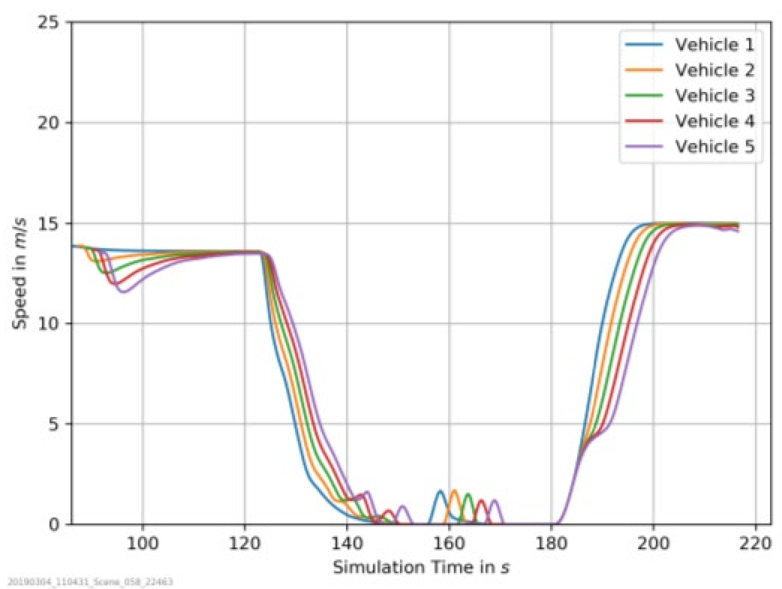
[8] This is known throughout the rest of this report as the "large distance gap."

[9] This is known throughout the rest of this report as the "short distance gap."

4.9.2 Analysis

The following analysis focuses on the results of the two extremes of the simulation parameters for this scenario: a time gap setting of 0.6 s with a short distance gap and a time gap setting of 1.5 s with a long distance gap. Further plots for other parameter sets are depicted in APPENDIX C.

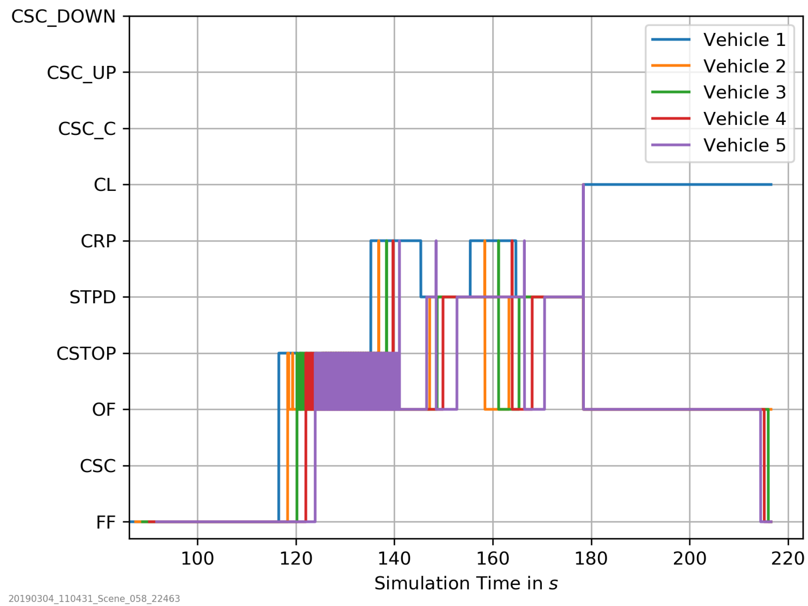
Figure 86 depicts the recorded vehicle speed for each of the five TOSCo vehicles approaching the intersection over the duration of the simulation with the time gap setting of 1.5 s and a set of long distance gap parameters. At around 118 s simulation runtime, vehicle 1 enters RSU communication range and enters CSTOP, vehicles 2-5 enter OF as they enter RSU communication range, and all TOSCo-enabled vehicles enter STOPPED after following their respective CSTOP profiles. Due to VISSIM only allowing vehicles to be introduced at a time gap of 1 s into the scenario, the first 118 seconds are used to both introduce the vehicles at a proper time in order for the TOSCo vehicles to approach the intersection as a non-TOSCo queue builds up at the intersection and establish the desired time gap of 1.5 s. The TOSCo vehicles would enter STOPPED at 135 s as they reach speeds below the creep speed threshold $\mathrm{v_{creep}}$; however, they each check to see if $\mathrm{d_{creepthreshold}}$ is met. Vehicle 1 enters CREEP with the following TOSCo vehicles also entering CREEP accordingly to within $\mathrm{d_{min}}$ of their respective targets. After the TOSCo string comes to a stop behind a DSRC-only string, the lead vehicle of the DSRC string makes a right turn while the signal phase is red. The remaining DSRC vehicles manually pull up to the stop bar or their respective stop locations by using VISSIM's internal driver model. As the lead TOSCo vehicle's fused object distance reaches more than the set $\mathrm{d_{creepthreshold}}$ at approximately 157 s, the vehicle again satisfies the condition to enter CREEP in the mode selection and accelerates up to 1.5 m/s. As the first TOSCo vehicle moves away from the next TOSCo-enabled vehicle, the condition to enter CREEP is satisfied for each consecutive vehicle and all TOSCo-enabled vehicles creep to their target stop locations. Once the green phase begins at 179 s, the TOSCo vehicles enter CL after the DSRC string launches.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 86: Creep at Intersection Scenario: Simulation Time vs. Speed for TOSCo-enabled Vehicles at 1.5 s Time Gap with Large Distance Gap

Figure 87 shows the operation of the TOSCo-enabled vehicles as they approach and depart the intersection. At approximately 135 s simulation time, vehicle 1 switches to CREEP from CSTOP, with vehicles 2-5 momentarily switching to CREEP consecutively shortly after. These vehicles check for a preceding TOSCo vehicle and switch to OF immediately. At 157 s, vehicle 1 again satisfies the conditions to reenter CREEP, with the other TOSCo vehicles consecutively entering CREEP.



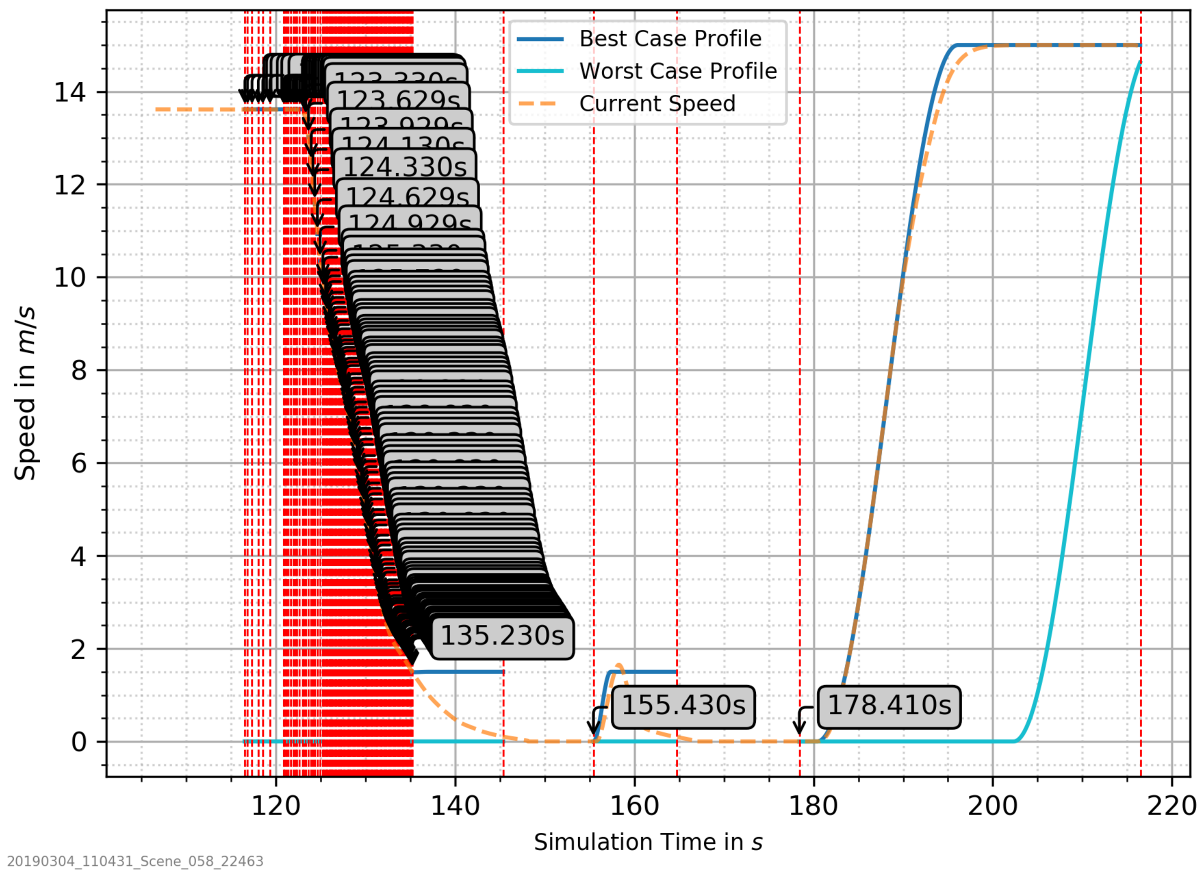
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 87: Creep at Intersection Scenario: Simulation Time vs. Operating Mode for TOSCo-enabled Vehicles at 1.5 s Time Gap with Large Distance Gap

At 179 s, all vehicles enter CL. Between 119 s and 141 s, vehicles 2-5 continuously fluctuate between the OF mode and both CSTOP followed by CREEP as they satisfy the condition for the latter and recalculate their respective speed profiles. The vehicles continuously recomputed their speed profiles due to fluctuations in the data outputted by the infrastructure, this fluctuation has insignificant effects on the behavior of the system as is detailed in Section 4.8.

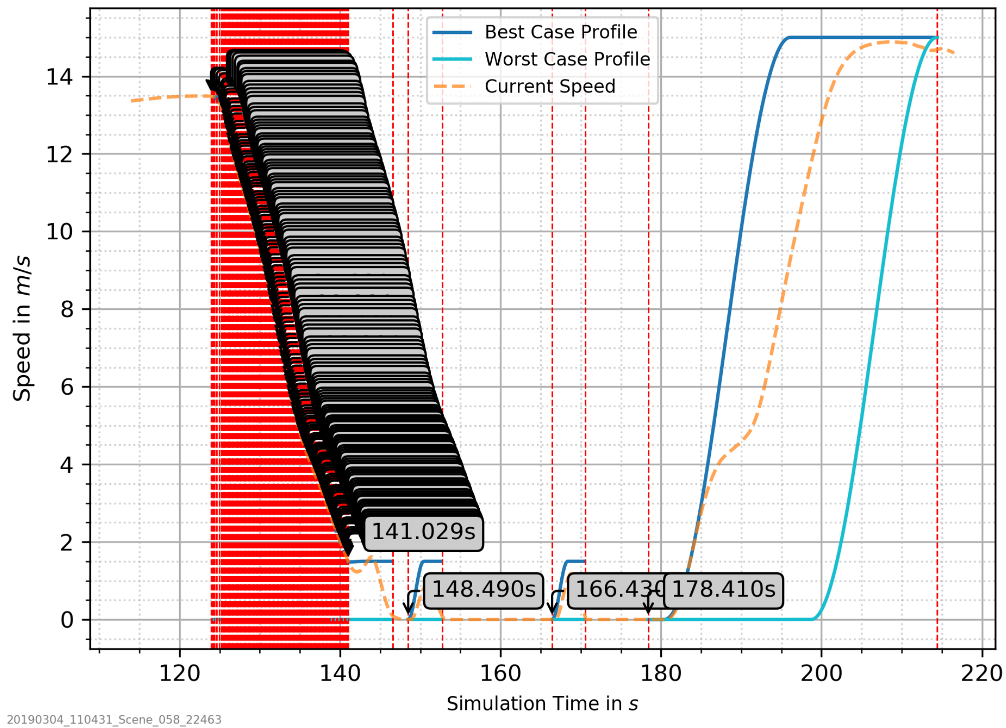
Figure 88 and Figure 89 show the *best-case* and *worst-case* speed profiles as well as the actual speed for vehicles 1 and 5, in order to view the progressive effects down the string in CREEP mode. In addition, these figures depict the points in time at which the system recalculates its speed profiles due to an external conditions check. The numerous vertical red lines in Figure 88 show that vehicle 1 continuously recalculates its speed profiles, similarly to vehicles 2-5 as shown in Figure 87 between 120s and 140s simulation time. As vehicle 1 is the leader of the string, it does not switch between OF and CSTOP. In Figure 88 at 138 s, vehicle 1 would enter STOPPED but instead checks for and enters CREEP. This is evident due to the existence of a computed *best-case* and *worst-case* speed profiles, depicted by dark and light blue lines, respectively. Vehicle 1's speed profile is a smooth, monotonically decreasing function, as shown when vehicle 1 transitions from time-gap-based speed control to distance-based speed control, the distance to its target, the DSRC string, is large. The following TOSCo vehicles, however, transition from time-gap based to a distance-based speed control with a much lower distance from their respective fused objects, giving a small perturbation into the respective speed profiles. As each vehicle in the string progressively gets slower, this effect amplifies down the string, to the point at which vehicle 5 (depicted in Figure 89) comes to a stop. In Figure 89, vehicle 5 is shown to come to a stop at 141 s, and reenters CREEP at 148 s as its fused object distance increases when vehicle 4 moves forward, again satisfying the conditions for CREEP.

