Traffic Optimization for Signalized Corridors (TOSCo) Phase 1 Project

Vehicle System Requirements and Architecture Specification Report

www.its.dot.gov/index/htm
Final Report – June 28, 2019
FHWA-JPO-20-793

U.S. Department of Transportation
Federal Highway Administration

Produced by Crash Avoidance Metrics Partners LLC in response to Cooperative Agreement Number DTFH6114H00002

U.S. Department of Transportation
Federal Highway Administration

Notice

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA-JPO-20-793		

4. Title and Subtitle Traffic Optimization for Signalized Corridors (TOSCo) Phase 1 Project Vehicle System Requirements and Architecture Specification	**5. Report Date** **6. Performing Organization Code**
7. Author(s) Guenther, Hendrik-Joern; Williams, Richard; Yoshida, Hiroyuki; Yumak, Tuncer; Moradi-Pari, Ehsan; Hussain, Shah; Naes, Tyler; Vijaya Kumar, Vivek; Probert, Neal; Sommerwerk, Kay; Bondarenko, Dennis; Wu, Guoyuan; Deering, Richard; Goudy, Roy	**8. Performing Organization Report No.**
9. Performing Organization Name And Address Crash Avoidance Metrics Partners LLC on behalf of the Vehicle-to-Infrastructure Consortium 27220 Haggerty Road, Suite D-1 Farmington Hills, MI 48331	**10. Work Unit No. (TRAIS)** **11. Contract or Grant No.** DTFH6114H00002
12. Sponsoring Agency Name and Address Intelligent Transportation Systems Joint Program Office U.S. Department of Transportation 1200 New Jersey Ave, SE Washington, DC 20590	**13. Type of Report and Period Covered** Final Report **14. Sponsoring Agency Code**

15. Supplementary Notes

16. Abstract

This report provides details for the TOSCo vehicle system requirements and architecture. After an introduction of the overall TOSCo concept, this report provides descriptions of the seven TOSCo operating modes and the transitions from one operating mode to another that are allowed and not allowed. This report also provides detailed descriptions of the various traffic scenarios that the TOSCo system is expected to encounter before providing details of the vehicle algorithm architecture, including the software architecture and the architecture for the mode selection which is the core of the TOSCo vehicle system. This report concludes with a list of requirements needed to enact the TOSCo system, which include both vehicle-side and infrastructure-side requirements as well as data elements needed from the roadside.

17. Key Words	18. Distribution Statement

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	78	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

Table of Contents

List of Figures

List of Tables

1 Introduction

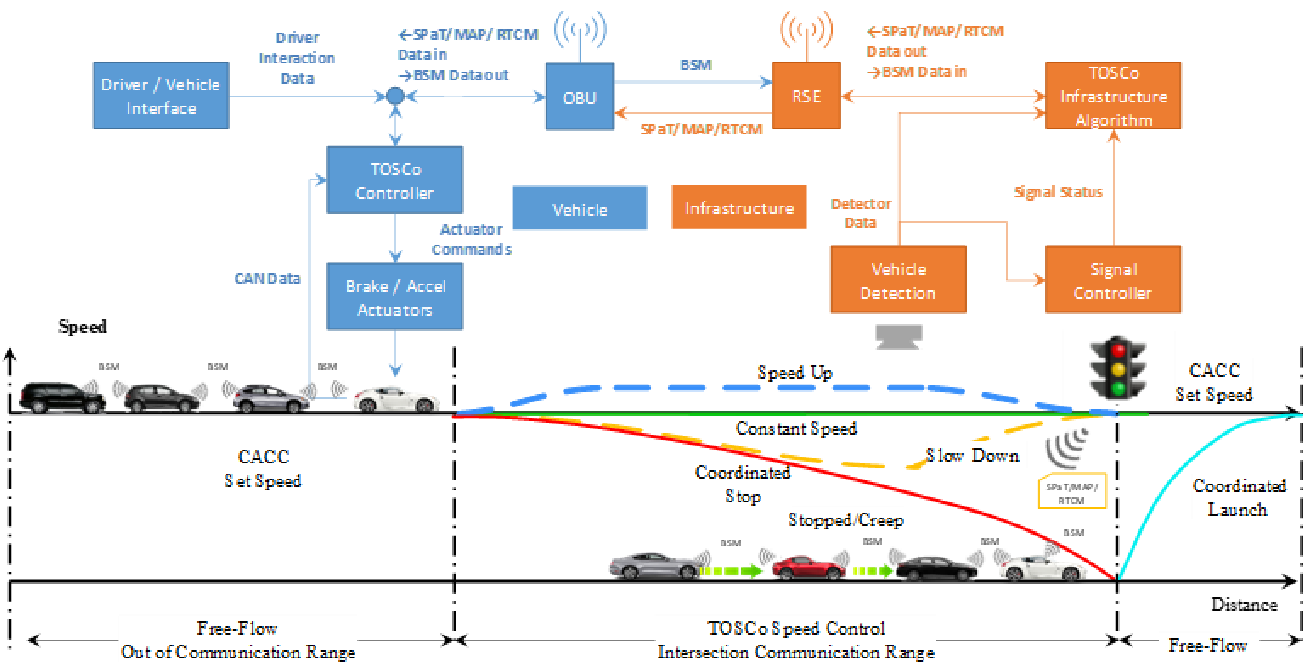
1.1 TOSCo Description

Traffic Optimization for Signalized Corridors (TOSCo) is a system comprised of both in-vehicle and infrastructure-based equipment. The in-vehicle equipment employs data transmitted via wireless communications from Roadside Units (RSU) to optimize vehicle fuel economy, emissions reduction and traffic mobility along a signalized corridor equipped to provide information required for TOSCo to operate.

The on-board application collects Signal Phase and Timing (SPaT) and intersection geometry (SAE J2735 MAP Data Message, or MAP) as well as data from nearby vehicles using Vehicle-to-Vehicle (V2V) communications to calculate the vehicle's optimal speed to pass through one or more traffic signals on a green light or to decelerate to a stop and subsequently launch in the most performance-optimized manner. Information is then sent to longitudinal vehicle control capabilities in the Host Vehicle (HV) to support partial automation.

1.2 TOSCo System Architecture Overview

The figure below is a high-level illustration of the overall TOSCo system architecture.



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

Figure 1: TOSCo System Architecture

1.3 TOSCo System Definitions

Following Vehicle

- Following Vehicle is defined as any vehicle following a preceding vehicle. For TOSCo, a vehicle is considered a following vehicle if a preceding vehicle is present at a distance of within 100 feet (30.5 m) for speeds up to 20 mph (32 km/h) or within a time gap of 5 seconds for speeds greater than 20 mph (32 km/h).

Host Vehicle

- Host Vehicle is defined as the vehicle that is the subject of discussion. It can also be referred to as the subject vehicle or ego vehicle.

Lead Vehicle

- Lead Vehicle is defined as the vehicle at the head of a string. The length of the string can be as short as one vehicle (e.g., no following vehicles). A vehicle is considered a Lead Vehicle if a preceding vehicle is not present or is greater than a distance up to 100 feet (30.5 m) for speeds up to 20 mph (32 km/h) or a time gap of 5 seconds for speeds greater than 20 mph (32 km/h).

Preceding Vehicle

- Preceding Vehicle is defined as a vehicle present ahead of and in the same as the HV at a distance up to 100 feet (30.5 m) for speeds up to 20 mph (32 km/h) or a time gap of 5 seconds for speeds greater than 20 mph (32 km/h).

Remote Vehicle

- Remote Vehicle is defined as any vehicle, whether it's DSRC-equipped, TOSCo-equipped or unequipped, that is within proximity of the HV.

Imminent Launch Window

- Imminent Launch Window begins when the last cross street phase prior to the green phase for the HV approach transitions to yellow and ends when the signal phase for the HV approach transitions to green.

Minimum Stop Distance

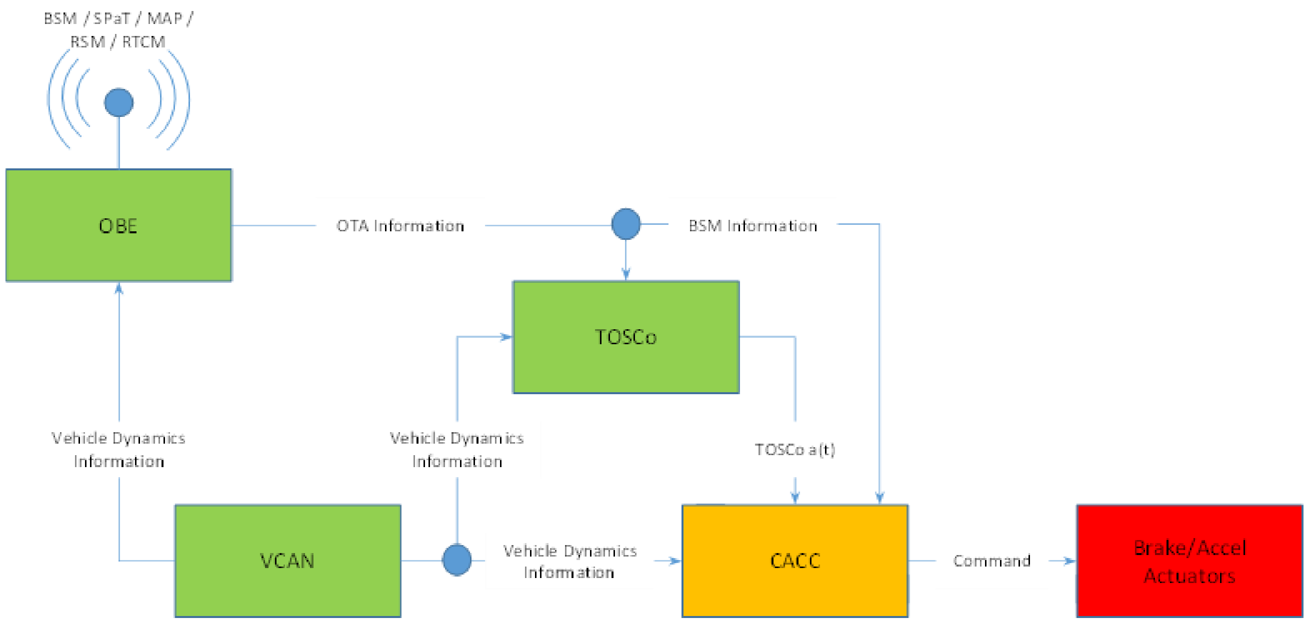
- Minimum Stop Distance is the distance equal to 3.5 meters measured from the back bumper of the preceding vehicle to the front bumper of the HV.

Green Window

- The Green Window is the period of time available for a vehicle to pass through an intersection unimpeded by a red light or the presence of a queue of vehicles. The Green Window opens at the onset of the green phase if no queue is present or when the last vehicle in the queue has cleared the intersection when a queue is present. The Green Window closes upon transition to the next red phase.

2 TOSCo Operating Modes

Seven operating modes are defined under TOSCo. TOSCo is dependent upon CACC for vehicle control as shown in the figure below.



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

Figure 2: TOSCo In-vehicle System Block Diagram

2.1 FREE_FLOW

If a TOSCo-equipped Host Vehicle (HV) is currently not receiving SPaT and MAP messages while the TOSCo function is active, the equipped vehicles operate in speed/gap control under CACC. HV speed range in Free Flow is from zero to CACC Set Speed.

2.2 COORDINATED_SPEED_CONTROL

A TOSCo-equipped Lead Vehicle (LV) enters this strategy when TOSCo is active, the LV is receiving SPaT and MAP messages from the nearest signalized intersection in the LV's path and there are no preceding vehicles in the path of the LV. The LV speed range in Coordinated Speed Control mode is from a minimum of v_{th} to a maximum of the posted speed limit, v_{lim}.

If the TOSCo-equipped LV determines that it will pass through the intersection prior to the amber phase, it employs SPaT message content to plan a speed profile that allows the vehicle to pass through the intersection by adjusting the TOSCo speed in order to achieve optimization objectives. One of three possible speed profiles may be employed, depending on current circumstances, slow down, speed up or maintain current speed.

2.3 COORDINATED_STOP

The TOSCo-equipped LV enters this strategy when TOSCo is active and receiving SPaT and MAP messages from the intersection in the vehicle's path. LV speed range in Coordinated Stop mode is from a TOSCo speed range of v_{lim}, to a final speed of zero.

If after processing information from the SPaT and MAP messages the TOSCo-equipped LV determines that it will not pass through the intersection prior to the amber phase, it employs the content of the messages to plan a speed profile that allows the vehicle to come to a stop at the stop bar or end of a queue while meeting optimization objectives.

2.4 STOPPED

The TOSCo-equipped vehicle is stationary at the stop bar or in a queue. During this time, all TOSCo-equipped vehicles are receiving SPaT messages that the TOSCo on-board system uses to determine the time remaining before the signal phase will transition to green. Vehicle speed range in Stopped mode is zero.

When the signal is about to change to green, the TOSCo on-board system prompts the driver's readiness for launch. The system first checks whether the driver has applied the brakes. If so, the system prompts the driver to release the brakes. If the brakes are not applied, the system notifies the driver of an impending launch at which point the driver must respond to indicate readiness for launch otherwise the vehicle will not move. This is applicable to all vehicles in the queue.

2.5 CREEP

The TOSCo-equipped vehicle is allowed to creep forward toward the stop bar to fill gaps left by vehicles that turned during the red phase. A common example would be a vehicle in the right lane of a multi-lane corridor making a permissible right turn during a red phase. Vehicle speed range in Creep mode is from a minimum of zero to a maximum of v_{creep}.

A less common example would be a vehicle making a permissible left turn during a red phase when the cross-street is a one-way street with traffic moving right to left from the point of view of the driver waiting at a red light.

Under these circumstances, the TOSCo-equipped vehicle would move forward to fill the gap created by the turning vehicle(s) but only after the driver acknowledges a prompt indicating it is possible to move forward in the queue.

2.6 COORDINATED_LAUNCH

The TOSCo-equipped vehicle broadcasts a coordinated launch message as it launches upon the signal transition to the green phase.

For members of the string, vehicles wait for a Coordinated Launch message and launch upon reception of the message under OPTIMIZED_FOLLOW mode. In the event the member of a string does not receive a Coordinated Launch message, and no preceding vehicles are present, the vehicle will transition to COORDINATED_LAUNCH as the new TOSCo-equipped LV and broadcasts a Coordinated Launch message as it launches.

For an analysis of the potential benefits that Coordinated Launch provides, please see APPENDIX A.

2.7 OPTIMIZED_FOLLOW

Under OPTIMIZED_FOLLOW, a TOSCo-equipped vehicle operates predominately as a member of a string under CACC speed and gap control, but it also continually receives SPaT and MAP messages to calculate its optimized speed profile which could cause it to leave the string and become the TOSCo-equipped LV in a new string if the vehicle determines that remaining in the string will cause it to operate outside its range of optimized control.

The vehicle also employs information from SPaT and MAP messages to determine whether it will be able to clear an approaching intersection before the next phase change. If the vehicle determines that it will not clear the intersection, it will transition to COORDINATED_STOP as the TOSCo-equipped LV in a newly formed string, otherwise it remains a member of a string under CACC speed and gap control.

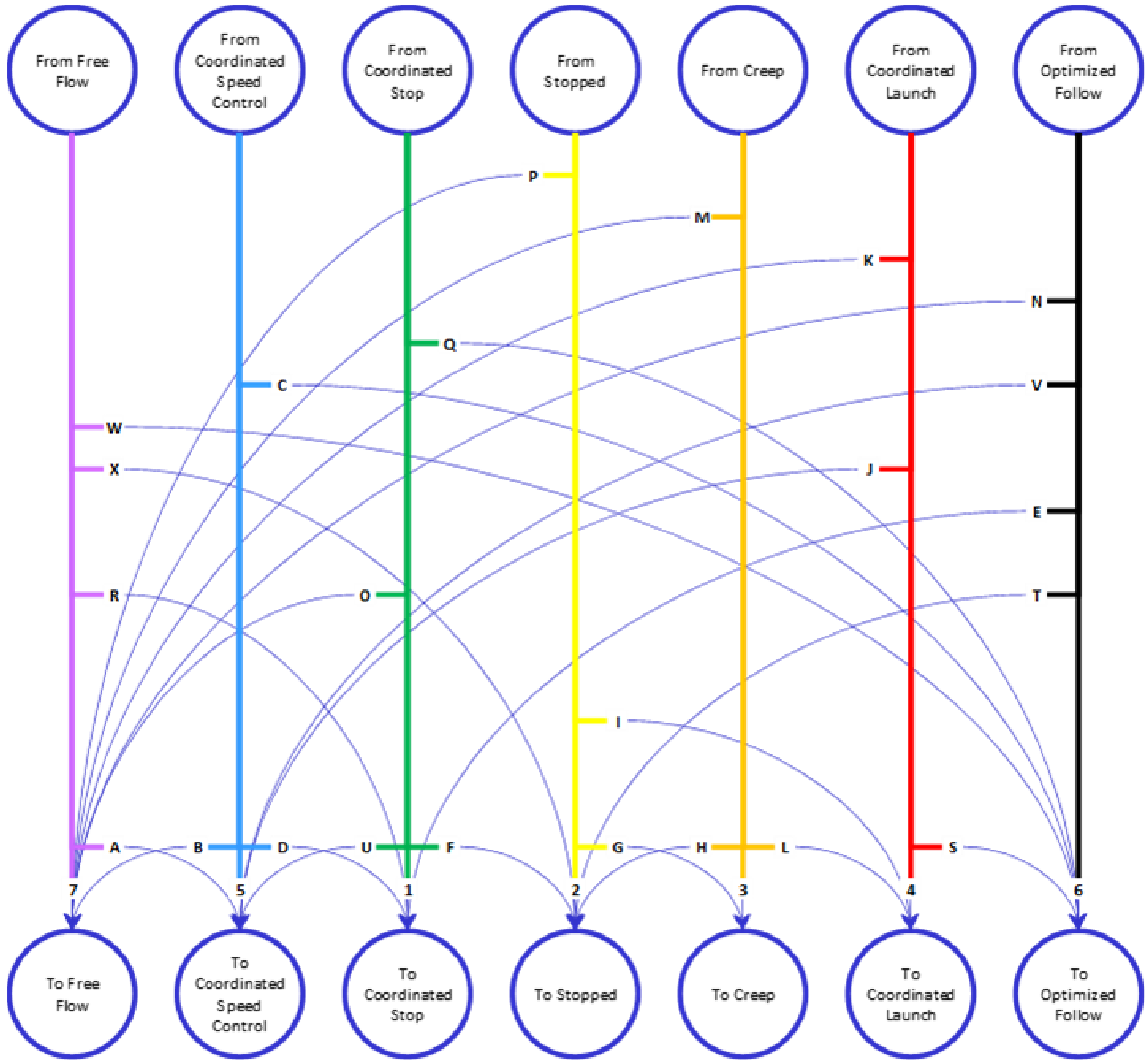
2.8 TOSCo Transitions

The numbers and capital letters in Table 1 below indicate transitions that are allowable while the lower case Greek letters indicate transitions that are not allowed. Figure 3 below illustrates all allowable TOSCo transitions.

Table 1: TOSCo Operating Modes Matrix

		Current Mode						
		CStop	Stopped	Creep	CLaunch	CSC	Opt Follow	Free Flow
Previous Mode	CStop	**1**	**F**	ζ	λ	**U**	**Q**	**O**
	Stopped	α	**2**	**G**	**I**	o	ρ	**P**
	Creep	β	**H**	**3**	**L**	π	σ	**M**
	CLaunch	γ	δ	η	**4**	**J**	**S**	**K**
	CSC	**D**	ε	θ	μ	**5**	**C**	**B**
	Opt Follow	**E**	**T**	ι	ν	**V**	**6**	**N**
	Free Flow	**R**	**X**	κ	ξ	**A**	**W**	**7**

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 3: Allowable TOSCo Transitions

The following paragraphs describe transitions between the TOSCo operating modes that are allowed and the TOSCo operating modes that are not allowed.

2.8.1 Allowed TOSCo Transitions

The following table (Table 2) identifies allowable transitions between TOSCo operating modes.

Table 2: Allowable TOSCo Transitions

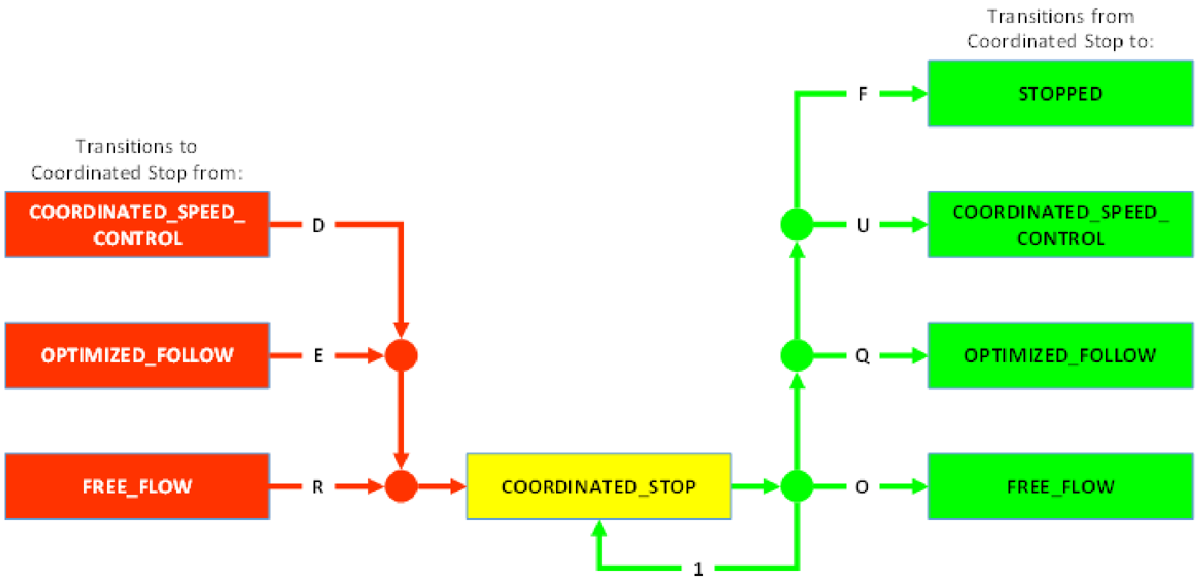
Transition	Operating Mode Before Transition	Operating Mode After Transition
A	Free Flow	Coordinated Speed Control
B	Coordinated Speed Control	Free Flow

Transition	Operating Mode Before Transition	Operating Mode After Transition
C	Coordinated Speed Control	Optimized Follow
D	Coordinated Speed Control	Coordinated Stop
E	Optimized Follow	Coordinated Stop
F	Coordinated Stop	Stopped
G	Stopped	Creep
H	Creep	Stopped
I	Stopped	Coordinated Launch
J	Coordinated Launch	Coordinated Speed Control
K	Coordinated Launch	Free Flow
L	Creep	Coordinated Launch
M	Creep	Free Flow
N	Optimized Follow	Free Flow
O	Coordinated Stop	Free Flow
P	Stopped	Free Flow
Q	Coordinated Stop	Optimized Follow
R	Free Flow	Coordinated Stop
S	Coordinated Launch	Optimized Follow
T	Optimized Follow	Stopped
U	Coordinated Stop	Coordinated Speed Control
V	Optimized Follow	Coordinated Speed Control
W	Free Flow	Optimized Follow
X	Free Flow	Stopped
1	Coordinated Stop	Coordinated Stop
2	Stopped	Stopped
3	Creep	Creep
4	Coordinated Launch	Coordinated Launch
5	Coordinated Speed Control	Coordinated Speed Control
6	Optimized Follow	Optimized Follow
7	Free Flow	Free Flow

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

2.8.1.1 Coordinated Stop

Figure 4 below illustrates the operating modes from which **Coordinated Stop** can be transitioned to and the operating modes that can be transitioned to from **Coordinated Stop**.



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

Figure 4: Transitions to / From Coordinated Stop

2.8.1.1.1 Transition to Coordinated Stop Mode from Another Operating Mode

TOSCo may transition to **Coordinated Stop** mode from one of the following operating modes, depending upon the circumstances present.

1. Coordinated Speed Control (Transition D)
2. Optimized Follow (Transition E)
3. Free Flow (Transition R)

Transition from Coordinated Speed Control Mode to Coordinated Stop Mode (Transition D)

Conditions for Transition:

- HV has determined from received SPaT / MAP messages that it will not arrive at the intersection within the green window

TOSCo Actions:

- HV broadcasts Coordinated Stop flag
- HV implements Coordinated Stop speed profile to stop at desired location

Transition from Optimized Follow Mode to Coordinated Stop Mode (Transition E)

Conditions for Transition:

- HV has determined from received SPaT / MAP messages that it will not arrive at the intersection within the green window

TOSCo Actions:

- HV checks whether it received a Coordinated Stop flag from a Preceding Vehicle
    - If no Coordinated Stop flag was received from a Preceding Vehicle, HV transitions to Coordinated Stop mode
- HV broadcasts Coordinated Stop flag

- HV implements Coordinated Stop speed profile to stop at desired location

Transition from Free-flow Mode to Coordinated Stop Mode (Transition R)

Conditions for Transition:

- HV has received SPaT / MAP messages for a minimum of two seconds
- HV has determined that a preceding vehicle is not present
- HV has determined from received SPaT / MAP messages that it will not arrive at the intersection within the green window

TOSCo Actions:

- HV checks whether it received a Coordinated Stop flag from a Preceding Vehicle
    - If no Coordinated Stop flag was received from a Preceding Vehicle, HV transitions to Coordinated Stop mode
- HV broadcasts Coordinated Stop flag
- HV implements Coordinated Stop speed profile to stop at desired location

2.8.1.1.2 Transition from Coordinated Stop Mode to Another Operating Mode

TOSCo may remain in **Coordinated Stop** mode or transition to one of the following operating modes, depending upon the circumstances present.