After the DSRC queue partially dissipates, vehicle 1's distance to its target changes, and vehicle 1 recalculates a set of target speed profiles for CREEP at 155.430 s. All vehicles correctly choose a speed profile within the solution space created by the *best-case* and *worst-case* speed profiles, and creep to their respective stop locations.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

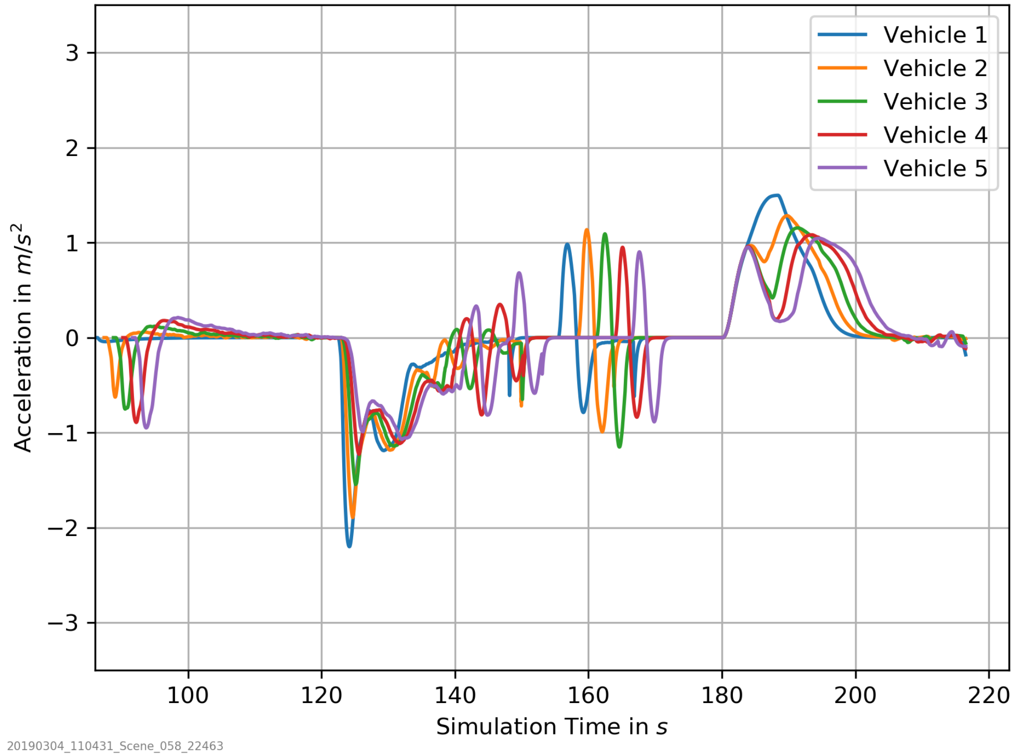
Figure 88: Creep at Intersection Scenario: Vehicle 1 Requested and Actual Speed Profiles at 1.5 s Time Gap with Large Distance Gap



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 89: Creep at Intersection Scenario: Vehicle 5 Requested and Actual Speed Profiles at 1.5 s Time Gap with Large Distance Gap

Figure 90 shows the acceleration of the TOSCo-enabled vehicles as they approach and depart the intersection. As the TOSCo vehicles enter the CREEP mode at approximately 135 s simulation time, each vehicle maintains acceleration in order to reach their respective stop locations. It is of note that the vehicles' accelerations at this point slightly increase down the TOSCo string but not to significant values. At 142 s, vehicles 4 and 5 accelerate again in order to maintain their respective distance gaps in CREEP. At 157 s, all TOSCo vehicles enter CREEP as the DSRC queue partially dissipates Vehicle 1 accelerates to 1 m/s^2, vehicle 2 accelerates to 1.1 m/s^2 and vehicles 3-5 accelerate to progressively decreasing amounts down the string. Accelerations down the string decrease because each vehicle is following another vehicle that is travelling along a TOSCo profile. Vehicle 1's acceleration profile is based upon following the DSRC vehicles that are controlled by the VISSIM driver model and each following vehicle's acceleration is based upon following its respective preceding vehicle, which is TOSCo enabled. At approximately 180 s simulation time, vehicles enter CLAUNCH. Further details regarding CLAUNCH behavior are described in Section 4.5.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 90: Creep at Intersection Scenario: Simulation Time vs. Acceleration for TOSCo-enabled Vehicles at 1.5 s Time Gap with Large Distance Gap

Figure 91 depicts the recorded vehicle speed for each of the five TOSCo vehicles approaching the intersection over the duration of the simulation with a 0.6 second time gap and a small distance gap. Figure 91 also shows no significant difference from Figure 86 in the transitional behavior between CSTOP and CREEP, where the vehicles switch from a time-gap-based speed control to a distance-based gap speed control at approximately 140 s simulation time. It can be then inferred that set time gap does not have a significant effect on the functionality of the CREEP operating mode. Along the string, the same speed profile is generated for all vehicles but each vehicle can only follow the *best-case* speed profiles to diminishing degrees due to the presence of a preceding vehicle. This effect is more pronounced for this short distance gap parameter set. This can be shown from 158-170 s in Figure 91.

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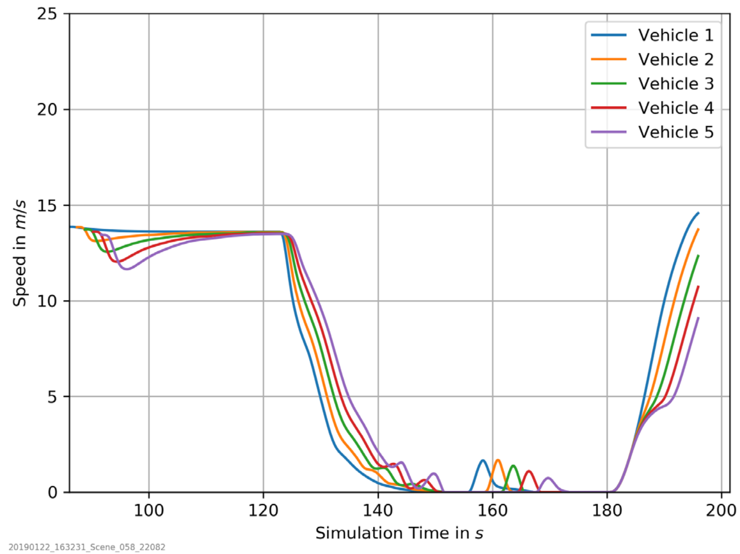
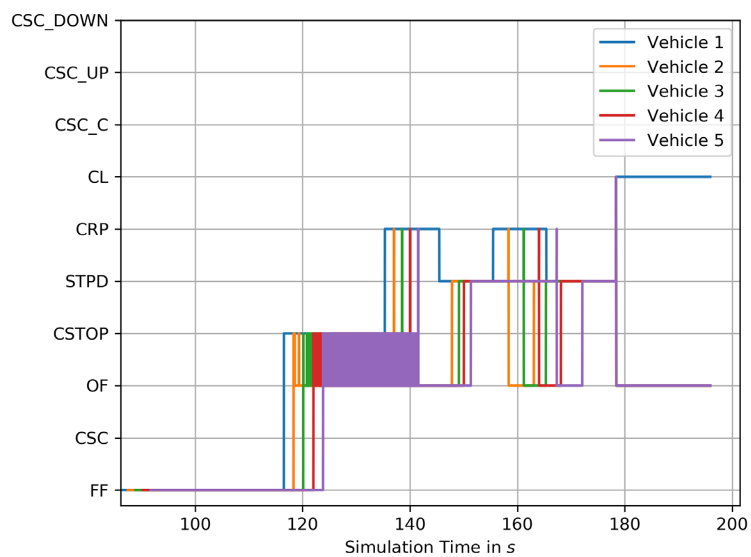


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 91: Creep at Intersection Scenario: Simulation Time vs. Speed for TOSCo-enabled Vehicles at 0.6 s Time Gap with Small Distance Gap

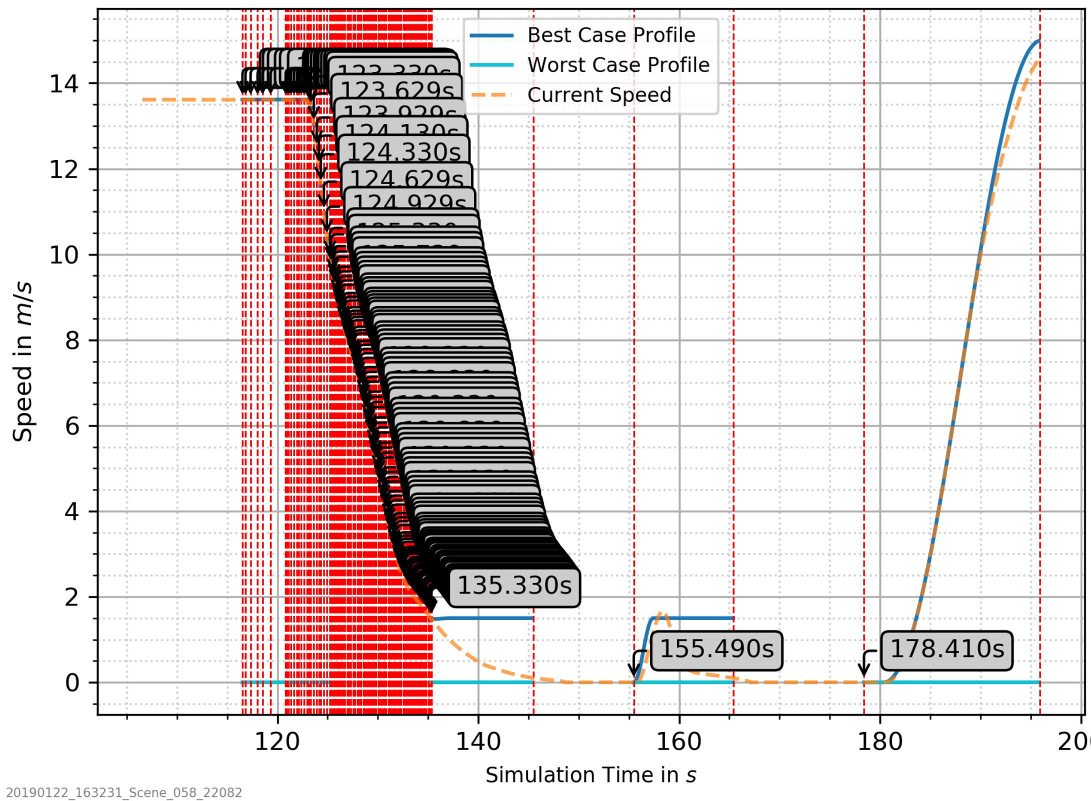
Figure 92 depicts the operating modes for each TOSCo vehicle for the duration of the simulation run. There is no difference from the operating mode diagram depicted in Figure 87 except that since the vehicles have a smaller distance gap parameter set, the changes between modes are closer together.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

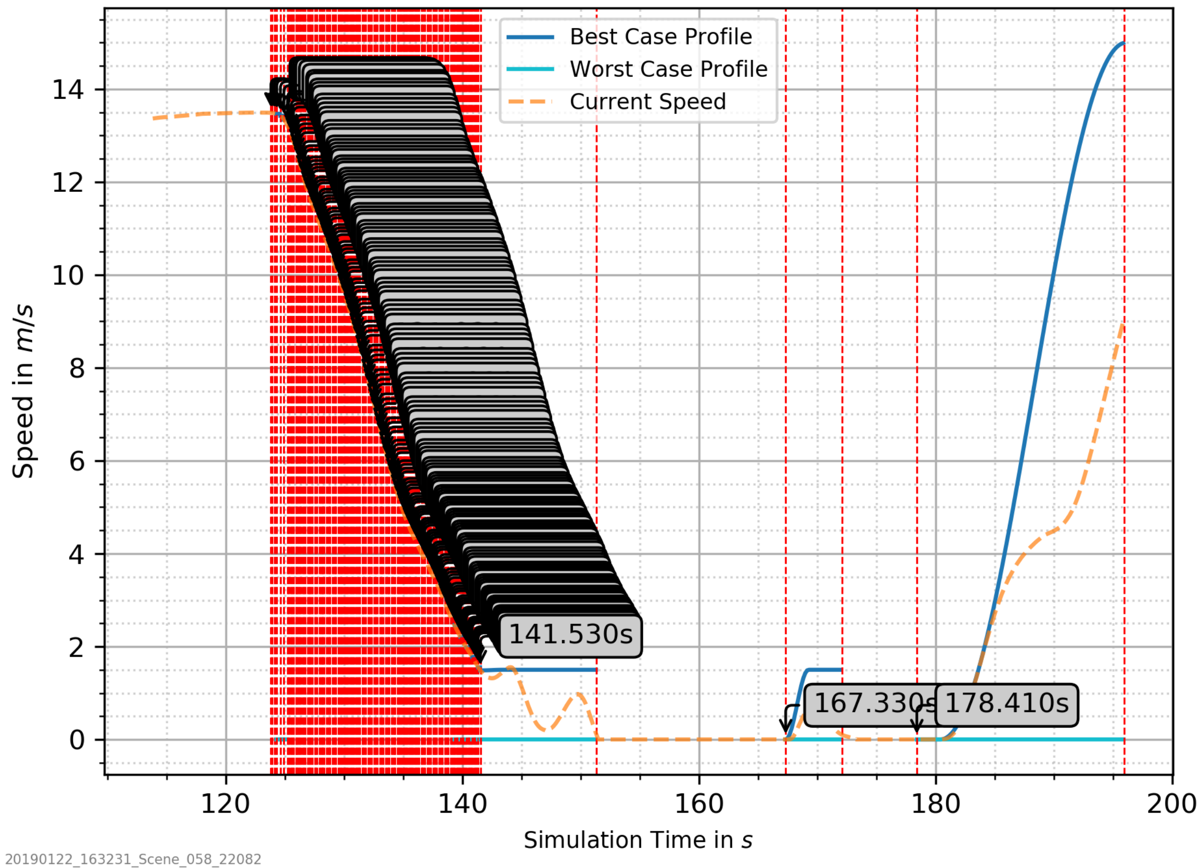
Figure 92: Creep at Intersection Scenario: Simulation Time vs. Operating Mode for TOSCo-enabled Vehicles at 0.6 s Time Gap with Small Distance Gap