1. Stopped (Transition F)
2. Coordinated Speed Control (Transition U)
3. Optimized Follow (Transition Q)
4. Free Flow (Transition O)

Transition from Coordinated Stop Mode to Stopped Mode (Transition F)

Conditions for Transition:

- HV approaches to within the minimum stop distance of the stop bar

TOSCo Actions:

- HV brakes to zero speed

Transition from Coordinated Stop Mode to Coordinated Speed Control Mode (Transition U)

Conditions for Transition:

- HV determines it can clear the approaching intersection within the green window

TOSCo Actions:

- HV implements Coordinated Speed Control speed profile

Transition from Coordinated Stop Mode to Optimized Follow Mode (Transition Q)

Conditions for Transition:

- HV detects the presence of a Preceding Vehicle

TOSCo Actions:

- HV implements CACC control
- Continues acting on SPaT / MAP messages

Transition from Coordinated Stop Mode to Free-flow Mode (Transition O)

Conditions for Transition:

- HV has not received SPaT / MAP / messages for a minimum of two seconds

TOSCo Actions:

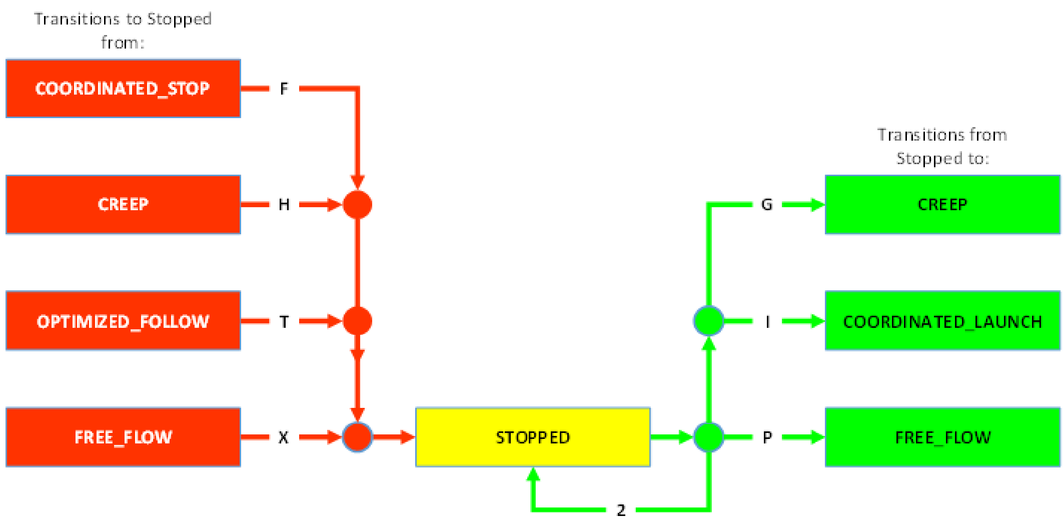
- HV maintains calculated Coordinated Stop speed profile
- HV notifies river of transition to Free-flow mode (need to notify driver that HV may not enter Coordinated Launch due to loss of SPaT data)

OR

- HV implements CACC control

2.8.1.2 Stopped

Figure 5 below illustrates the operating modes from which **Stopped** mode can be transitioned to and the operating modes that can be transitioned to from **Stopped** mode.



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

Figure 5: Transitions to / From Stopped Mode

2.8.1.2.1 Transition to Stopped Mode from Another Operating Mode

TOSCo may transition to **Stopped** mode from one of the following operating modes, depending upon the circumstances present.

1. Coordinated Stop (Transition F)
2. Creep (Transition H)
3. Optimized Follow (Transition T)
4. Free Flow (Transition X)

Transition from Coordinated Stop Mode to Stopped Mode (Transition F)

Conditions for Transition:

- HV approaches to within the minimum stop distance of the stop bar

TOSCo Actions:

- HV brakes to zero speed

Transition from Creep Mode to Stopped Mode (Transition H)

Conditions for Transition:

- HV approaches to within the minimum stop distance of the stop bar

  OR

- HV approaches to within the minimum stop distance of the Preceding Vehicle

  OR

- SPaT or MAP information is not available AND
  - No Preceding Vehicle is present and HV is less than or equal to minimum stop distance of the stop bar

TOSCo Actions:

- HV brakes to zero speed

Transition from Optimized Follow Mode to Stopped Mode (Transition T)

Conditions for Transition:

- HV approaches to within the minimum stop distance of the Preceding Vehicle

TOSCo Actions:

- HV brakes to zero speed

Transition from Free-flow Mode to Stopped Mode (Transition X)

Conditions for Transition:

- HV is stopped
- HV has received SPaT / MAP messages for a minimum of two seconds

TOSCo Actions:

- HV brakes to zero speed

2.8.1.2.2 Transition from Stopped Mode to Another Operating Mode

TOSCo may remain in **Coordinated Stop** mode or transition to one of the following operating modes, depending upon the circumstances present.

1. Creep (Transition G)
2. Coordinated Launch (Transition I)
3. Free Flow (Transition P)

Transition from Stopped Mode to Creep Mode (Transition G)

Conditions for Transition:

- Traffic signal is Red AND either
  - Distance to the Preceding Vehicle is greater than 2 times the minimum stop distance

    OR

  - Distance to stop bar is greater than 2 times minimum stop distance with no Preceding Vehicle present

TOSCo Actions:

- HV prompts Driver with a Creep indication
- Driver acknowledges the prompt by a defined action (e.g., press of a button)
- HV remains in Stopped mode until Driver acknowledges prompt

Transition from Stopped Mode to Coordinated Launch Mode (Transition I)

Conditions for Transition:

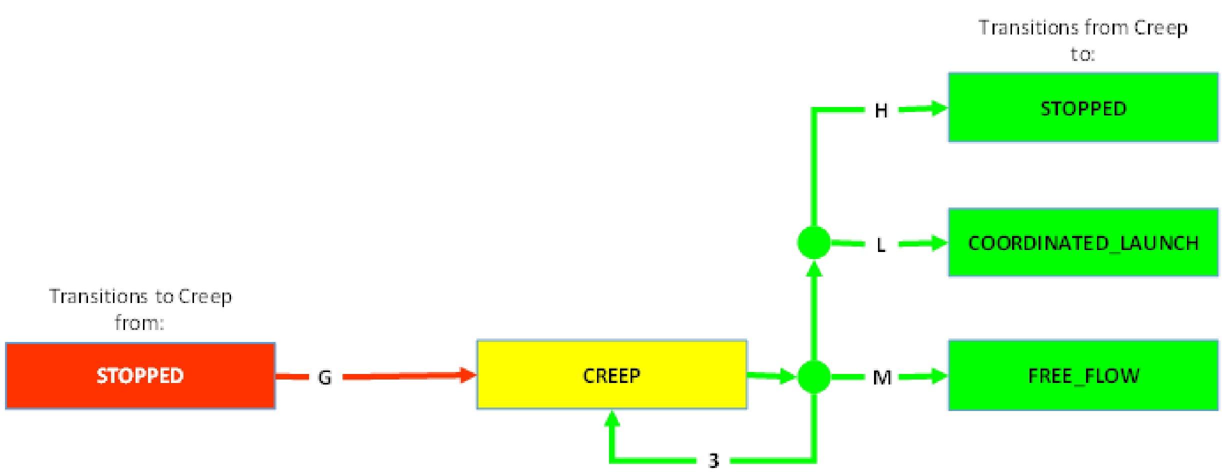
- HV is stationary
- HV is receiving SPaT / MAP messages from current intersection
- Imminent Launch Window opens

TOSCo Actions:

- Prior to transition to Green signal:
  - HV prompts Driver with a Coordinated Launch indication
    - Driver acknowledges the prompt by a defined action (e.g., press of a button)
    - HV remains in Stopped mode until Driver acknowledges prompt
- Upon transition to Green signal:
  - HV verifies no Preceding Vehicle is present
    - HV Broadcasts Coordinated Launch flag
    - HV implements Coordinated Launch speed profile
  - HV verifies Preceding Vehicle is present
- HV transitions to Optimized Follow mode (Transition S)

2.8.1.3 Creep

Figure 6 below illustrates from where **Creep** mode can be transitioned to and the operating modes that can be transitioned to from **Creep** mode.



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

Figure 6: Transitions to / From Creep

2.8.1.3.1 Transition to Creep Mode from Another Operating Mode

TOSCo may transition to **Creep** mode only from Stopped mode.

Transition from Stopped Mode to Creep Mode (Transition G)

Conditions for Transition:

- Traffic signal is Red AND either
  - Distance to the Preceding Vehicle is greater than 2 times the minimum stop distance

    OR

  - Distance to stop bar is greater than 2 times minimum stop distance with no Preceding Vehicle present

TOSCo Actions:

- HV prompts Driver with a Creep indication
- Driver acknowledges the prompt by a defined action (e.g., press of a button)

HV remains in Stopped mode until Driver acknowledges prompt

2.8.1.3.2 Transition from Stopped Mode to Another Operating Mode

TOSCo can remain in **Creep** mode or transition to one of the following operating modes, depending upon the circumstances present.

1. Stopped (Transition H)
2. Coordinated Launch (Transition L)
3. Free Flow (Transition M)

Transition from Creep Mode to Stopped Mode (Transition H)

Conditions for Transition:

- HV approaches to within the minimum stop distance of the stop bar

  OR

- HV approaches to within the minimum stop distance of the Preceding Vehicle

  OR

- SPaT or MAP information is not available AND
  - No Preceding Vehicle is present and HV is less than or equal to minimum stop distance of the stop bar

TOSCo Actions:

- HV brakes to zero speed

Transition from Creep Mode to Coordinated Launch Mode (Transition L)

Conditions for Transition:

- HV speed is within 1.5 m/s
- HV is receiving SPaT / MAP messages from current intersection
- Imminent Launch Window opens
- Distance to Preceding Vehicle is greater than minimum stop distance at the time signal will transition to Green

OR

- No Preceding Vehicle is present, and HV is within minimum stop distance of the stop bar at the time signal will transition to Green

TOSCo Actions:

- Prior to transition to Green signal:
  - HV prompts Driver with a Coordinated Launch indication
    - Driver acknowledges the prompt by a defined action (e.g., press of a button)
    - HV remains in Creep mode until
      - Driver acknowledges prompt

        OR

      - HV stops at stop bar
- Upon transition to Green signal:
  - HV verifies no Preceding Vehicle is present
    - HV Broadcasts Coordinated Launch flag
    - HV implements Coordinated Launch speed profile
  - HV verifies Preceding Vehicle is present
    - HV transitions to Optimized Follow mode (Transition S)

Transition from Creep Mode to Free-flow Mode (Transition M)

Conditions for Transition:

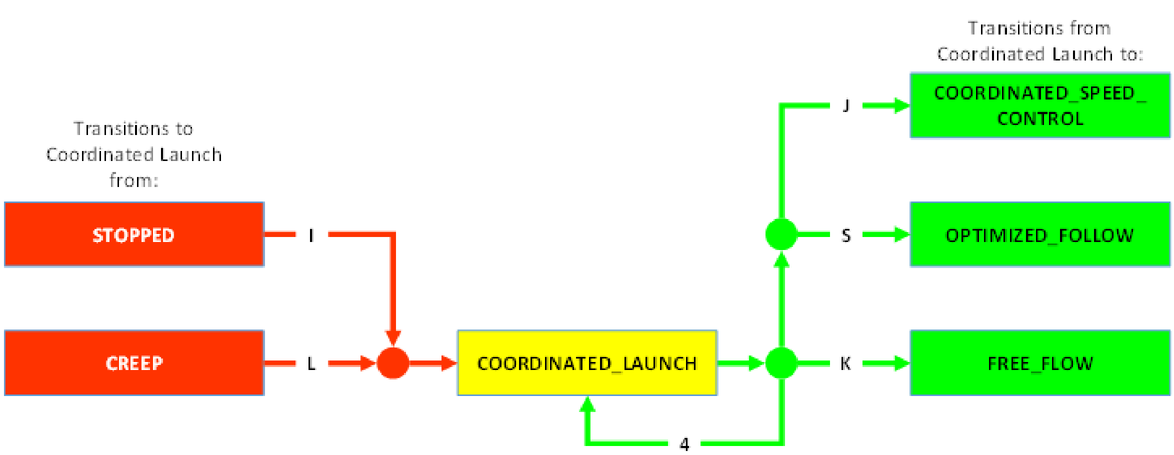
- HV has not received SPaT / MAP messages for a minimum of two seconds

TOSCo Actions:

- HV implements CACC control

2.8.1.4 Coordinated Launch

Figure 7 below illustrates the operating modes from which **Coordinated Launch** mode can be transitioned to and the operating modes that can be transitioned to from **Coordinated Launch** mode.



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

Figure 7: Transitions to / From Coordinated Launch Mode

2.8.1.4.1 Transition to Coordinated Launch Mode from Another Operating Mode

TOSCo may transition to **Coordinated Launch** mode from one of the following operating modes, depending upon the circumstances present.

1. Stopped (Transition I)
2. Creep (Transition L)

Transition from Stopped Mode to Coordinated Launch Mode (Transition I)

Conditions for Transition:

- HV is stationary
- HV is receiving SPaT / MAP messages from current intersection
- Imminent Launch Window opens

TOSCo Actions:

- Prior to transition to Green signal:
  - HV prompts Driver with a Coordinated Launch indication
    - Driver acknowledges the prompt by a defined action (e.g., press of a button)
    - HV remains in Stopped mode until Driver acknowledges prompt
- Upon transition to Green signal:
  - HV verifies no Preceding Vehicle is present
    - HV Broadcasts Coordinated Launch flag
    - HV implements Coordinated Launch speed profile
  - HV verifies Preceding Vehicle is present
    - HV transitions to Optimized Follow mode (Transition S)

Transition from Creep Mode to Coordinated Launch Mode (Transition L)

Conditions for Transition:

- HV speed is within 1.5 m/s
- HV is receiving SPaT / MAP messages from current intersection
- Imminent Launch Window opens
- Distance to Preceding Vehicle is greater than minimum stop distance at the time signal will transition to Green

  OR

- No Preceding Vehicle is present HV is within minimum stop distance of the stop bar at the time signal will transition to Green

TOSCo Actions:

- Prior to transition to Green signal:
  - HV prompts Driver with a Coordinated Launch indication
    - Driver acknowledges the prompt by a defined action (e.g., press of a button)
    - HV remains in Creep mode until
      - Driver acknowledges prompt

        OR

      - HV stops at stop bar
- Upon transition to Green signal:
  - HV verifies no Preceding Vehicle is present
    - HV Broadcasts Coordinated Launch flag

        - HV implements Coordinated Launch speed profile
    - HV verifies Preceding Vehicle is present
        - HV transitions to Optimized Follow mode (Transition S)

2.8.1.4.2 Transition from Coordinated Launch Mode to Another Operating Mode

TOSCo may remain in **Coordinated Launch** mode or transition to one of the following operating modes, depending upon the circumstances present.

1. Coordinated Speed Control (Transition J)
2. Optimized Follow (Transition S)
3. Free Flow (Transition K)

Transition from Coordinated Launch Mode to Coordinated Speed Control Mode (Transition J)

Conditions for Transition:

- HV reaches steady-state speed control as defined for Coordinated Speed Control mode

TOSCo Actions:

- HV implements Coordinated Speed Control speed profile

Transition from Coordinated Launch Mode to Optimized Follow Mode (Transition S)

Conditions for Transition:

- HV determines that a Preceding Vehicle is present

TOSCo Actions:

- HV implements CACC control
- Continues acting on SPaT / MAP messages

Transition from Coordinated Launch Mode to Free-flow Mode (Transition K)

Conditions for Transition:

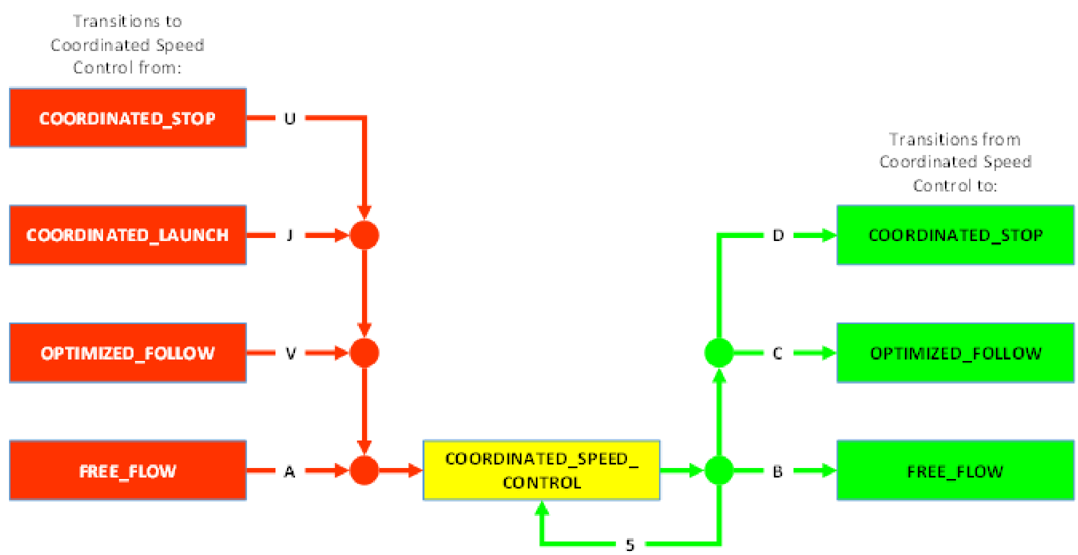
- HV has not received SPaT / MAP messages for a minimum of two seconds

TOSCo Actions:

- HV implements CACC control

2.8.1.5 Coordinated Speed Control

Figure 8 below illustrates the operating modes from which **Coordinated Speed Control** can be transitioned to and the operating modes that can be transitioned to from **Coordinated Speed Control** mode.



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

Figure 8: Transitions to / From Coordinated Speed Control

2.8.1.5.1 Transition to Coordinated Speed Control Mode from Another Operating Mode

TOSCo may transition to **Coordinated Speed Control** mode from one of the following operating modes, depending upon the circumstances present.

1. Coordinated Stop (Transition U)
2. Coordinated Launch (Transition J)
3. Optimized Follow (Transition V)
4. Free Flow (Transition A)

Transition from Coordinated Stop Mode to Coordinated Speed Control Mode (Transition U)

Conditions for Transition:

- HV determines it can clear the approaching intersection within the green window

TOSCo Actions:

- HV implements Coordinated Speed Control speed profile

Transition from Coordinated Launch Mode to Coordinated Speed Control Mode (Transition J)

Conditions for Transition:

- HV reaches steady-state speed control as defined for Coordinated Speed Control mode

TOSCo Actions:

- HV implements Coordinated Speed Control speed profile

Transition from Optimized Follow Mode to Coordinated Speed Control Mode (Transition V)

Conditions for Transition:

- HV determines that a Preceding Vehicle is not present

TOSCo Actions:

- HV implements Coordinated Speed Control speed profile

Transition from Free-flow Mode to Coordinated Speed Control Mode (Transition A)

Conditions for Transition:

- HV has received SPaT / MAP messages for a minimum of two seconds
- HV has determined that a preceding vehicle is not present
- HV has determined from received SPaT / MAP messages that it will arrive at the intersection within the green window

TOSCo Actions:

- HV implements Coordinated Speed Control speed profile

2.8.1.5.2 Transition from Coordinated Speed Control Mode to Another Operating Mode

TOSCo may remain in **Coordinated Speed Control** mode or transition to one of the following operating modes, depending upon the circumstances present.

1. Coordinated Stop (Transition D)
2. Optimized Follow (Transition C)
3. Free Flow (Transition B)

Transition from Coordinated Speed Control Mode to Coordinated Stop Mode (Transition D)

Conditions for Transition:

- HV has determined from received SPaT / MAP messages that it will not arrive at the intersection within the green window

TOSCo Actions:

- HV broadcasts Coordinated Stop flag
- HV implements Coordinated Stop speed profile to stop at desired location

Transition from Coordinated Speed Control Mode to Optimized Follow Mode (Transition C)

Conditions for Transition:

- HV determines that a Preceding Vehicle is present

TOSCo Actions:

- HV implements CACC control
- HV Continues acting on SPaT / MAP messages

Transition from Coordinated Speed Control Mode to Free-flow Mode (Transition B)

Conditions for Transition:

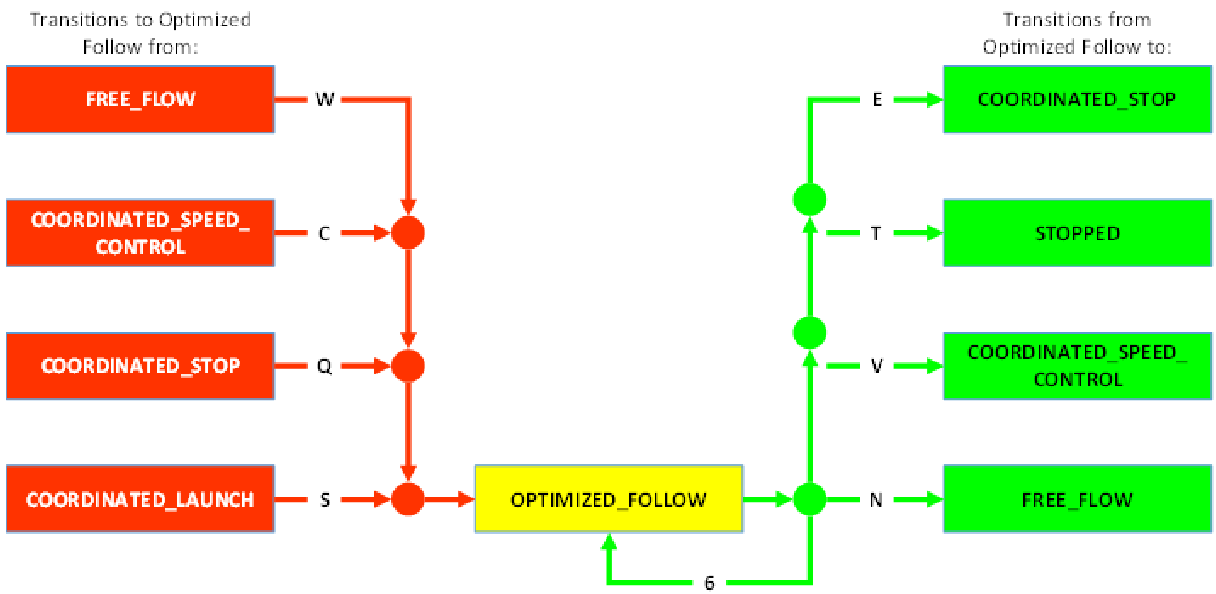
- HV has not received SPaT / MAP messages for a minimum of two seconds

TOSCo Actions:

- HV implements CACC control

2.8.1.6 Optimized Follow

Figure 9 below illustrates the operating modes from which **Optimized Follow** mode can be transitioned to and the operating modes that can be transitioned to from **Optimized Follow** mode.



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

Figure 9: Transitions to / From Optimized Follow

2.8.1.6.1 Transition to Optimized Follow Mode from Another Operating Mode

TOSCo may transition to **Optimized Follow** mode from one of the following operating modes, depending upon the circumstances present.

1. Free Flow (Transition W)
2. Coordinated Speed Control (Transition C)
3. Coordinated Stop (Transition Q)
4. Coordinated Launch (Transition S)

Transition from Free-flow Mode to Optimized Follow Mode (Transition W)

Conditions for Transition:

- HV has received SPaT / MAP messages for a minimum of two seconds
- HV has detected the presence of a preceding vehicle
- HV has determined from received SPaT / MAP messages that it will arrive at the intersection within the green window

TOSCo Actions:

- HV implements CACC control
- HV Continues acting on SPaT / MAP messages

Transition from Coordinated Speed Control Mode to Optimized Follow Mode (Transition C)

Conditions for Transition:

- HV determines that a Preceding Vehicle is present

TOSCo Actions:

- HV implements CACC control
- HV Continues acting on SPaT / MAP messages

Transition from Coordinated Stop Mode to Optimized Follow Mode (Transition Q)

Conditions for Transition:

- HV detects the presence of a Preceding Vehicle

TOSCo Actions:

- HV implements CACC control
- Continues acting on SPaT / MAP messages

Transition from Coordinated Launch Mode to Optimized Follow Mode (Transition S)

Conditions for Transition:

- HV determines that a Preceding Vehicle is present

TOSCo Actions:

- HV implements CACC control
- Continues acting on SPaT / MAP messages

2.8.1.6.2 Transition from Optimized Follow Mode to Another Operating Mode

TOSCo may remain in **Optimized Follow** mode or transition to one of the following operating modes, depending upon the circumstances present.