Figure 93 and Figure 94 show the *best-case*, *worst-case*, and recorded speed for vehicles 1 and 5, in order to view the progressive effects down the string in CREEP mode. In addition, these figures depict the points in time at which the system recalculates its speed profiles, as depicted by the vertical red lines in the diagram, due to a change in the distance to its target. As also shown in Figure 88, vehicle 1's speed profile is smooth as it transitions from time-gap-based speed control to distance based speed control. In a similar manner to the other parameter set, the following TOSCo vehicles transition from time gap based to a distance based speed control with a much lower distance from their respective fused objects, giving small but increasingly large perturbations into each vehicles' respective speed profiles down the string. Comparing Figure 89 and Figure 94 shows that, with a short distance gap parameter set, no vehicle needs to enter STOPPED and reenter CREEP, as the minimum threshold distance in order for the vehicles to enter STOPPED from CREEP $\mathrm{d_{min}}$ is lower. All vehicles correctly calculate and execute their target speed profiles, starting with vehicle 1 at 155.490 s in Figure 93 and ending with vehicle 5 at 167.330 s in Figure 94.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

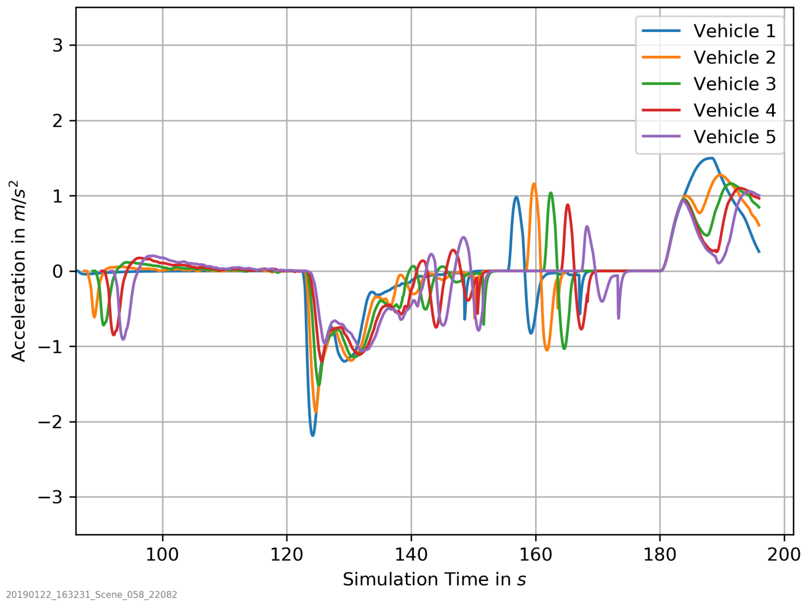
Figure 93: Creep at Intersection Scenario: Vehicle 1 Requested and Actual Speed Profiles at 0.6 s Time Gap with Small Distance Gap



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 94: Creep at Intersection Scenario: Vehicle 5 Requested and Actual Speed Profiles at 0.6 s Time Gap with Small Distance Gap

Figure 95 shows the acceleration of the TOSCo-enabled vehicles as they approach and depart the intersection. As the TOSCo vehicles enter the CREEP mode at approximately 135 s simulation time, each vehicle maintains acceleration in order to reach their respective stop locations. When all TOSCo vehicles transition between CSTOP and CREEP, their achieved accelerations increase down the string, but the maximum acceleration values never exceed 1 m/s^2. At 155 s, vehicle 1 starts to accelerate in CREEP, with the other TOSCo vehicles following suit. Similarly to the parameter set with a long distance gap, the acceleration values progressively decrease along the string, with the exception of vehicle 2. Comparing Figure 90 and Figure 95, the parameter set with a short distance gap allows the vehicles to accelerate to smaller values than the long distance gap parameter set. This effect is attributed to the lower values of $\mathrm{d}_{\mathrm{creepthreshold}}$ and $\mathrm{d}_{\mathrm{min}}$, as with the transition from CSTOP to CREEP described by Figure 94, thus, having lower threshold values means having a smaller distance to each vehicle's target stop location.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 95: Creep at Intersection Scenario: Simulation Time vs. Acceleration for TOSCo-enabled Vehicles at 0.6 s Time Gap with Small Distance Gap

4.9.3 Scenario Summary

The Creep at Intersection Scenario successfully demonstrates that the developed TOSCo system is able to properly transition to and from the CREEP operating mode from both a case in which the vehicles are in CSTOP behind a forming queue of non-TOSCo vehicles as well as for a case in which vehicles move forward to a new target stop location when a preceding queue partially dissipates. This was successfully verified in simulation by varying the set time gap and distance gap parameters. Two parameter sets from each extreme were analyzed to both verify the performance of TOSCo-enabled vehicles accelerating to a specified CREEP-Mode Speed $\mathrm{v}_{\mathrm{creep}}$ from rest and the performance of TOSCo-enabled vehicles transitioning from time-gap-based control to distance-gap-based control. The findings from these parameter variations are as follows:

- TOSCo vehicle time gap settings do not significantly affect the behavior of TOSCo vehicles transitioning from time gap based to distance gap based speed control, with either small or large distance gaps.
- As TOSCo vehicles transition from CSTOP to CREEP, TOSCo vehicle behaviors while transitioning from time-gap based to distance-gap-based speed control have speed profiles with small but increasing perturbations down a string of TOSCo vehicles. After a certain point down the TOSCo string, the distance between the vehicles becomes small enough to leave the CREEP operating mode and enter STOPPED until the preceding vehicles are a distance $\mathrm{d}_{\mathrm{creepthreshold}}$ away, again satisfying the conditions to enter CREEP. With a large distance gap, the minimum stopping distance $\mathrm{d}_{\mathrm{min}}$ is more easily met, making more TOSCo vehicles leave CREEP and enter STOPPED. From this parameter exploration, it is advisable to have a smaller distance gap, but further investigations are needed to explore the minimum parameter settings for a set distance gap, especially if this system were to be implemented in-vehicle.

5 Summary and Outlook

This Vehicle-level Simulation Report for the TOSCo Project summarizes the analysis of the developed TOSCo vehicle-level software implementation in a simulation environment. This implementation differs from the traffic-level implementation, as vehicle-interfaces are modelled in more detail to allow for the deployment of the developed software in an actual vehicle environment. The different simulation scenarios, each representing a unique traffic situation, successfully demonstrate and validate the operations of the TOSCo vehicle-level software implementation. This chapter summarizes the findings on a higher level in Section 5.1. Since each simulation scenario is used to validate and identify further improvements to be implemented in future work, Section 5.2 provides a high-level guideline to potential next steps.

5.1 Summary

The TOSCo vehicle-level algorithm specified as part of the TOSCo System Specification [7] has been implemented in a rapid prototyping environment that will allow the development team to run the same software revision in both a simulation environment and in an actual vehicle in a later stage. It is thereby imperative to be able to test and verify the operations of the software in simulation by performing a set of repeatable, unique scenarios in which the TOSCo system will have to operate as specified. This ability reduces the development time as incremental improvements can be tested without the need for a prototype vehicle and a test track, and it, therefore, also reduces the costs associated to the development process.

This report introduces the developed simulation environment in Chapter 2. Even when provided with a simulation framework to test different revisions of the vehicle software, an underlying process called a *simulation workflow* is required to perform *purposeful* simulations. Hence, before running a simulation, the development team specifies the software revision to be tested, parameterizes and documents the simulation run and creates a simulation report for each run. From each run, a corresponding set of changes to the software is developed and implemented before the next run. This allows for a high development *velocity* while providing the flexibility to change the software, compared to an elementary waterfall development process which does not allow for simple changes of the initial specification. The employed simulation environment, to a large extent, has been adopted from the CAMP CACC-SST Project and adapted to reflect the requirements of the TOSCo Project. Three different computers are interlinked and run different components of the simulations. The *Development Environment* runs the vehicle-ready TOSCo algorithm implementation for multiple vehicles, the *Simulation Environment* provides the dynamics models for each vehicle along and synchronizes the different simulation software and the *Driving Environment* provides the virtual environment in which the TOSCo vehicles are driving, along with the communicating infrastructure component and a traffic-light equipped intersection.

When approaching the intersection, each member of the string of TOSCo-enabled vehicles selects an appropriate *TOSCo operating mode*, which is associated with either a speed up, slow down or a full stop of the vehicle in front of the traffic light. Chapter 3 introduces these different operating modes, along with the *speed profiles* and the optimized longitudinal vehicle approach strategies corresponding to each TOSCo operating mode. These profiles are based on piecewise trigonometric functions. The chapter also introduces the concept of *best-* and *worst-case* speed profiles. Whenever a TOSCo operating mode is selected, two sets of speed profiles are computed. The *best-case* profile resembles the profile provided to the longitudinal controller and aims at reaching the intersection as early within the green window as possible. The corresponding *worst-case* profile aims at reaching the intersection as late as possible, but still within the green window. Every possible speed profile between these two profiles resembles the *solution space* which allows the vehicle to pass the intersection within the current green window, albeit only the *best-case* profile allows vehicles to reach the intersection at the earliest point in time (within system and comfort boundaries).

The developed simulation environment has been employed to perform an extensive set of simulations, as presented in Chapter 4. The chapter is based on eight distinct simulation scenarios, each focusing on a different approach constellation for TOSCo-enabled vehicles. Each scenario is thereby based on the identical underlying road topology and traffic light schedule, varying only by the introduction times of the TOSCo-enabled vehicles so that these arrive at the intersection at different times throughout the traffic-light schedule. The scenario roughly corresponds to the different TOSCo operating modes: A Speed-up Scenario causes vehicles to increase their speed to speed limit, potentially forcing a string of approaching TOSCo-vehicles to split up, in case not all vehicles are able to pass within the provided green window. A Slow-down Scenario causes vehicles to slow down to a predetermined speed in order to reach the intersection at the time the traffic light turns green, while a Stop scenario causes all vehicles to come to a full stop. In this case, as soon as the traffic light turns green again, all vehicles within the TOSCo string are performing a *coordinated launch*, in which all vehicles pick up speed simultaneously to improve throughout at the intersection.

Each section within the chapter thereby follows the same methodology: As the expected scenario outcome will be compared to the observation of the simulation result when employing the TOSCo algorithm, each section first introduces the idealized vehicle behavior by introducing the stylized speed-time diagram of the scenario and by indicating the expected TOSCo operating modes throughout the scenario. Each section also details the different simulation parameters that are varied for a specific scenario. It should be noted that each scenario does not vary the same parameters, since different effects, caused by different parameters, are studied in each scenario. The number of parameter variations can thereby vary. Each section then presents an extensive analysis of the scenario, focusing on the specific aspects for which the scenario was initially developed. A scenario-specific summary lists potential future work items, if identified. This methodology allows for an independent interpretation of each scenario and each section can therefore be read independently.

The following briefly summarizes the main findings of performing these simulation scenarios. Section 5.2 provides further details in case recommendations for future work have been derived from a specific scenario.

- In general, the TOSCo algorithm is able to perform as specified in most of the simulation scenarios without the need of further modifications. In some specific cases, the expected behavior differs from the observation which is mainly caused by different initial velocities and, as a result, frequent re-computations of the speed-profiles.
- In the Constant Speed Scenario, it is successfully demonstrated that the developed TOSCo system is able to create a constant speed profile and is able to successfully transition to a *Coordinated Speed Control – Speed Up* TOSCo operating mode. This works for different time gaps and speed levels. With mild parameter settings, vehicles select a speed profile close to the *best-case* speed profile, with shorter time gap settings and on roadways with higher speeds. Chosen speed profiles deviate from the *best-case* profile progressively down the string but still remain well within the solution space created by the best and *worst-case* profiles.
- In the Speed-up Scenario, the developed TOSCo system is not only able to speed up vehicles in a string to pass the intersection but also to split up the vehicle string when it detects situations in which not all of the members of a vehicle string can pass the intersection in the current green window. It was also observed that in case of re-computations occurring while a vehicle is already

decelerating, the current speed profile definitions are insufficient, as initial accelerations are not considered.

- In the Slow-down Scenario, as a vehicle enters the RSU communication range, the *Slow Down* operating mode is entered. The vehicles compute a time duration for which the predetermined target speed is maintained until the vehicles pass the intersection. Different parameter variations resulted in successful deceleration of the TOSCo-string vehicles to a predetermined target speed to pass the intersection in the oncoming green window. As expected, the analysis of different parameter variation showed that not all vehicles in the TOSCo string enter the *Slow Down* operating mode as the green window for each vehicle depends on its distance to the stop bar. Vehicles at the end of the TOSCo string might be able to maintain their speed or speed up to pass through the intersection (if they had no vehicle in front). However, the presence of a preceding vehicle enables their CACC operation to enter *OF* operating mode instead of following its own computed speed profile. It was also noted that the predetermined target speed limits the vehicle's capability to decelerate earlier and to choose a more appropriate target speed which would allow a vehicle to arrive at the stop bar at the highest possible speed. This calls for a modification of the speed profile computation for determining the target speed: A vehicle's target speed when slowing down should be computed dynamically, based on the current distance and timing constraints as opposed to slowing down to a predetermined target speed.

- In the Coordinated Stop and Launch Scenario, it is demonstrated that all vehicles within the TOSCo string are able to come to a full stop in case the pre-defined slow-down speed is insufficient to reach the oncoming green window (otherwise, slowing down rather than coming to a full stop is preferred for reasons of traffic efficiency and energy consumption). For all variations of time gap-settings and approach speeds, the vehicles are able to come to a complete stop. Upon receiving information from the infrastructure, vehicles switch to the CSTOP mode in which they maintain their current cruising speed until they need to decelerate to come to a full stop at the stop location. For the higher approach speed scenarios, however, vehicles are able to intercept the change from green to yellow of the traffic light cycle, resulting in a re-computation of the speed profiles as external conditions have changed. It is found that in contrast to the findings of the Speed-up Scenario, not taking initial accelerations into account when computing the speed profiles has less of an effect for the CSTOP mode, as long as the re-computation occurs during the initial cruising phase of the profile, in which the vehicle maintains its current speed until it has to decelerate. From this, however, it can be inferred that for a different scenario setup, in which the re-computation would occur while the vehicle is decelerating, an erroneous vehicle behavior would occur. It is, therefore, imperative to revisit the speed-profile computation in future work.

- In the Speed-up with Dissipating Queue at Intersection Scenario, the developed TOSCo system successfully demonstrates the ability to operate in cases of a queue present at the intersection. It is shown that in case a queue is detected, the underlying CACC system can control the vehicle to deviate from its computed *best-case* trajectory.

- In the Slow-down with Dissipating Queue at Intersection Scenario, the introduction times of the vehicles were varied in order for the approaching TOSCo string to reach the end of a queue of non-TOSCo vehicles just at the moment the traffic light turns green and the queue dissipates. The setup in which the TOSCo string arrives at the intersection when the queue has almost disappeared is identical to the Slow-down Scenario, as the impact of the queue presence at the green window does not alter the approach strategy of the approaching TOSCo string. Hence, the TOSCo vehicles successfully slow down to the predetermined speed in order to pass the intersection. For the setup in which the TOSCo string arrives at the end of the queue earlier, when the last queued vehicle just starts to move when the TOSCo vehicle arrives behind it, the TOSCo string has decided to come to a stop rather than slowing down. The observed behavior is thereby incorrect because the first TOSCo vehicle does not come to a stop, thereby impeding the coordinated launch triggered by the following vehicles. This calls for a modification of the mode selection at low-speed scenarios: A transition from an approach, albeit at low speeds, to the coordinated launch mode should be introduced.

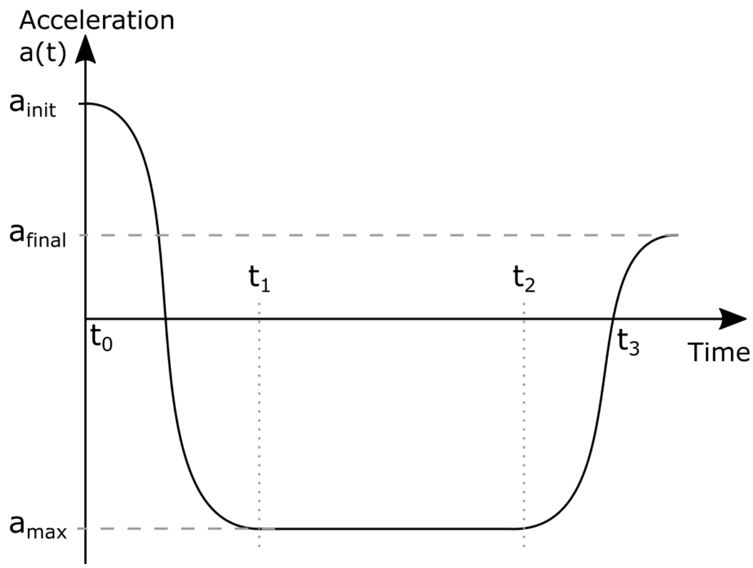
- In the Coordinated Stop and Launch with Dissipating Queue at Intersection Scenario, it is demonstrated that all vehicles in the RSU communication range can come to a full stop when approaching the end of a queue of DSRC-only-equipped vehicles. Upon receiving information from the infrastructure, vehicles correctly enter the CSTOP mode and appropriately recalculate their speed profiles due to constantly updated green windows and queue length information. As seen in similar scenarios, the following vehicles correctly switch to the OF operating mode while within the solution space generated by their respective CSTOP profiles. When the queue of the DSRC-equipped vehicles dissipates, the TOSCo-equipped vehicles enter CL operating mode to pick-up speed simultaneously.
- In the Creep at Intersection Scenario, it is successfully demonstrated that the developed TOSCo system is able to stop the vehicles behind the end of a queue. In this scenario, the first non-TOSCo vehicle of the queue waiting at the intersection turns right on red, causing every other waiting vehicle to creep forward. It is shown that the transition to and from the CREEP mode in this scenario operates as intended. This scenario was verified in simulation with two sets of parameters, time gap setting and inter-vehicle distance. When comparing the most extreme sets of parameters, it was found that the time gap setting had little effect on the transitional behavior between time gap and distance-gap-based speed control. A shorter distance gap was found to be more beneficial, as vehicles progressively accelerated less down the string due to the lower thresholds that satisfy the STOPPED versus the CREEP case. Future investigations need to be conducted to discuss the minimum values for distance gap while still safely implementing the system in simulation and especially in-vehicle.

5.2 Outlook

As a result of the eight simulation scenarios and different parameter variations, several key work items to be considered for future development have been identified. The following items should be addressed before implementing the software in an actual vehicle environment:

Speed Profile Definitions: The specification of the speed profiles has to be revisited for cases in which the vehicle is currently decelerating when computing the optimized profile. The current definition does not take potential initial acceleration into account, resulting in undesirable behavior in case the vehicle is currently decelerating. This occurs frequently especially in scenarios where the state of the traffic light changes and a vehicle is already decelerating (e.g., a vehicle decelerates while approaching a traffic light that is about to turn red), as this change in *external conditions* triggers a re-computation of the optimized speed profiles.

Additionally, by inspecting the speed profile diagrams computed, it is apparent that the profiles do not reflect the deceleration- or acceleration-behavior as expected by a driver. Rather than adopting a monotonously increasing acceleration level up to a predetermined peak value, to then monotonously decrease the acceleration level (half-sinusoid), a calculated acceleration level should be maintained over a certain duration before decreasing the acceleration level. This will additionally increase the optimization space of the TOSCo algorithm.



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 96: Alternative Definition of Acceleration Behavior

Figure 96 details a preferred, more realistic acceleration profile that would result in an increase solution space, when computing the *best*- and *worst-case* speed profiles for the different operating modes. The depicted acceleration profile, which is then consecutively integrated to derive the speed- and distance-travelled profile, starts at any initial acceleration $\mathrm{a_{init}}$ that may persist when computing the profile. Based on a pre-defined maximum jerk level, acceleration would be decreased (deceleration) up to a maximum acceleration value $\mathrm{a_{max}}$. This value would be maintained for a duration $t_2 - t_1$ until transitioning to a desired final acceleration value $\mathrm{a_{final}}$, which is 0 m/s^2 in most cases. This profile resembles the actual braking behavior of traffic participants today. Brake pressure is increased until a subjective sufficient deceleration level $\mathrm{a_{max}}$ is reached (at t_1). This deceleration level is then held constant by maintaining this brake pressure until the brakes can be released again (at t_2) to then reduce the brake pressure until the desired target velocity is reached. Compared to the profiles in Chapter 3, the proposed profile will result in an increased solution space since the maximum deceleration level is maintained over a longer duration as compared to the peak acceleration in the half-sinusoidal profiles which is decreased immediately once reached.

Compared to the speed profiles in Chapter 3, which are aiming at modelling a profile showcasing a pre-defined average speed computed by the remaining distance to the stop location and the remaining time to green / end of the green window, the proposed profile in Figure 96 takes on a more generic approach at which the comfort boundaries are pre-defined (by the maximum jerk level), but any combination of target maximum acceleration and target final speed are variable. Although increasing computation complexity, since these two unknowns need to be determined by using an optimization (iterative) method, the solution space is increased dramatically, resulting in more scenarios in which TOSCo can be activated. This will be vital to a prospective deployment of TOSCo, especially when operating in real-life traffic conditions.

The simulation scenarios outlined in this report are operating a fixed-timing traffic signal. When deploying TOSCo in a real-life scenario, TOSCo has to be able to operate with actuated traffic signals as well. As a result, green windows will alter frequently, causing (inevitable) re-evaluations and thus re-computations of speed profiles. If initial acceleration values are not taken into account, the current TOSCo specification based on the speed profiles introduced in Chapter 3 will result in undesired vehicle behaviors.

As a general observation, communication ranges with the RSU have to be adapted to the speed limit to provide sufficient space for optimizing vehicle behavior. This can be realized by employing directional antennas or by other suitable means. Based on the underlying speed profile methodology, earlier information increases the solution space and thereby the chance of not having to stop in front of a red traffic light.

Mode Selection Refinements: For any constellations in which the stopping duration is very short, mainly caused by the previous observation, not all vehicles within the TOSCo string might come to a full stop. In this situation, the current specification does not allow for a transition to a coordinated launch mode. Future work should therefore aim at revisiting the behavior of TOSCo vehicles, especially at low speeds. Due to increased difficulty of low-speed vehicle control, a real-life test will provide valuable insight into vehicle- and controller-behavior. In situations where a TOSCo-equipped vehicle slowly creeps towards its stop location (e.g., behind another vehicle) and the traffic light changes to green, the current specification does not allow a vehicle to then pick up speed. Instead, the current specification only allows a transition from Stopped to the coordinated launch state. By adopting a speed profile definition outlined above, this undesirable behavior can be alleviated since a speed-up profile can be computed from any initial speed and acceleration level.

Simulation Environment Refinements: One challenge faced by the TOSCo development team while running simulations is the lack of automation of the simulation environment. Although not effecting the TOSCo algorithm itself, future work should aim at automating the simulation process. Due to the number of different interlinked simulation software and, therefore, initialization steps that have to be performed manually, simulation runs tend to be time-consuming and error prone, especially when setting up the simulation environment for a particular run. Since very different simulation tools from different vendors are running on the three simulation computers, an automation framework is not readily available. However, custom scripting can help to address these issues by simplifying the simulation setup and observing the different states of the simulation software.

APPENDIX A. List of Acronyms

ACC	Adaptive Cruise Control
ADTF	Automotive Data- and Time-Triggered Framework
BSM	Basic Safety Message
CACC	Cooperative Adaptive Cruise Control
CACC-SST	Cooperative Adaptive Cruise Control – Small-scale Test Project
CAMP	Crash Avoidance Metrics Partners LLC
CAN	Controller Area Network
CL	Coordinated Launch
CSC	Coordinated Speed Control Operating Mode
CSC_CONST	Coordinated Speed Control – Constant Speed Operating Mode
CSC_DOWN	Coordinated Speed Control – Slow Down Operating Mode
CSC_UP	Coordinated Speed Control – Speed Up Operating Mode
CSTOP	Coordinated Stop
Dev-Env	Development Environment
DSRC	Dedicated Short Range Communication
ECU	Electronic Control Unit
FF	Free Flow Mode
FHWA	Federal Highway Administration
GNSS	Global Navigation Satellite System
JSON	JavaScript Object Notation
MAP	MapData Message
OF	Optimized Follow Operating Mode
RSU	Roadside Unit
SHA	Secured Hash Algorithm
Sim-Env	Simulation Environment
SPaT	Signal Phase and Timing Message
TOSCo	Traffic Optimization for Signalized Corridors
TTI	Texas A&M Transportation Institute
UCR	University of California-Riverside
UMTRI	University of Michigan Transportation Research Institute
V2I	Vehicle-to-Infrastructure
V2X	Vehicle-to-Everything
VISSIM	Verkehr in Städten - Simulationsmodell
WGS84	World Geodetic System 1984

APPENDIX B. References

[1] Feng, Yiheng; Florence, David; Balke, Kevin; Leblanc, David; Wu, Guoyuan; Adla, Rawa; Guenther, Hendrik-Joern; Hussain, Shah; Moradi-Pari, Ehsan; Naes, Tyler; Probert, Neal; Vijaya Kumar, Vivek; Williams, Richard; Yoshida, Hiroyuki; Yumak, Tuncer; Deering, Richard; Goudy, Roy, *Traffic Optimization for Signalized Corridors (TOSCo) Phase 1 Project – Interim Report on Traffic-Level Simulation and Performance Analysis*, publication in process (2019).