1. Coordinated Stop (Transition E)
2. Stopped (Transition T)
3. Coordinated Speed Control (Transition V)
4. Free Flow (Transition N)

Transition from Optimized Follow Mode to Coordinated Stop Mode (Transition E)

Conditions for Transition:

- HV has determined from received SPaT / MAP messages that it will not arrive at the intersection within the green window

TOSCo Actions:

- HV checks whether it received a Coordinated Stop flag from a Preceding Vehicle
    - If no Coordinated Stop flag was received from a Preceding Vehicle, HV transitions to Coordinated Stop mode
- HV broadcasts Coordinated Stop flag
- HV implements Coordinated Stop speed profile to stop at desired location

Transition from Optimized Follow Mode to Stopped Mode (Transition T)

Conditions for Transition:

- HV approaches to within the minimum stop distance of the Preceding Vehicle

TOSCo Actions:

- HV brakes to zero speed

Transition from Optimized Follow Mode to Coordinated Speed Control Mode (Transition V)

Conditions for Transition:

- HV determines that a Preceding Vehicle is not present

TOSCo Actions:

- HV implements Coordinated Speed Control speed profile

Transition from Optimized Follow Mode to Free-flow Mode (Transition N)

Conditions for Transition:

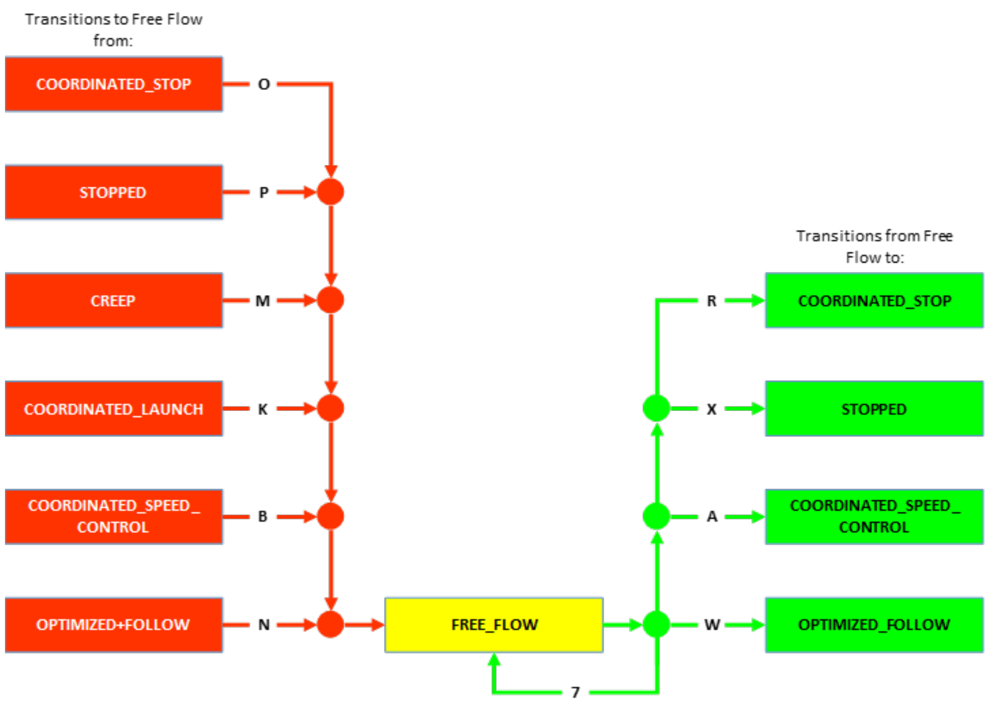
- HV has not received SPaT / MAP messages for a minimum of two seconds

TOSCo Actions:

- HV implements CACC control

2.8.1.7 Free Flow

Figure 10 below illustrates the operating modes from which **Free-flow** mode can be transitioned to and the operating modes that can be transitioned to from **Free-flow** mode.



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

Figure 10: Transitions to / From Free Flow

2.8.1.7.1 Transition to Free-flow Mode from Another Operating Mode

TOSCo may transition to **Free-flow** mode from one of the following operating modes, depending upon the circumstances present.

1. Coordinated Stop (Transition O)
2. Stopped (Transition P)
3. Creep (Transition M)
4. Coordinated Launch (Transition K)
5. Coordinated Speed Control (Transition B)
6. Optimized Follow (Transition N)

Transition from Coordinated Stop Mode to Free-flow Mode (Transition O)

Conditions for Transition:

- HV has not received SPaT / MAP messages for a minimum of two seconds

TOSCo Actions:

- HV maintains calculated Coordinated Stop speed profile
- HV notifies Driver of transition to Free-flow mode (Need to notify Driver that HV may not enter Coordinated Launch due to loss of SPaT data)

OR

- HV implements CACC control

Transition from Stopped Mode to Free-flow Mode (Transition P)

Conditions for Transition:

- HV has not received SPaT / MAP messages for a minimum of two seconds

TOSCo Actions:

- HV implements CACC control

Transition from Creep mode to Free-flow mode (Transition M)

Conditions for Transition:

- HV has not received SPaT / MAP messages for a minimum of two seconds

TOSCo Actions:

- HV implements CACC control

Transition from Coordinated Launch Mode to Free-flow Mode (Transition K)

Conditions for Transition:

- HV has not received SPaT / MAP messages for a minimum of two seconds

TOSCo Actions:

- HV implements CACC control

Transition from Coordinated Speed Control Mode to Free-flow Mode (Transition B)

Conditions for Transition:

- HV has not received SPaT / MAP messages for a minimum of two seconds

TOSCo Actions:

- HV implements CACC control

Transition from Optimized Follow mode to Free-flow Mode (Transition N)

Conditions for Transition:

- HV has not received SPaT / MAP messages for a minimum of two seconds

TOSCo Actions:

- HV implements CACC control

2.8.1.7.2 Transition from Free-flow Mode to Another Operating Mode

TOSCo may remain in **Free-flow** mode or transition to one of the following operating modes, depending upon the circumstances present.

5. Coordinated Stop (Transition R)
6. Stopped (Transition X)
7. Coordinated Speed Control (Transition A)
8. Optimized Follow (Transition W)

Transition from Optimized Follow Mode to Free-flow Mode (Transition R)

Conditions for Transition:

- HV has received SPaT / MAP messages for a minimum of two seconds
- HV has determined that a preceding vehicle is not present
- HV has determined from received SPaT / MAP messages that it will not arrive at the intersection within the green window

TOSCo Actions:

- HV checks whether it received a Coordinated Stop flag from a Preceding Vehicle
    - If no Coordinated Stop flag was received from a Preceding Vehicle, HV transitions to Coordinated Stop mode
- HV broadcasts Coordinated Stop flag
- HV implements Coordinated Stop speed profile to stop at desired location

Transition from Free-flow Mode to Stopped Mode (Transition X)

Conditions for Transition:

- HV is stopped
- HV has received SPaT / MAP messages for a minimum of two seconds

TOSCo Actions:

- HV brakes to zero speed

Transition from Optimized Follow Mode to Free-flow Mode (Transition A)

Conditions for Transition:

- HV has received SPaT / MAP messages for a minimum of two seconds
- HV has determined that a preceding vehicle is not present
- HV has determined from received SPaT / MAP messages that it will arrive at the intersection within the green window

TOSCo Actions:

- HV implements Coordinated Speed Control speed profile

Transition from Optimized Follow Mode to Free-flow Mode (Transition W)

Conditions for Transition:

- HV has received SPaT / MAP messages for a minimum of two seconds
- HV has detected the presence of a preceding vehicle
- HV has determined from received SPaT / MAP messages that it will arrive at the intersection within the green window

TOSCo Actions:

- HV implements CACC control
- HV Continues acting on SPaT / MAP messages

2.8.2 TOSCo Transitions Not Allowed

Table 3 below lists the transitions that are not allowed.

Table 3: TOSCo Transitions Not Allowed

Transition	Operating Mode Before Transition	Operating Mode After Transition
α	Stopped	Coordinated Stop
β	Creep	Coordinated Stop
γ	Coordinated Launch	Coordinated Stop
δ	Coordinated Launch	Stopped
ε	Coordinated Speed Control	Stopped
ζ	Coordinated Stop	Creep
η	Coordinated Launch	Creep
θ	Coordinated Speed Control	Creep
ι	Optimized Follow	Creep
κ	Free Flow	Creep
λ	Coordinated Stop	Coordinated Launch
μ	Coordinated Speed Control	Coordinated Launch
ν	Optimized Follow	Coordinated Launch
ξ	Free Flow	Coordinated Launch
o	Stopped	Coordinated Speed Control
π	Creep	Coordinated Speed Control
ρ	Stopped	Optimized Follow
σ	Creep	Optimized Follow

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

Transition from Stopped Mode to Coordinated Stop Mode (Transition α)

- HV has entered Stopped mode from Coordinated Stop mode, therefore, there would be no reason to transition back to Coordinated Stop mode

Transition from Creep Mode to Coordinated Stop Mode (Transition β)

- HV has transitioned from Stopped mode prior to entering Creep mode, therefore, there is no reason to ever transition back to Coordinated Stop mode

Transition from Coordinated Launch Mode to Coordinated Stop Mode (Transition γ)

- To transition from Coordinated Launch mode to Coordinated Stop mode, the HV would first have to transition from Coordinated Launch mode to either Coordinated Speed Control, Optimized Follow or Free-flow modes prior to transitioning to Coordinated Stop mode

Transition from Coordinated Launch Mode to Stopped Mode (Transition δ)

- To transition from Coordinated Launch mode to Stopped mode, the HV would first have to transition from Coordinated Launch mode to either Coordinated Speed Control, Optimized Follow or Free-flow modes then Coordinated Stop mode prior to transitioning to Stopped mode

Transition from Coordinated Speed Control Mode to Stopped Mode (Transition ε)

- To transition from Coordinated Speed Control mode to Stopped mode, the HV would first have to transition from Coordinated Speed Control mode to Coordinated Stop mode prior to transitioning to Stopped mode

Transition from Coordinated Stop Mode to Creep Mode (Transition ζ)

- To transition from Coordinated Stop mode to Creep mode, the HV would first have to transition from Coordinated Stop mode to Stopped mode prior to transitioning to Creep mode

Transition from Coordinated Launch Mode to Creep Mode (Transition η)

- To transition from Coordinated Launch mode to Creep mode, the HV would first have to transition from Coordinated Launch mode to either Coordinated Speed Control, Optimized Follow or Free-flow modes then Coordinated Stop mode and finally Stopped mode prior to transitioning to Creep mode

Transition from Coordinated Speed Control Mode to Creep Mode (Transition θ)

- To transition from Coordinated Speed Control mode to Creep mode, the HV would first have to transition from Coordinated Speed Control mode to either Coordinated Stop, Optimized Follow or Free-flow modes then Stopped mode prior to transitioning to Creep mode

Transition from Optimized Follow Mode to Creep Mode (Transition ι)

- To transition from Optimized Follow mode to Creep mode, the HV would first have to transition from Optimized Follow mode to Stopped mode prior to transitioning to Creep mode

Transition from Free-flow Mode to Creep Mode (Transition κ)

- To transition from Free-flow mode to Creep mode, the HV would first have to transition from Free-flow mode to Stopped mode prior to transitioning to Creep mode

Transition from Coordinated Stop Mode to Coordinated Launch Mode (Transition λ)

- To transition from Coordinated Stop mode to Coordinated Launch mode, the HV would first have to transition from Coordinated Stop mode to Stopped mode prior to transitioning to Coordinated Launch mode

Transition from Coordinated Speed Control Mode to Coordinated Launch Mode (Transition μ)

- To transition from Coordinated Speed Control mode to Coordinated Launch mode, the HV would first have to transition from Coordinated Speed Control mode to Coordinated Stop mode then to Stopped mode prior to transitioning to Coordinated Launch mode

Transition from Optimized Follow Mode to Coordinated Launch Mode (Transition ν)

- To transition from Optimized Follow mode to Coordinated Launch mode, the HV would first have to transition from Optimized Follow mode to Stopped mode prior to transitioning to Coordinated Launch mode

Transition from Free-flow Mode to Coordinated Launch Mode (Transition ξ)

- To transition from Free-flow mode to Coordinated Launch mode, the HV would first have to transition from Free-flow mode to Stopped mode prior to transitioning to Coordinated Launch mode

Transition from Stopped Mode to Coordinated Speed Control Mode (Transition o)

- To transition from Stopped mode to Coordinated Speed Control mode, the HV would first have to transition from Stopped mode to Coordinated Launch mode prior to transitioning to Coordinated Speed Control mode

Transition from Creep Mode to Coordinated Speed Control Mode (Transition π)

- To transition from Creep mode to Coordinated Speed Control mode, the HV would first have to transition from Creep mode to Coordinated Launch mode prior to transitioning to Coordinated Speed Control mode

Transition from Stopped Mode to Optimized Follow Mode (Transition ρ)

- To transition from Stopped mode to Optimized Follow mode, the HV would first have to transition from Stopped mode to Coordinated Launch mode prior to transitioning to Optimized Follow mode