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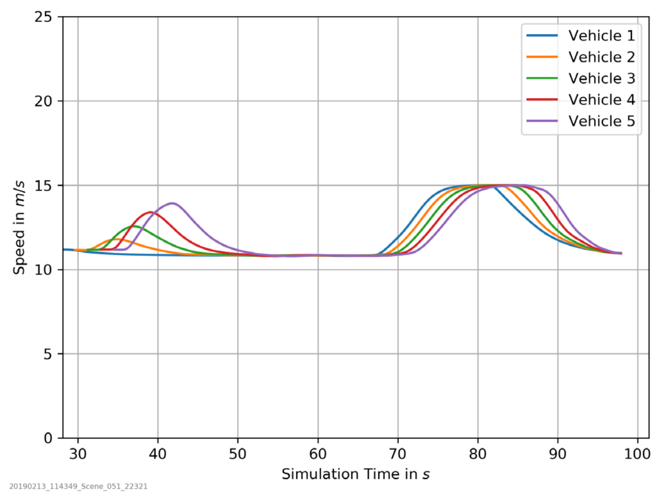
[8] O. Altan, G. Wu, M. Barth, K. Boriboonsomsin and J. A. Stark, *GlidePath: Eco-Friendly Automated Approach and Departure at Signalized Intersections, IEEE Transactions on Intelligent Vehicles, V*ol. 2, No. 4, pp. 266-277, 2017.

APPENDIX C. Further Findings

This section lists at least the Speed, Acceleration and TOSCo operating mode diagrams for each simulation run outlined in Chapter 4.

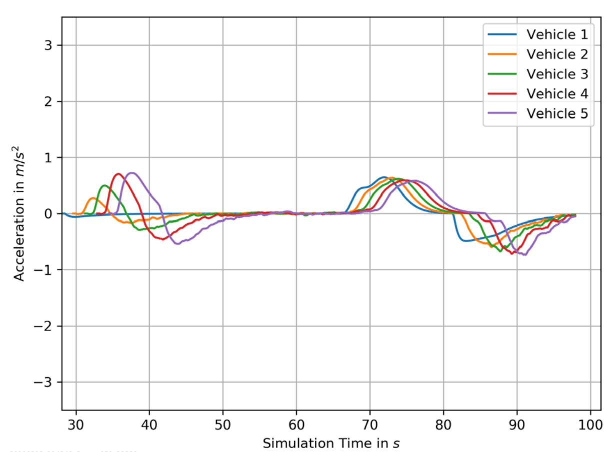
Constant Speed Scenario

Parameter setting: Time gap: 0.6 s; 35 mph speed limit



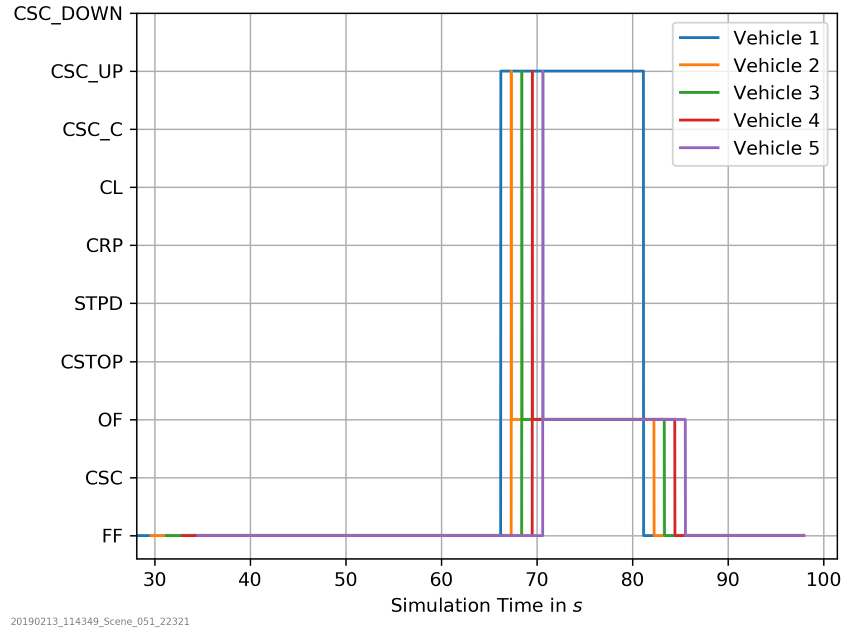
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 97:Constant Speed Scenario: Simulation Time vs. Speed for TOSCo-enabled Vehicles at 0.6 s Time Gap and 35 mph Speed Limit



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

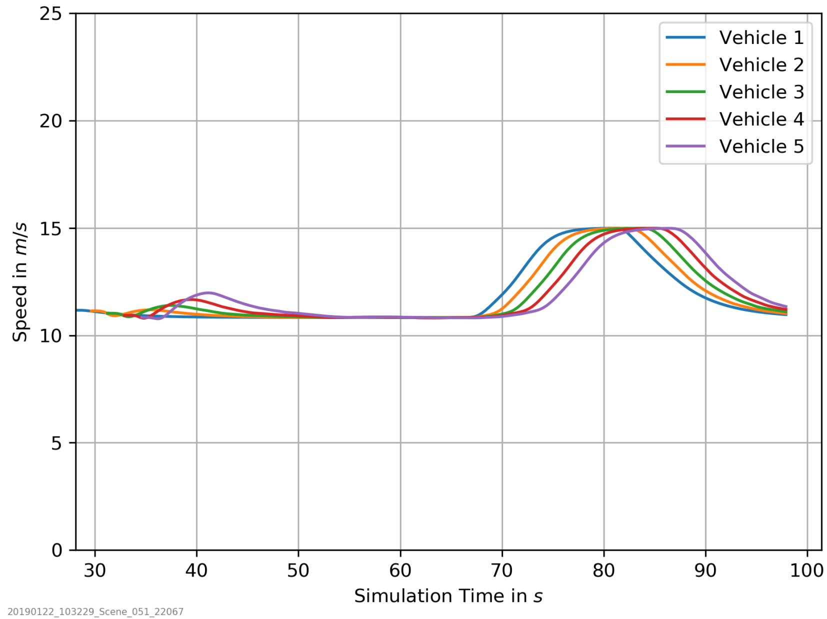
Figure 98: Constant Speed Scenario: Simulation Time vs. Acceleration for TOSCo-enabled Vehicles at 0.6 s Time Gap and 35 mph Speed Limit



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

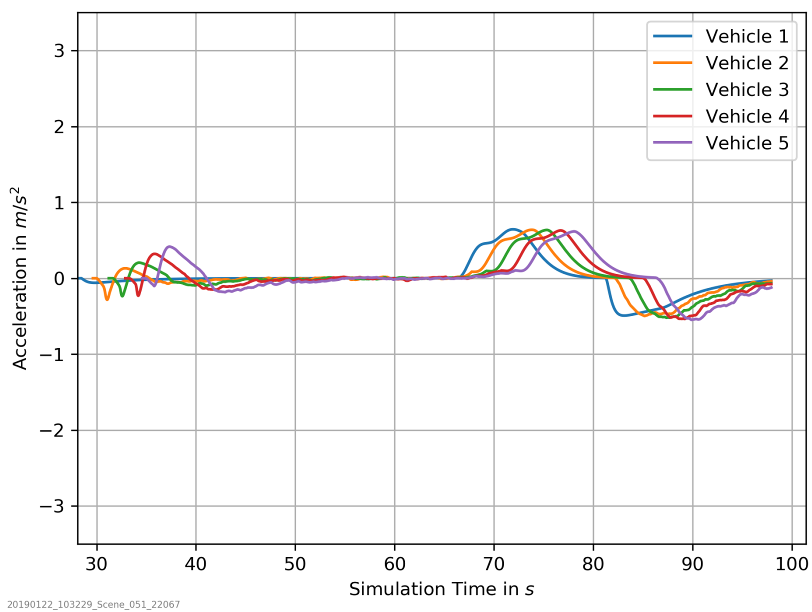
Figure 99: Constant Speed Scenario: Simulation Time vs. Operating Mode for TOSCo-enabled Vehicles at 0.6 s Time Gap and 35 mph Speed Limit

Parameter setting: Time gap: 1.0 s; 35 mph speed limit



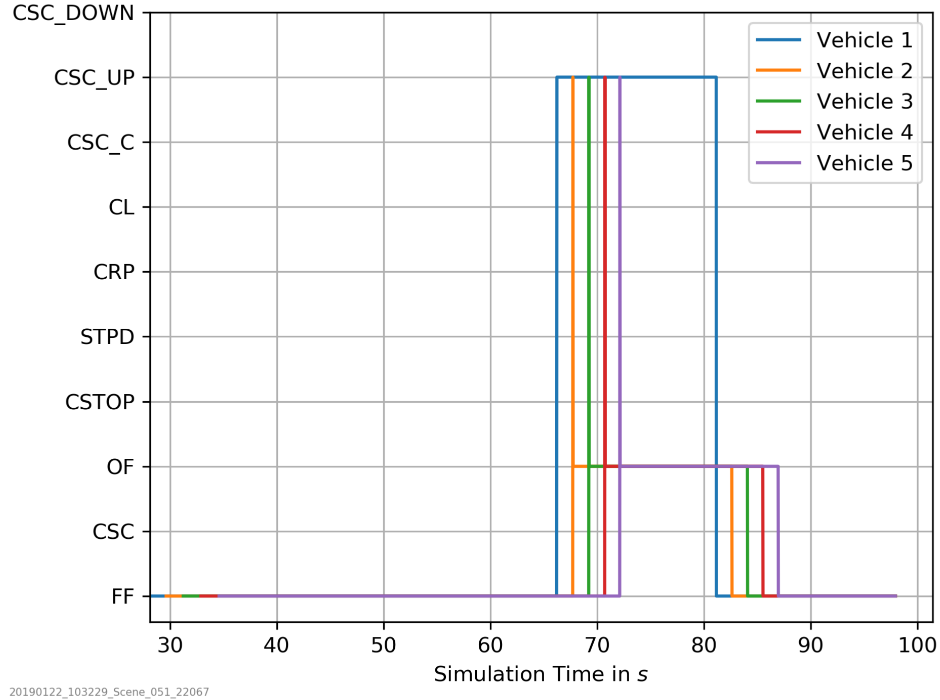
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 100: Constant Speed Scenario: Simulation Time vs. Speed for TOSCo-enabled Vehicles at 1.0 s Time Gap and 35 mph Speed Limit



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 101: Constant Speed Scenario: Simulation Time vs. Acceleration for TOSCo-enabled Vehicles at 1.0 s Time Gap and 35 mph Speed Limit

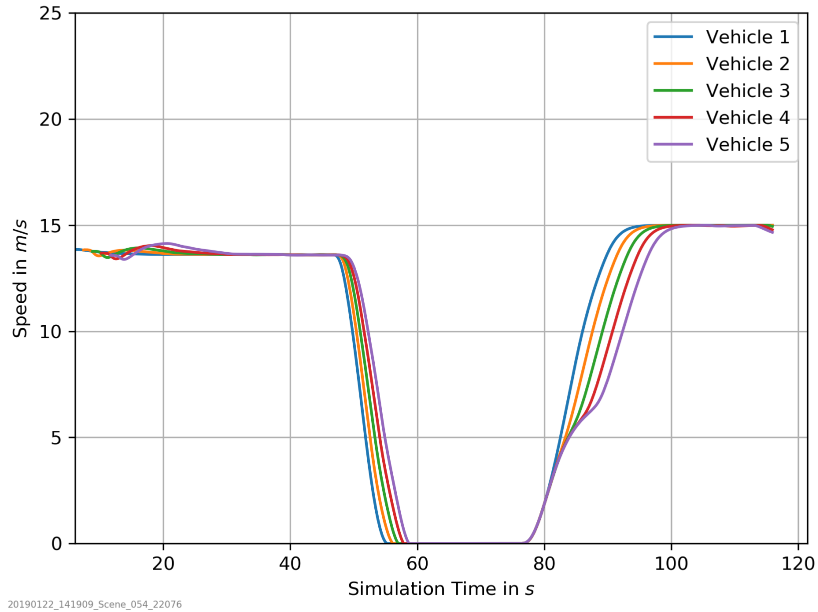


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 102: Constant Speed Scenario: Simulation Time vs. Operating Mode for TOSCo-enabled Vehicles at 1.0 s Time Gap and 35 mph Speed Limit

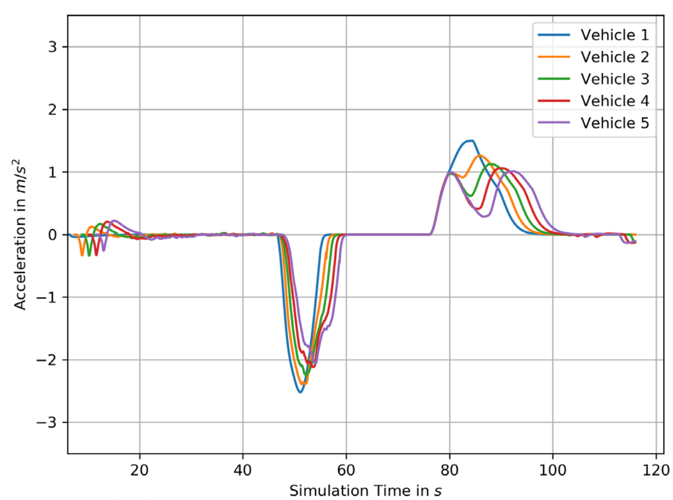
Coordinated Stop and Launch Scenario

Parameter-setting: Time gap: 1.0 s, 35 mph speed limit



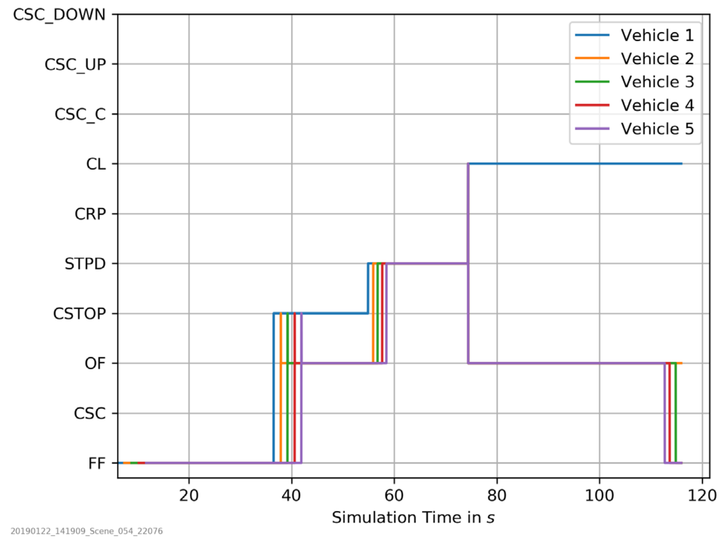
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 103: Coordinated Stop and Launch Scenario: Simulation Time vs. Speed for TOSCo-enabled Vehicles at 1.0 s Time Gap and 35 mph Speed Limit



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

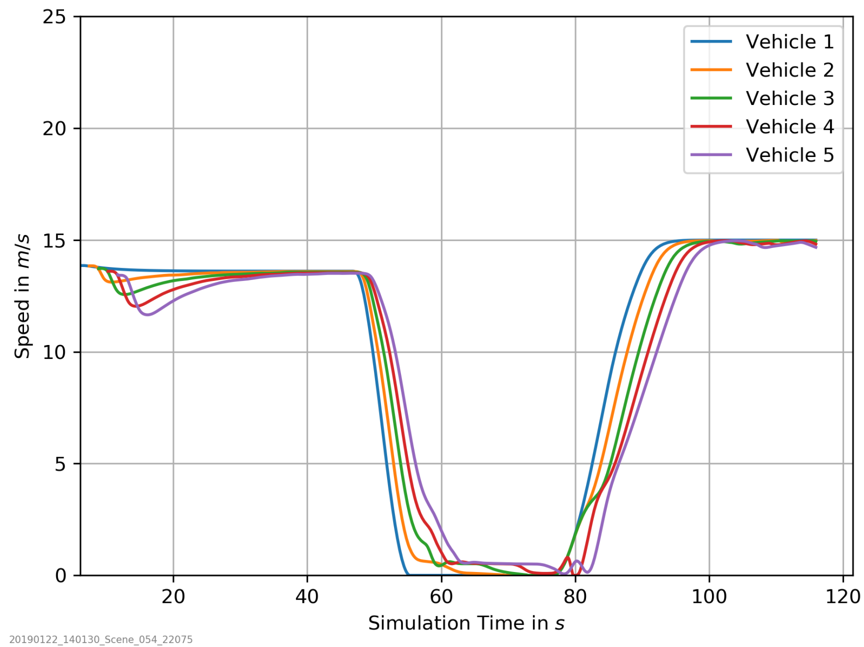
Figure 104: Coordinated Stop and Launch Scenario: Simulation Time vs. Acceleration for TOSCo-enabled Vehicles at 1.0 s Time Gap and 35 mph Speed Limit



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

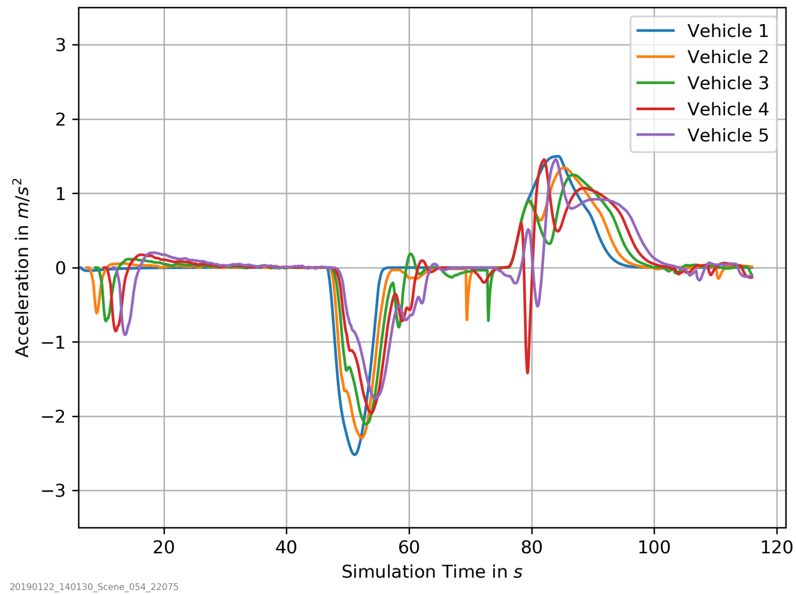
Figure 105: Coordinated Stop and Launch Scenario: Simulation Time vs. Operating Mode for TOSCo-enabled Vehicles at 1.0 s Time Gap and 35 mph Speed Limit

Parameter-setting: Time gap: 1.5 s, 35 mph speed limit



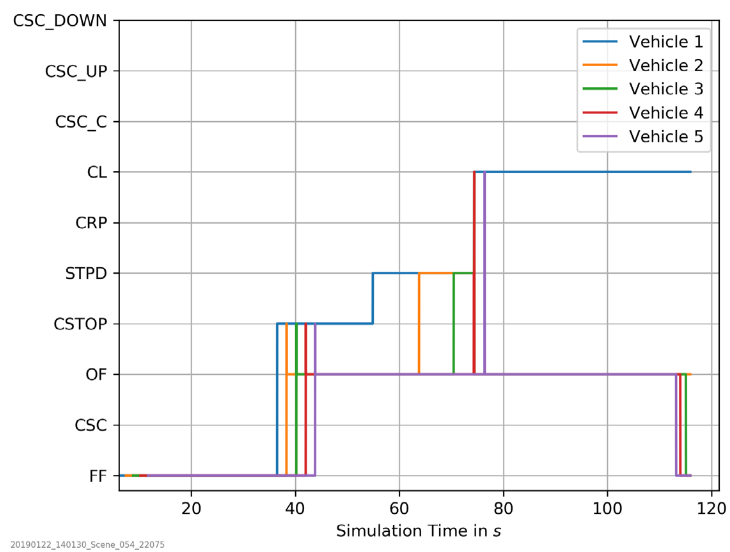
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 106: Coordinated Stop and Launch Scenario: Simulation Time vs. Speed for TOSCo-enabled Vehicles at 1.5 s Time Gap and 35 mph Speed Limit



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

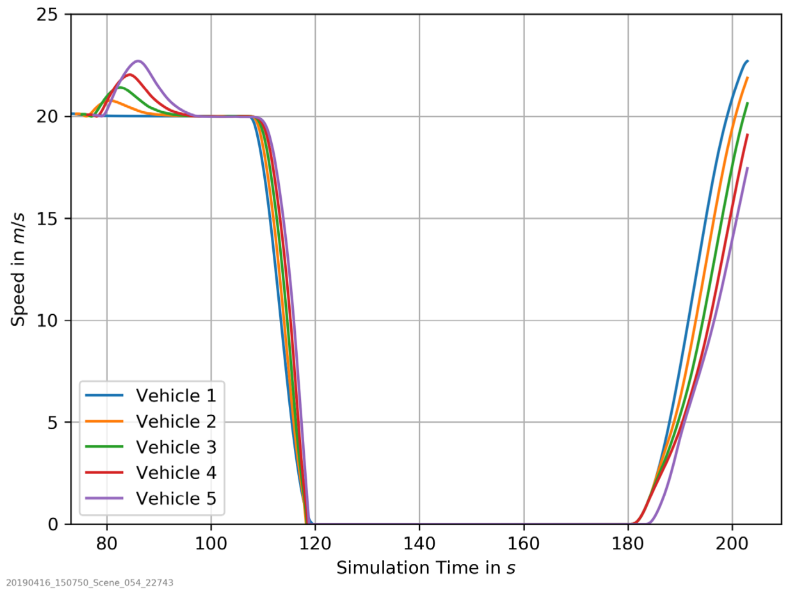
Figure 107: Coordinated Stop and Launch Scenario: Simulation Time vs. Acceleration for TOSCo-enabled Vehicles at 1.5 s Time Gap and 35 mph Speed Limit



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

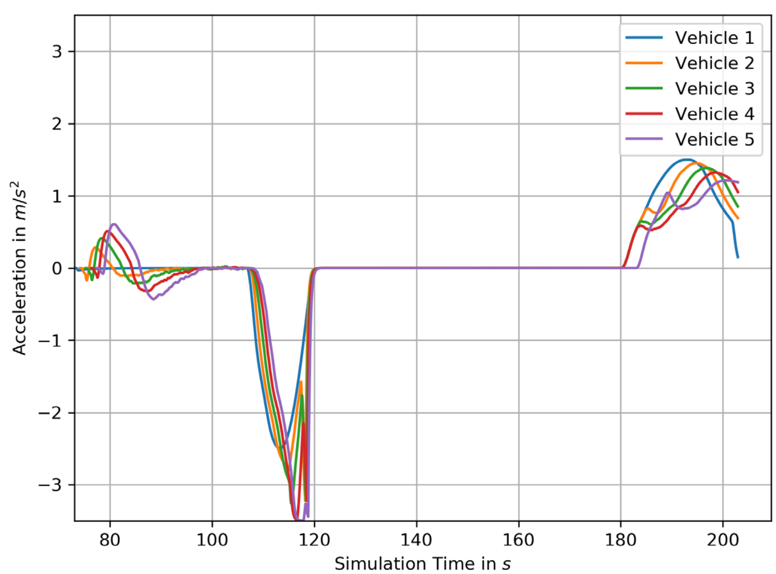
Figure 108: Coordinated Stop and Launch Scenario: Simulation Time vs. Operating Mode for TOSCo-enabled Vehicles at 1.5 s Time Gap and 35 mph Speed Limit

Parameter-setting: Time gap: 0.6 s, 55 mph speed limit



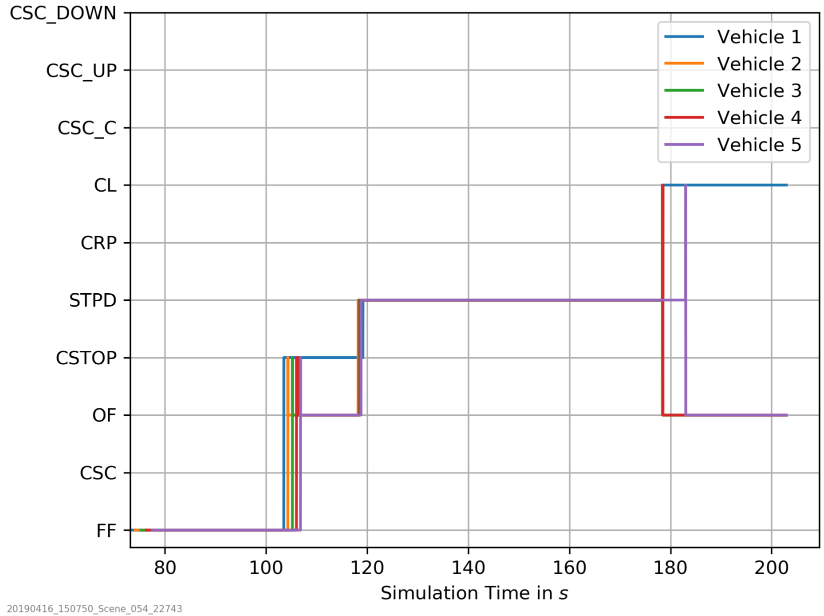
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 109: Coordinated Stop and Launch Scenario: Simulation Time vs. Speed for TOSCo-enabled Vehicles at 0.6 s Time Gap and 55 mph Speed Limit