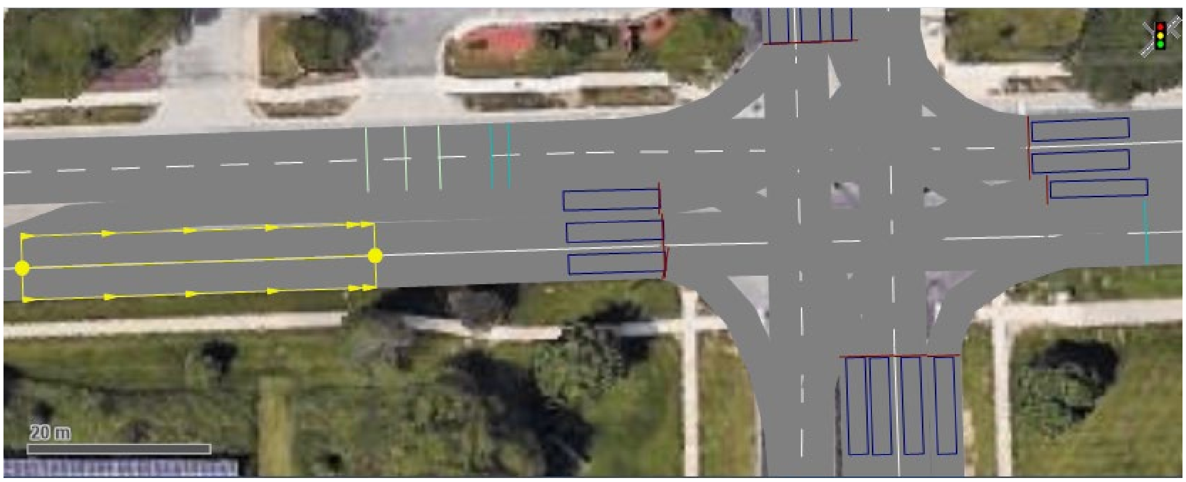
Transition from Creep Mode to Optimized Follow Mode (Transition σ)

- To transition from Creep mode to Optimized Follow mode, the HV would first have to transition from Creep mode to Coordinated Launch mode prior to transitioning to Optimized Follow mode

3 Traffic Scenarios Encountered by TOSCo

This chapter introduces the various traffic scenarios that are encountered while operating a vehicle under the TOSCo functionality. Each section of this chapter outlines a definition, visualization, and various parameters that correspond to the respective scenario. In simulation, the following scenarios are set up in a similar manner to the environment detailed further in the *CACC Final Report*. The parameters defined in this chapter were implemented into a Simulink model, as defined in the "Model CPU" subsection of the *CACC Final Report*. The driving behaviors were defined in the VISSIM Traffic Simulator Version 9 and is further defined in the "Traffic Simulation CPU" subsection of the same report.

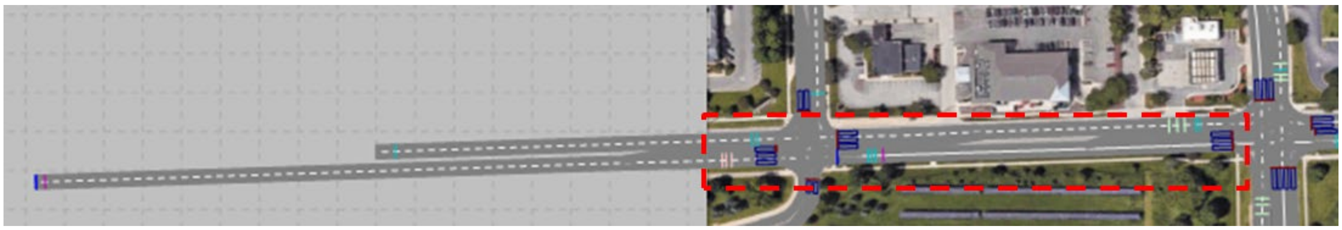
In VISSIM, the simulation corridor is defined by a set of links that vehicles travel along. Vehicles are created at the start of specified links and travel along the link to the adjacent link in the same direction. The stop bar for the simulation intersection is clearly defined by a marking that is at the end of a link, which allows for vehicles to be defined in order to take one of multiple attached links. This enables vehicles to either make a turn or continue straight through the intersection.



Source: Background image from Imagery ©2019 Google. Map Data ©2019 Google; VISSIM model from UMTRI

Figure 11: Defined Links and Stop Bar in VISSIM Version 9

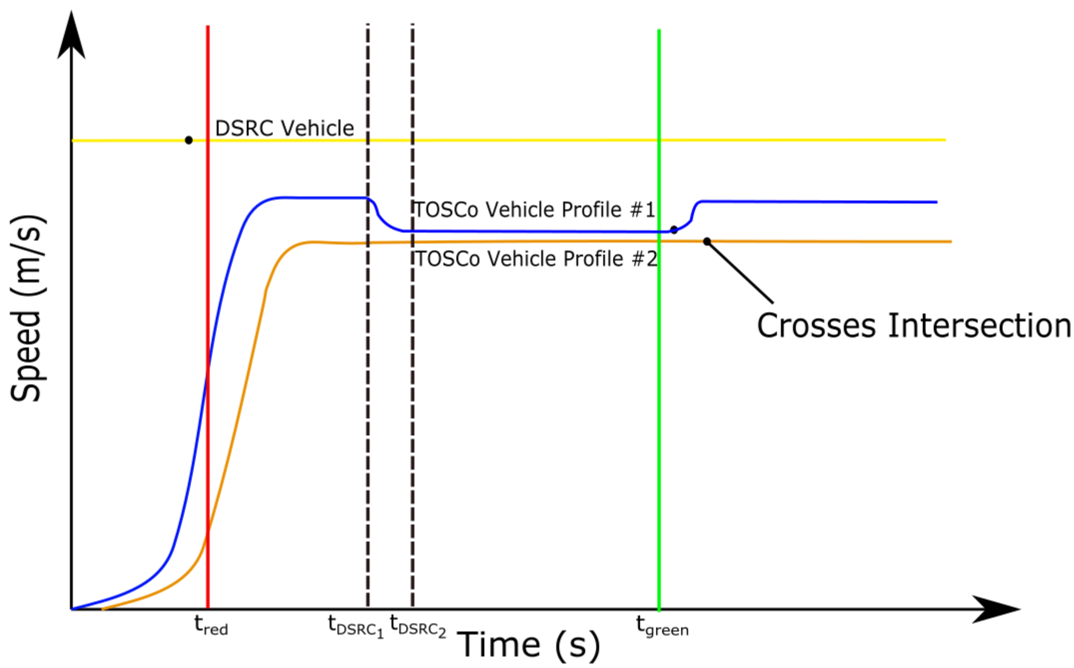
These scenarios originally included both a short track and an extended track which connected to the corridor that was used in simulation. The vehicles generated in simulation would be instantiated at the beginning of the first link defining the track. The shorter track was ultimately not used in simulation as the vehicles generated at the beginning of the first link would not have sufficient time to create the stable string of vehicles necessary to properly evaluate TOSCo functionality.



Source: Background image from Imagery ©2019 Google. Map Data ©2019 Google; VISSIM model and drawing from UMTRI

Figure 12: Short Track (Outlined) and its Extension, VISSIM Version 9

Figure 13 and the legend are used to interpret the visualizations for each of the scenarios.



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

Figure 13: Example Visualization

$t_{red} = Start\ of\ Red\ Phase$

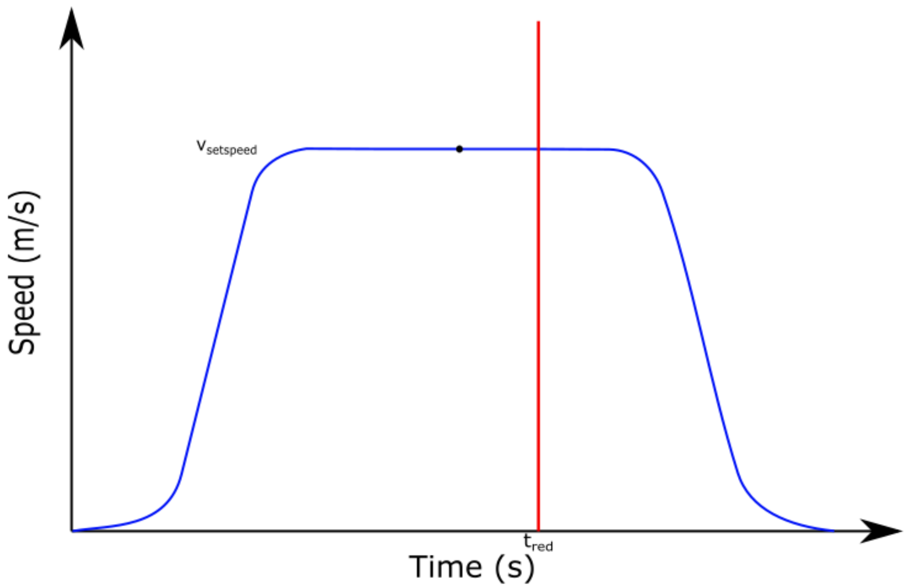
$t_{green} = Start\ of\ Green\ Phase$

$t_{DSRC_1} = Time\ at\ Which\ TOSCo\ Vehicle\ Profile\ 1\ Enters\ DSRC\ Range$

$t_{DSRC_2} = Time\ at\ Which\ TOSCo\ Vehicle\ Profile\ 2\ Enters\ DSRC\ Range$

3.1 Constant Speed Intersection Crossing

This scenario consists of 5 TOSCo-enabled vehicles travelling through an intersection at a constant speed. After being created, a TOSCo vehicle in this string accelerates from rest to the Adaptive Cruise Control (ACC) Set Speed and cruises through the intersection. Subsequent vehicles in the TOSCo string follow the same behavior at a specified time gap setting. See Figure 14 and Table 4 below.



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

Figure 14: Constant Speed Intersection Crossing

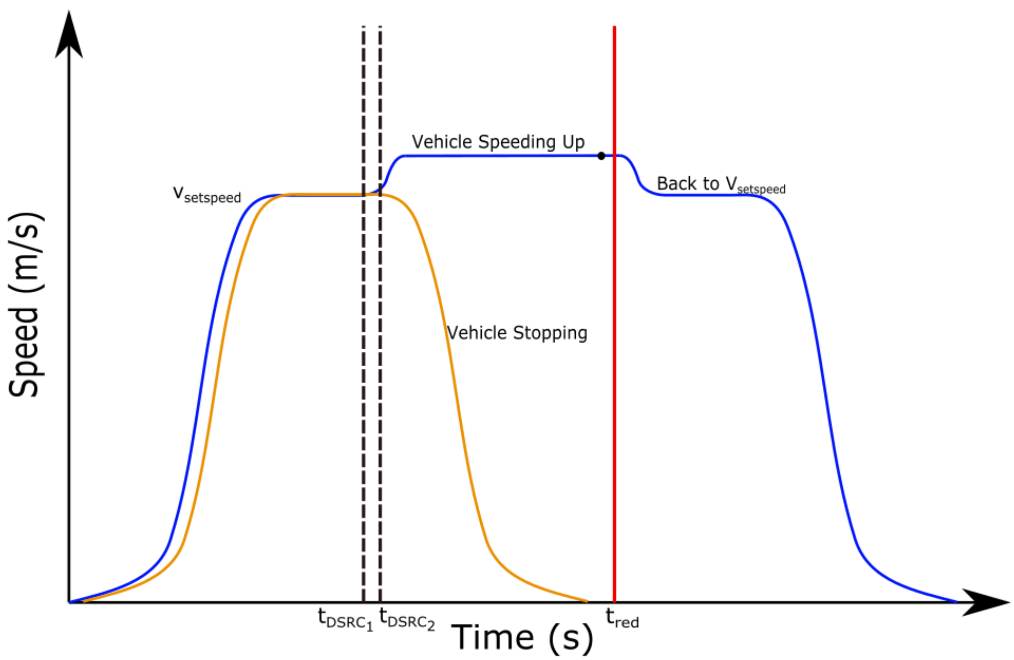
Table 4: Constant Speed Intersection Crossing Parameters

Simulation Set Up	Run Time	70	seconds
	Posted Speed Limit	33.75	mph
Vehicle Set Up	Number of Vehicles	5 TOSCo	
	VISSIM Initial Speed	25	mph
	ACC Set Speed	Vehicle 1: 25 mph Vehicles 2-5: 32 mph	

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

3.2 Speed Up Intersection Crossing

In order to evaluate the Coordinate Speed Control: Speed Up functionality, this scenario consists of a string of 5 TOSCo-enabled vehicles with a part of the string entering Coordinated Speed Control: Speed Up in order to traverse the intersection before the end of the current green window. Once the vehicles enter within DSRC range, each vehicle will check to see if it can speed up to a value between the ACC Set Speed and the posted speed limit in order to pass through the intersection before the end of the green window (see Chapter 4.3, TOSCo Core: Mode Selection). The remaining vehicles in the string that cannot Speed Up will enter Coordinated Stop and decelerate to rest at the intersection. Figure 15 and Table 5 below depict typical profiles for both vehicles that enter Coordinated Speed Control and those that enter Coordinated Stop.