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

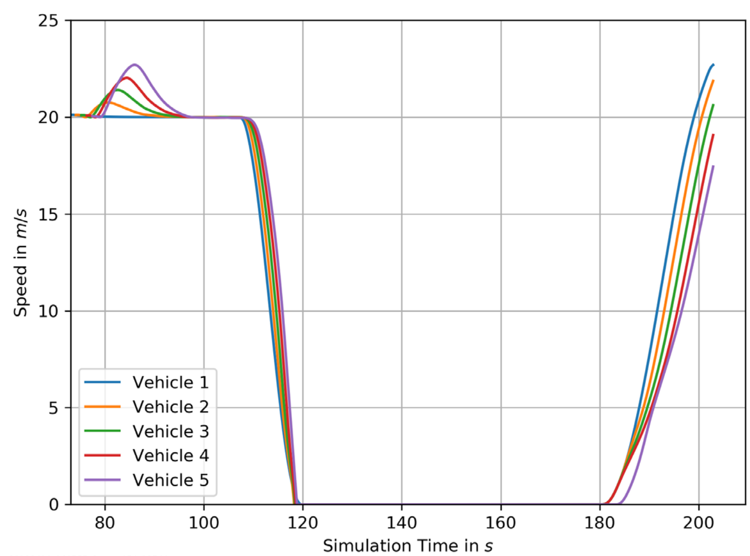
Figure 110: Coordinated Stop and Launch Scenario: Simulation Time vs. Acceleration for TOSCo-enabled Vehicles at 0.6 s Time Gap and 55 mph Speed Limit



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

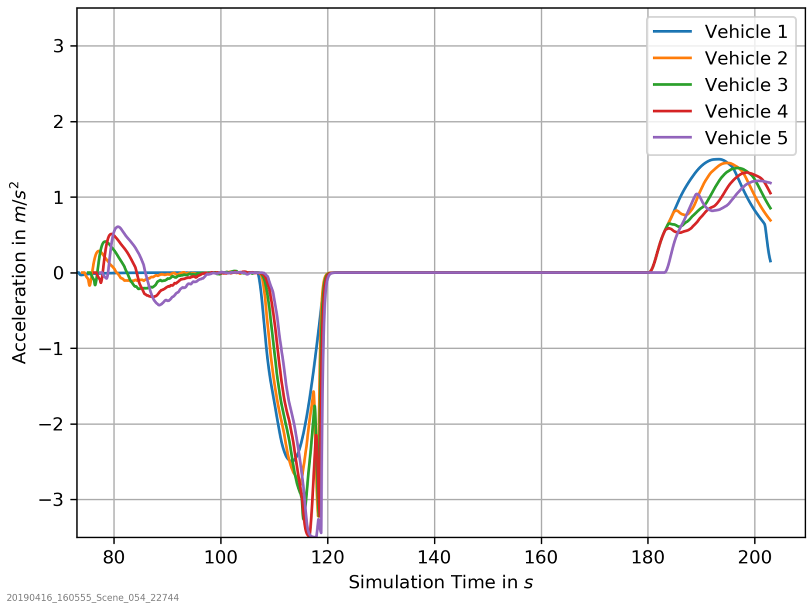
Figure 111: Coordinated Stop and Launch Scenario: Simulation Time vs. Operating Mode for TOSCo-enabled Vehicles at 0.6 s Time Tap and 55 mph Speed Limit

Parameter-setting: Time gap: 1.0 s, 55 mph speed limit



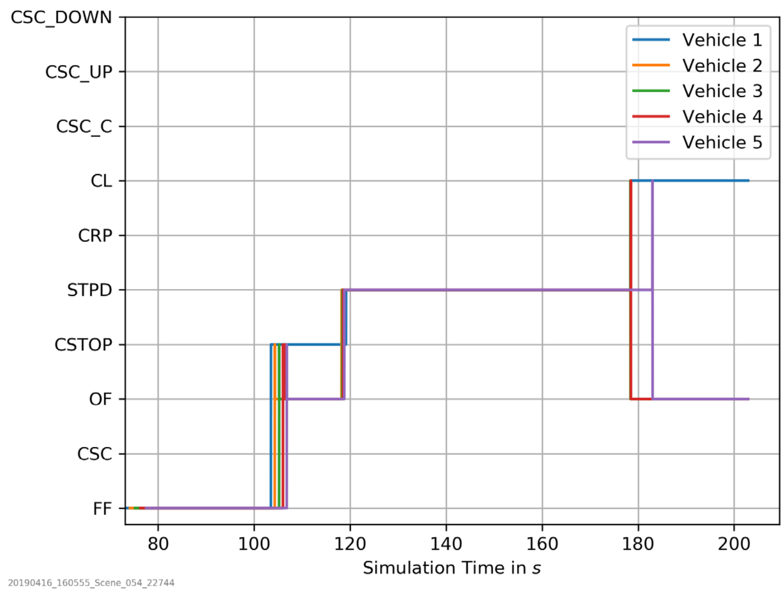
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 112: Coordinated Stop and Launch Scenario: Simulation Time vs. Speed for TOSCo-enabled Vehicles at 1.0 s Time Gap and 55 mph Speed Limit



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 113: Coordinated Stop and Launch Scenario: Simulation Time vs. Acceleration for TOSCo-enabled Vehicles at 1.0 s Time Gap and 55 mph Speed Limit

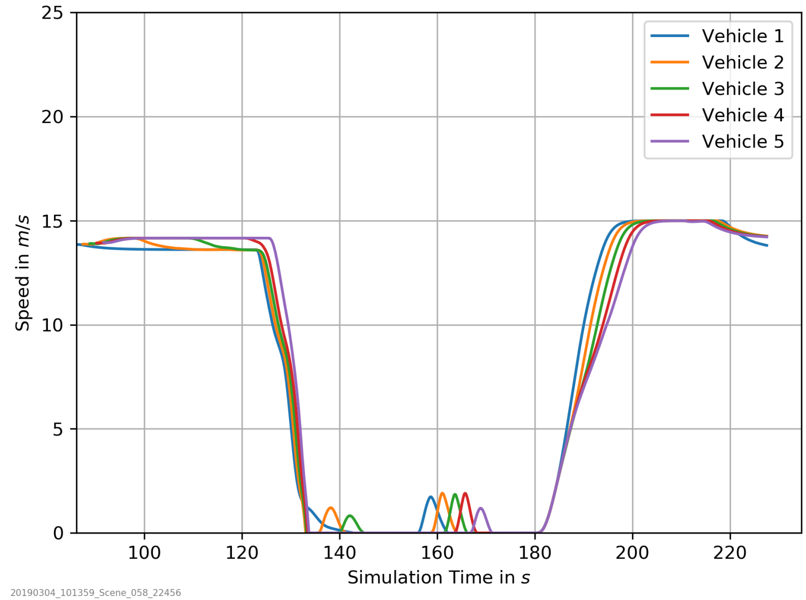


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 114: Coordinated Stop and Launch Scenario: Simulation Time vs. Operating Mode for TOSCo-enabled Vehicles at 1.0 s Time Gap and 55 mph Speed Limit

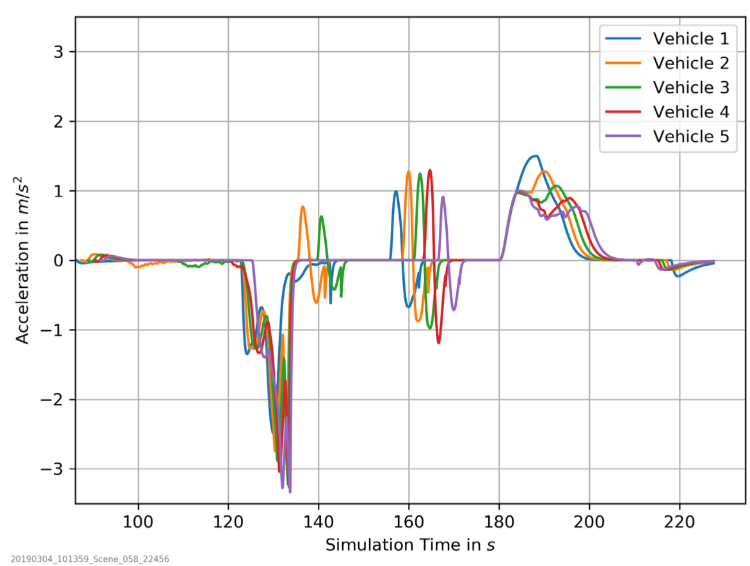
Creep at Intersection Scenario

Parameter setting: Time gap: 0.6 s; large distance gap



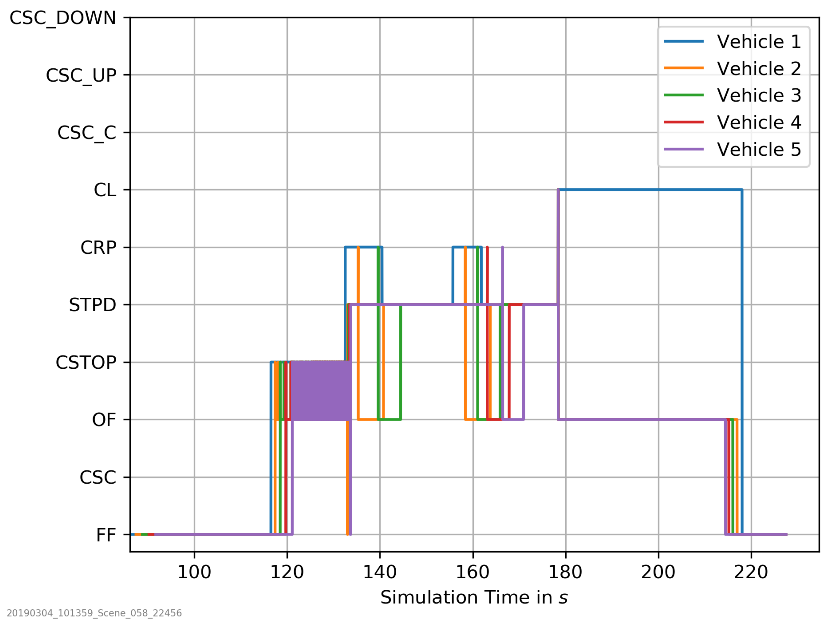
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 115: Creep at Intersection Scenario: Simulation Time vs. Speed for TOSCo-enabled Vehicles at 0.6 s Time Gap and Large Distance Gap



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

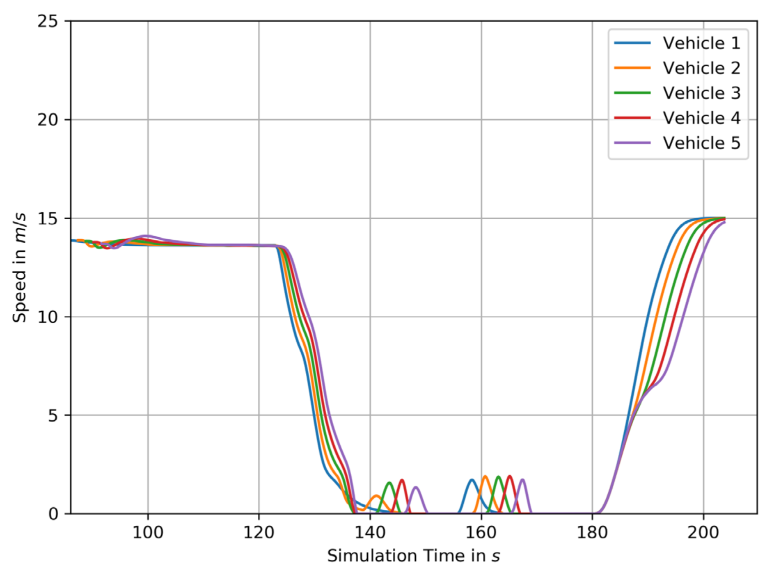
Figure 116: Creep at Intersection Scenario: Simulation Time vs. Acceleration for TOSCo-enabled Vehicles at 0.6 s Time Gap and Large Distance Gap