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

Figure 15: Speed Up Intersection Crossing

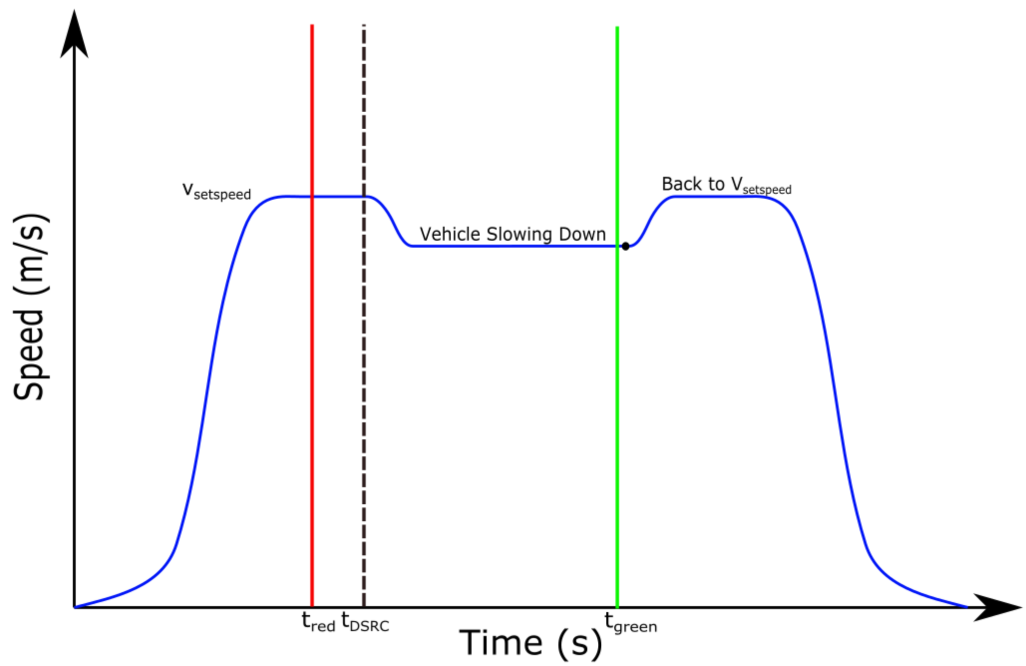
Table 5: Speed Up Intersection Crossing Parameters

Simulation Set Up	Run Time	80	seconds
	Posted Speed Limit	33.75	mph
Vehicle Set Up	Number of Vehicles	5 TOSCo	
	VISSIM Initial Speed	19	mph
	ACC Set Speed	Vehicle 1: 19 mph Vehicles 2-5: 32 mph	

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

3.3 Slow Down Intersection Crossing

In order to evaluate the Coordinate Speed Control: Slow Down functionality, this scenario consists of a string of 5 TOSCo-enabled vehicles with a part of the string entering Coordinated Speed Control: Slow Down in order to pass the intersection's stop bar at the beginning of the green window. Once the vehicles enter within DSRC range, each vehicle will check to see if it can slow down to a value between the ACC Set Speed and a defined minimum cruising speed in order to pass through the intersection at the start of the green window (see Chapter 4.3, TOSCo Core: Mode Selection). See Figure 16 and Table 6 below.



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

Figure 16: Slow Down Intersection Crossing

Table 6: Slow Down Intersection Crossing Parameters

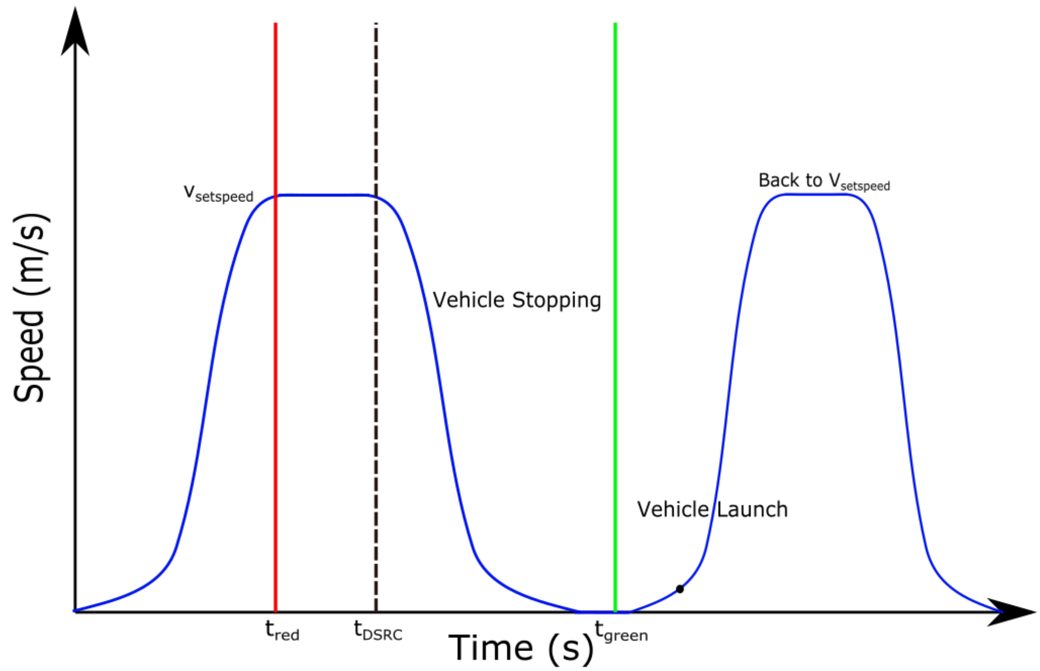
Simulation Set Up	Run Time	60	seconds
	Posted Speed Limit	33.75	mph
Vehicle Set Up	Number of Vehicles	5 TOSCo	
	VISSIM Initial Speed	31	mph
	ACC Set Speed	Vehicle 1: 31 mph Vehicles 2-5: 32 mph	

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

3.4 Stop Scenario at Stop Bar

In order to evaluate the functionalities of both Coordinated Stop and Coordinated Launch, this scenario consists of a string of 5 TOSCo-enabled vehicles that come to a stop at the stop bar after entering within

DSRC range. Once the intersection reaches the start of the green window, the vehicles launch simultaneously back to the ACC Set Speed. See Figure 17 and Table 7.



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

Figure 17: Stop Scenario at Stop Bar

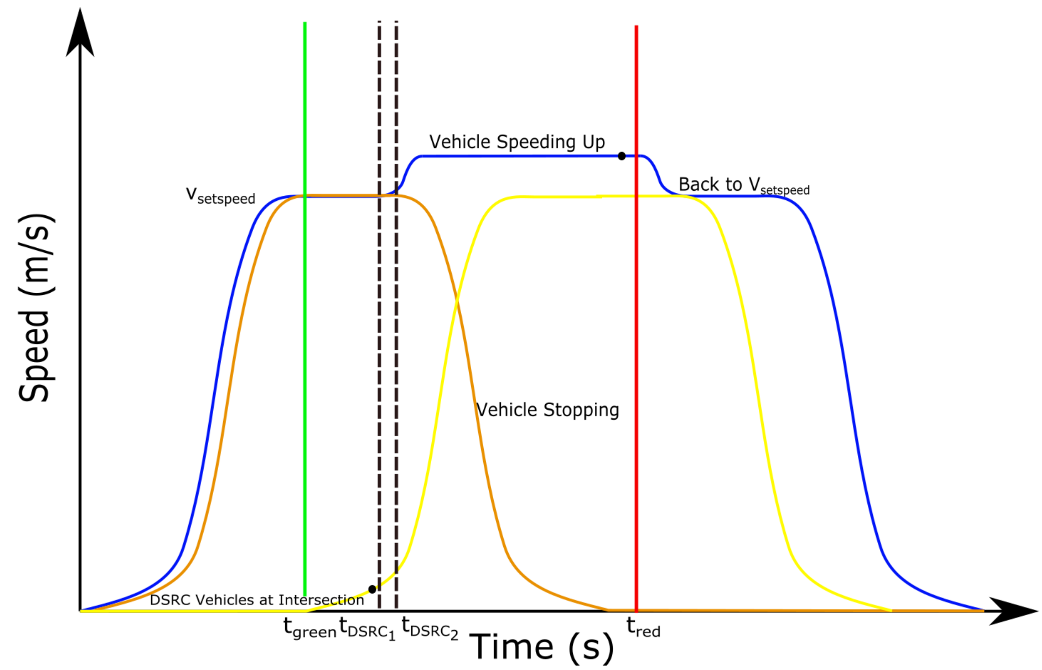
Table 7: Stop Scenario at Stop Bar Parameters

Simulation Set Up	Run Time	80	seconds
	Posted Speed Limit	33.75	mph
Vehicle Set Up	Number of Vehicles	5 TOSCo	
	VISSIM Initial Speed	31	mph
	ACC Set Speed	Vehicle 1: 31 mph Vehicles 2-5: 32 mph	

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

3.5 Speed Up Intersection Crossing with Queue

In order to further evaluate the Coordinate Speed Control: Speed Up functionality, this scenario contains a string of 5 TOSCo-enabled vehicles as well as a string of 4 DSRC-equipped vehicles that generate a queue at the intersection. The TOSCo-equipped vehicles behave in the same manner as in Section 3.2 but with the presence of a queue of vehicles that are currently stopped at the intersection. See Figure 18 and Table 8 below.



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

Figure 18: Speed Up Intersection Crossing with Queue

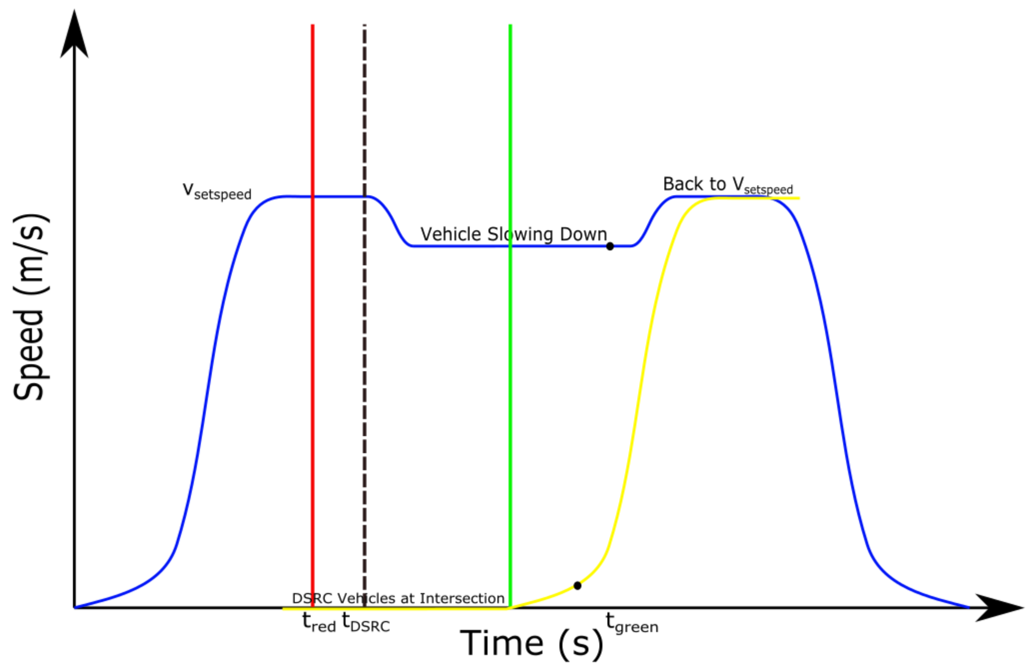
Table 8: Speed Up Intersection Crossing with Queue Parameters

Simulation Set Up	Run Time	80	seconds
	Posted Speed Limit	33.75	mph
Vehicle Set Up	Number of Vehicles	5 TOSCo, 4 DSRC	
	VISSIM Initial Speed	19	mph
	ACC Set Speed	Vehicle 1: 19 mph Vehicles 2-5: 32 mph	

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

3.6 Slow Down Intersection Crossing with Queue

In order to further evaluate the Coordinate Speed Control: Slow Down functionality, this scenario contains a string of 5 TOSCo-enabled vehicles as well as a string of 4 DSRC-equipped vehicles that generate a queue at the intersection. The TOSCo-equipped vehicles behave in the same manner as in Section 3.3 but with the presence of a queue of vehicles that are currently stopped at the intersection. See Figure 19 and Table 9 below.