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

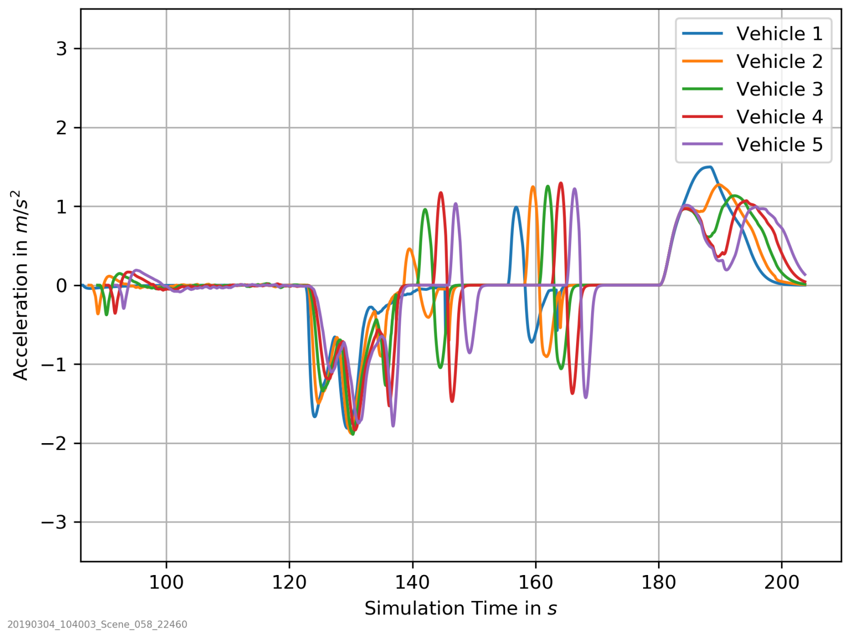
Figure 117: Creep at Intersection Scenario: Simulation Time vs. Operating Mode for TOSCo-enabled Vehicles at 0.6 s Time Gap and Large Distance Gap

Parameter Setting: Time gap: 1.0 s; Large Distance Gap



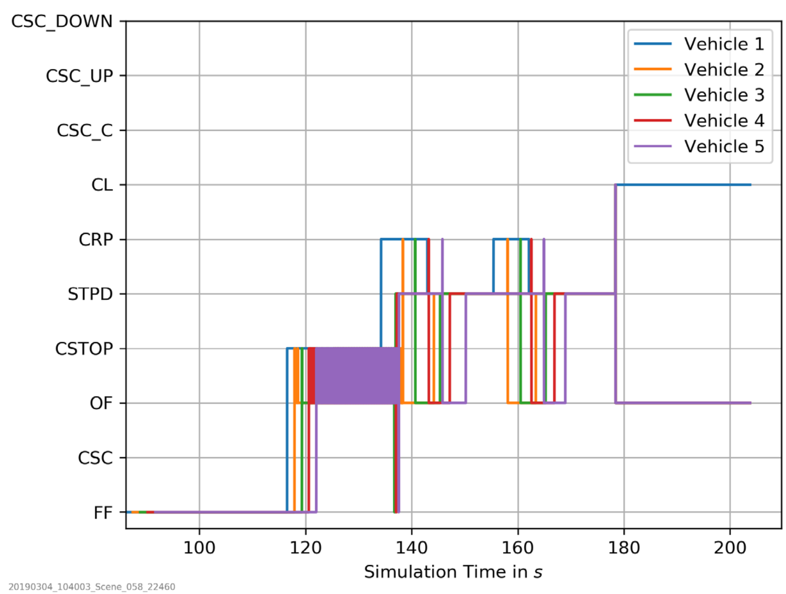
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 118: Creep at Intersection Scenario: Simulation Time vs. Speed for TOSCo-enabled Vehicles at 1.0 s Time Gap and Large Distance Gap



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

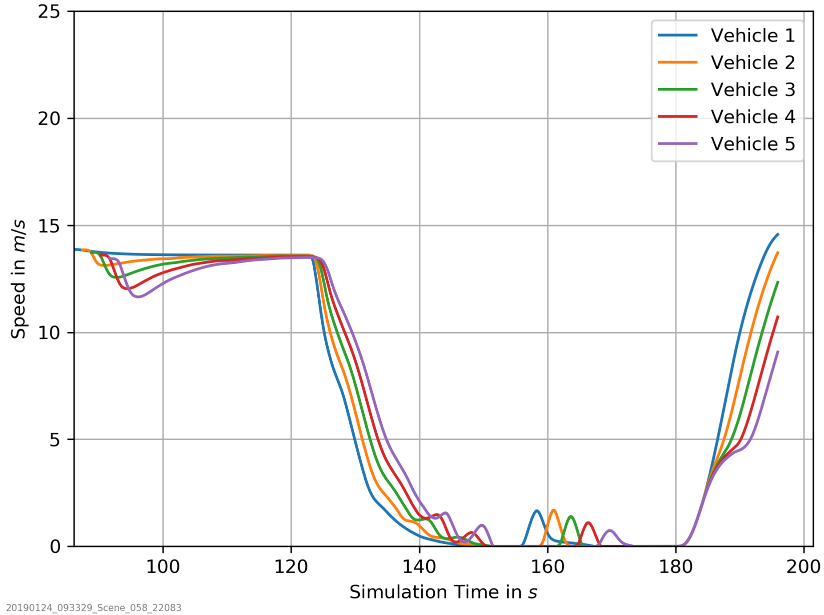
Figure 119: Creep at Intersection Scenario: Simulation Time vs. Acceleration for TOSCo-enabled Vehicles at 1.0 s Time Gap and Large Distance Gap



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

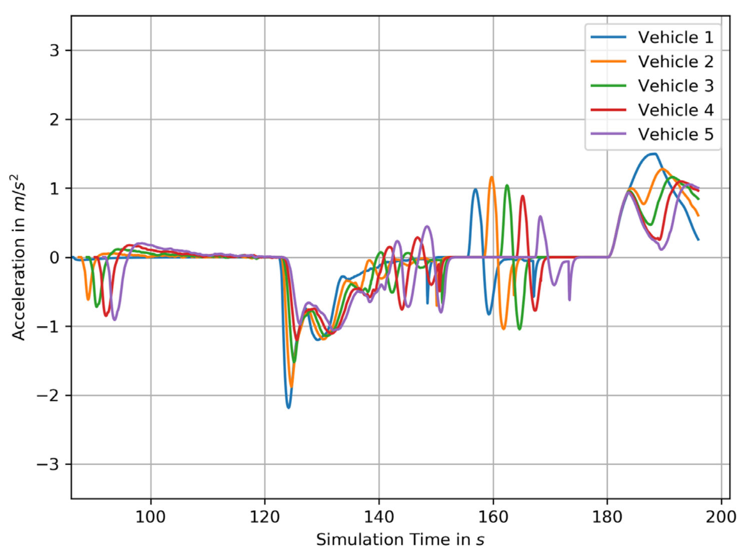
Figure 120: Creep at Intersection Scenario: Simulation Time vs. Operating Mode for TOSCo-enabled Vehicles at 1.0 s Time Gap and Large Distance Gap

Parameter Setting: Time Gap: 1.0 s; Small Distance Gap



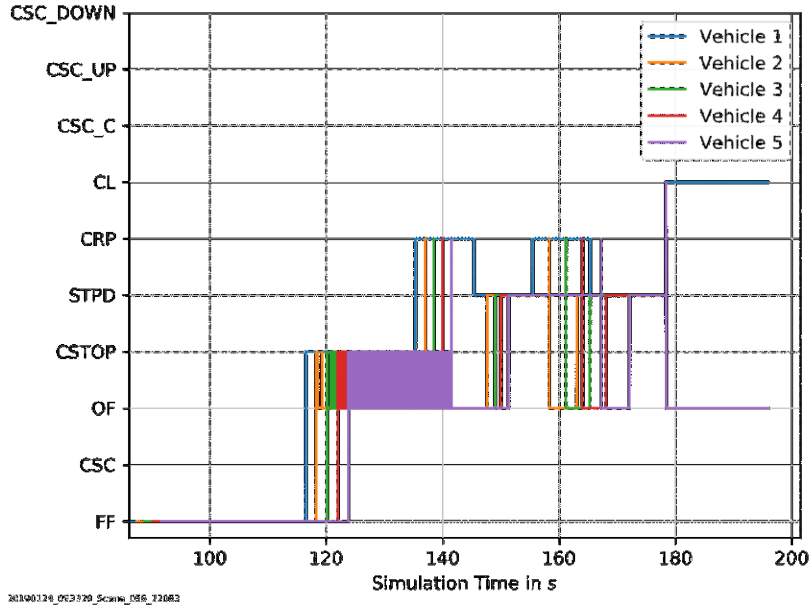
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 121: Creep at Intersection Scenario: Simulation Time vs. Speed for TOSCo-enabled Vehicles at 1.0 s Time Gap and Small Distance Gap



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

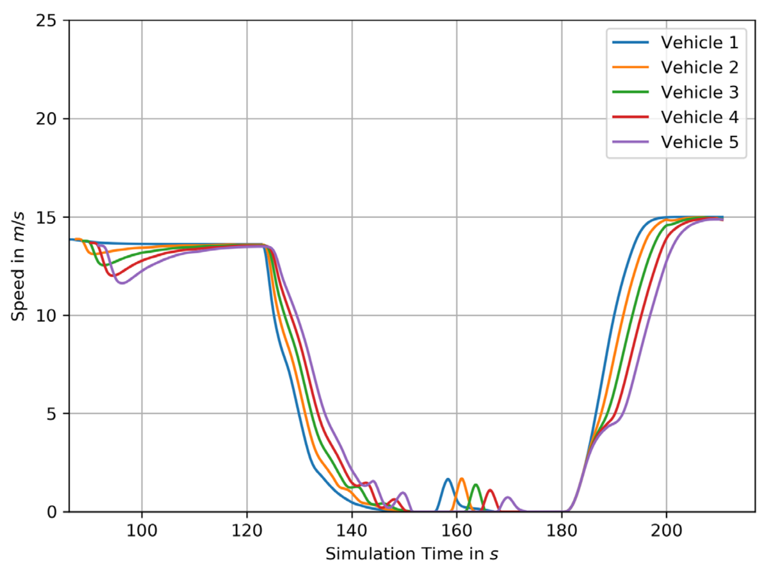
Figure 122: Creep at Intersection Scenario: Simulation Time vs. Acceleration for TOSCo-enabled Vehicles at 1.0 s Time Gap and Small Distance Gap



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

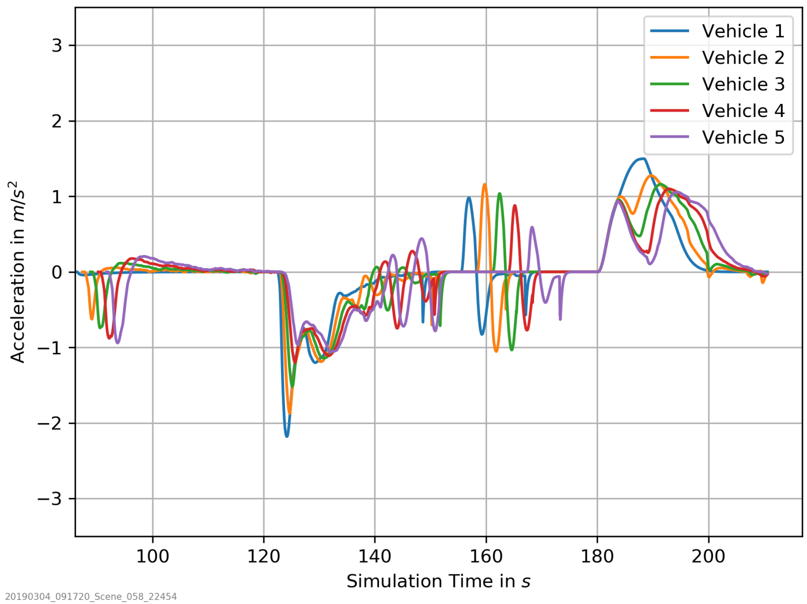
Figure 123: Creep at Intersection Scenario: Simulation Time vs. Operating Mode for TOSCo-enabled Vehicles at 1.0 s Time Gap and Small Distance Gap

Parameter Setting: Time gap: 1.5 s; Small Distance Gap



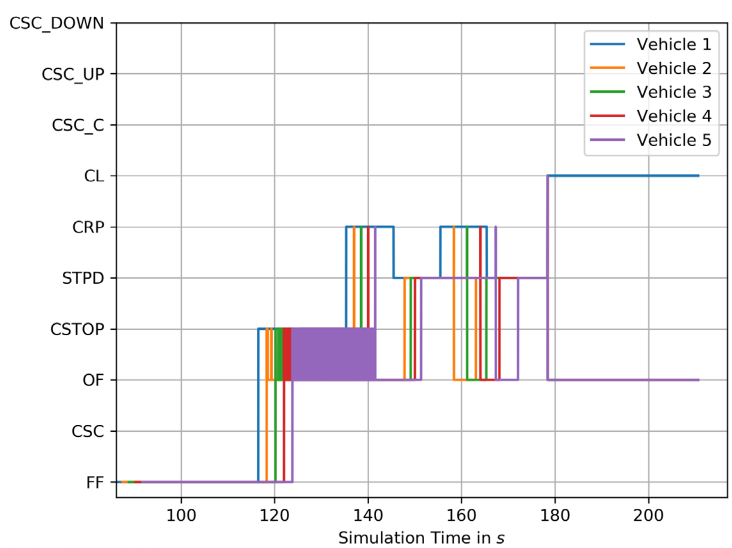
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 124: Creep at Intersection Scenario: Simulation Time vs. Speed for TOSCo-enabled Vehicles at 1.5 s Time Gap and Small Distance Gap



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 125: Creep at Intersection Scenario: Simulation Time vs. Acceleration for TOSCo-enabled Vehicles at 1.5 s Time Gap and Small Distance Gap



Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 126: Creep at Intersection Scenario: Simulation Time vs. Operating Mode for TOSCo-enabled Vehicles at 1.5 s Time Gap and Small Distance Gap