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

Figure 19: Slow Down Intersection Crossing with Queue

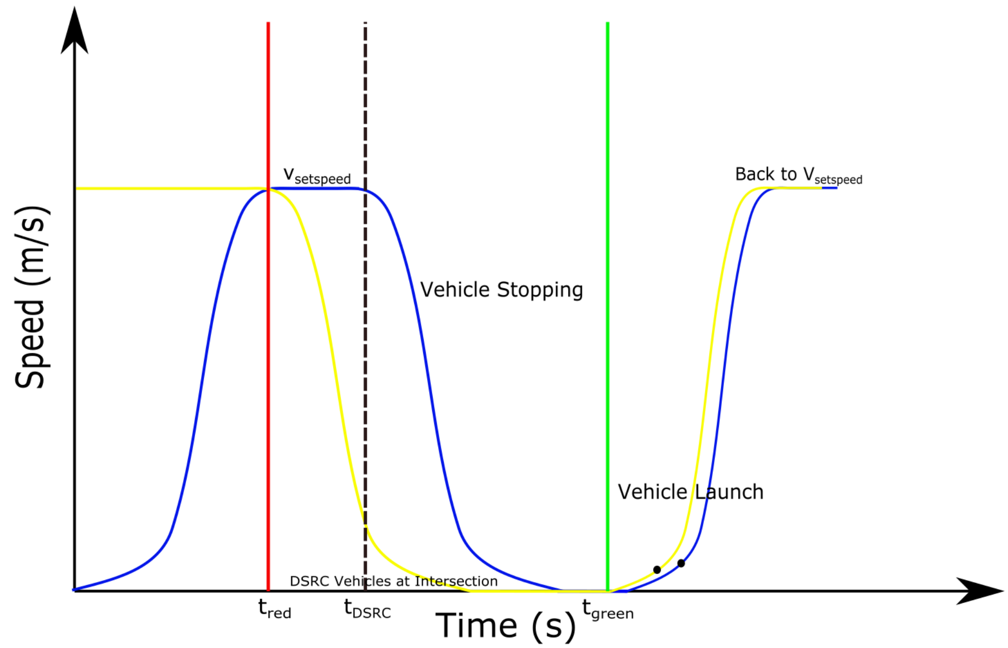
Table 9: Slow Down Intersection Crossing with Queue Parameters

Simulation Set Up	Run Time	64	seconds
	Posted Speed Limit	33.75	mph
Vehicle Set Up	Number of Vehicles	5 TOSCo, 4 DSRC	
	VISSIM Initial Speed	31	mph
	ACC Set Speed	Vehicle 1: 31 mph Vehicles 2-5: 32 mph	

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

3.7 Stop Scenario at Stop Location with Queue

In order to further evaluate the functionalities of both Coordinated Stop and Coordinated Launch, this scenario contains a string of 5 TOSCo-enabled vehicles as well as a string of 4 DSRC-equipped vehicles that generate a queue at the intersection. The TOSCo-equipped vehicles behave in the same manner as in Section 3.3 but with the presence of a queue of vehicles that are currently stopped at the intersection. See Figure 20 and Table 10 below.



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

Figure 20: Stop Scenario at Stop Location with Queue

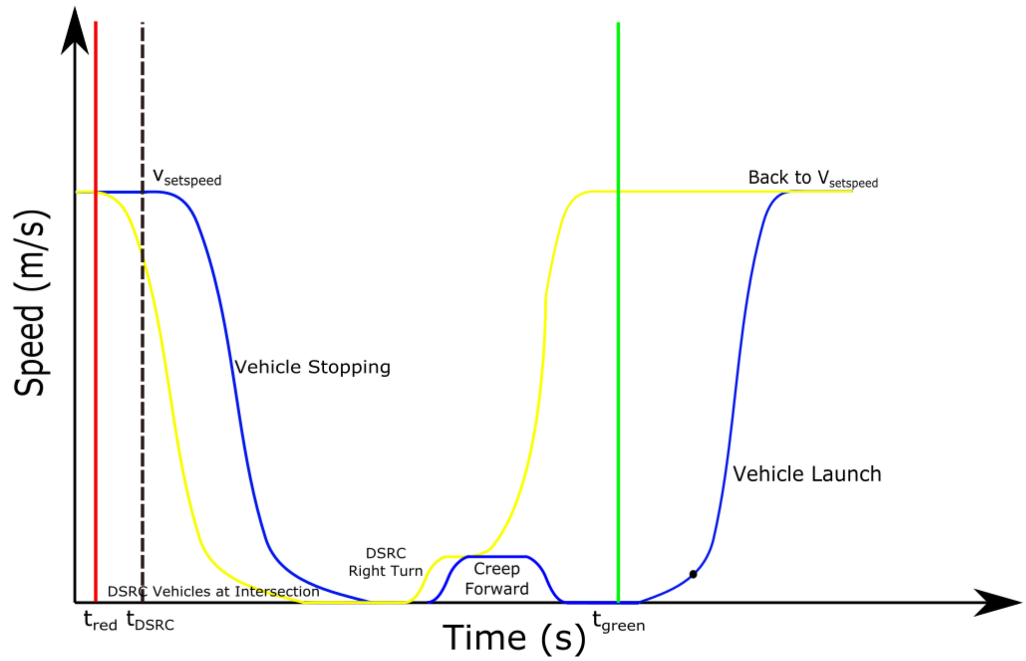
Table 10: Stop Scenario at Stop Location with Queue Parameters

Simulation Set Up	Run Time	89	seconds
	Posted Speed Limit	33.75	mph
Vehicle Set Up	Number of Vehicles	5 TOSCo, 4 DSRC	
	VISSIM Initial Speed	31	mph
	ACC Set Speed	Vehicle 1: 31 mph Vehicles 2-5: 32 mph	

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

3.8 Creep Scenario to the Stop Bar

In order to evaluate the functionality of Creep, this scenario contains a string of 5 TOSCo-enabled vehicles as well as a string of 4 DSRC-equipped vehicles that generate a queue at the intersection. The TOSCo-equipped vehicles come to stop behind the already-formed queue of DSRC vehicles, then the lead DSRC vehicle makes a right turn. This creates space for the other DSRC-enabled vehicles to move forward organically and for the TOSCo vehicles to enter Creep. See Figure 21 and Table 11 below.



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

Figure 21: Creep Scenario to the Stop Bar

Table 11: Creep Scenario to the Stop Bar Parameters

Simulation Set Up	Run Time	110	seconds
	Posted Speed Limit	33.75	mph
Vehicle Set Up	Number of Vehicles	5 TOSCo, 4 DSRC	
	VISSIM Initial Speed	31	mph
	ACC Set Speed	Vehicle 1: 31 mph Vehicles 2-5: 35 mph	

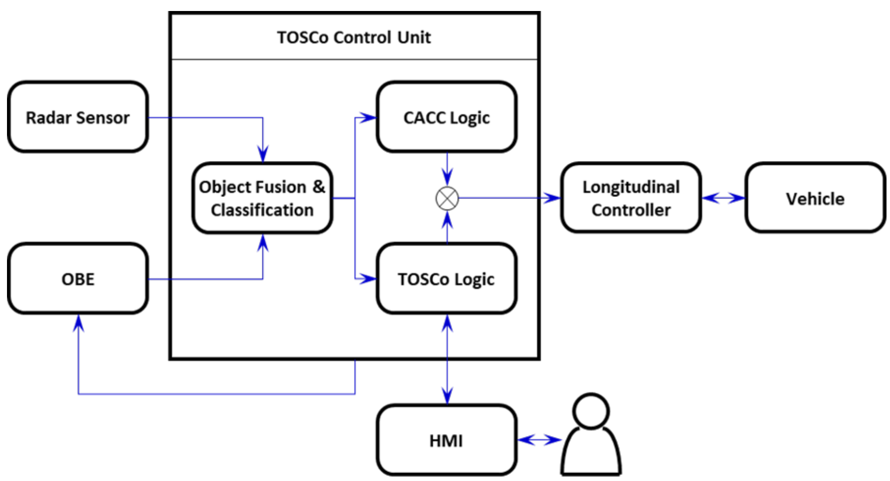
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

4 TOSCo Vehicle Algorithm Architecture

This chapter introduces the principles and corresponding software architecture of the implementation of the TOSCo algorithm for in-vehicle deployment. Section 4.1 outlines the basic components of the vehicle architecture that will be deployed in a prospective phase 2 of the TOSCo Project. From the envisioned vehicle architecture, the corresponding architecture of the vehicle-level software implementation is derived in Section 4.2. At the heart of the TOSCo algorithm implementation stands the *Mode Selection* component. Based on the given input data, as outlined in Chapter 1, this module determines the corresponding TOSCo mode. Section 4.3 provides a detailed presentation of the *Mode Selection* component within the software architecture.

4.1 Basic Vehicle Architecture

The objective of the architecture targets an implementation of the TOSCo system in test vehicles. The basic architecture and components found in the vehicle are depicted in Figure 22. It should be noted that the following diagram is a very abstract representation of the core components constituting a TOSCo system within a vehicle implementation environment.



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

Figure 22: Basic System Components

4.1.1 Radar Sensor

The radar sensor mounted at the front of the vehicle is responsible for detecting traffic participants in front of the vehicle, particularly those not equipped with communication capabilities. The TOSCo system utilizes the object list provided by the radar sensor to acquire a target object to be followed.

4.1.2 DSRC Radio

The TOSCo system relies on the existence of a direct communication link between other vehicles and the TOSCo infrastructure components, as outlined in Chapter 1. Incoming *BSMs* from other vehicles are utilized to detect surrounding traffic participants outside of the range of the onboard radar sensor. Object information gained by both radar and DSRC are fused. Incoming *RSMs* generated by the TOSCo infrastructure component provide information about the current green window, signal state, etc. Received MAP messages are utilized to generate a geometric representation of the intersection which a TOSCo vehicle is approaching. Along with the *SPaT* message, the current status of the traffic lights is conveyed. In order for TOSCo to provide augmented capabilities for a string of vehicles, the TOSCo system of a vehicle is also exchanging additional information about the current state of the TOSCo operating modes.

4.1.3 TOSCo Control Unit

A central computation unit runs several separate software components constituting the core TOSCo functionality. Whereas the radar sensor and the DSRC radio provide input data to the *TOSCo Control Unit* of which several software modules within the unit generate the output data to the vehicle's *Longitudinal Controller* and the Human Machine Interface (*HMI)*.

4.1.3.1 Object Fusion and Classification

Objects detected by the radar sensor and received information about other objects by DSRC are temporally and spatially aligned and fused within this module, providing an abstract representation of the vehicle's current driving environment. Based on received MAP messages, objects within this module are matched onto extracted lanes. The TOSCo-capability of other vehicles is also saved as attributes to maintained objects within this module. The output of the module is a consolidated object list containing the most recent state information about detected objects.

4.1.3.2 CACC Logic

The TOSCo system makes extensive use of the already existing Crash Avoidance Metrics Partners LLC (CAMP) CACC architecture. As such, the existing object filtering, target selection, CACC-state machine and vehicle prediction components are re-used. The *CACC Logic* component is active whenever driver clearance prevails. If vehicles are operated outside of the range of any TOSCo-enabled intersection, the system defaults back to the CACC behavior. For reasons of functional safety, the acceleration request output of the *CACC Logic* and the *TOSCo Logic* are merged to always apply the most conservative acceleration request.

4.1.3.3 TOSCo Logic

The *TOSCo Logic* component runs in parallel to the *CACC Logic* and is activated whenever driver clearance prevails and valid TOSCo input data is received from the infrastructure component. At the core of the *TOSCo Logic* stands the *Mode Selection* which is detailed below in Section 4.3. For reasons of functional safety, the acceleration request output of the *TOSCo Logic* and the *CACC Logic* are merged to always apply the most conservative acceleration request.

4.1.4 Longitudinal Controller

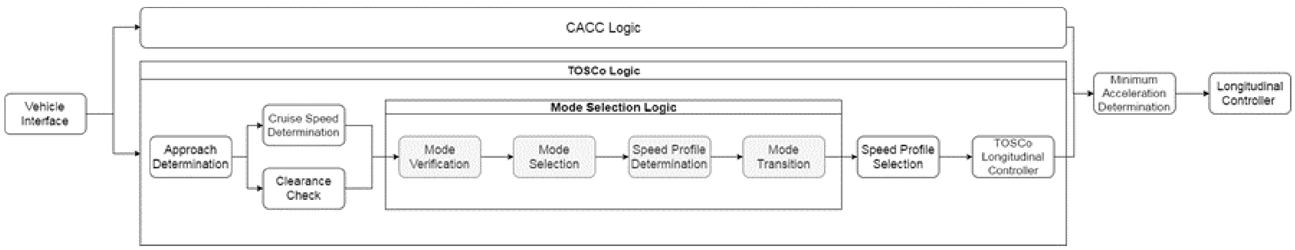
The acceleration command computed by the *TOSCo Control Unit* is provided to the *Longitudinal Controller*. The controller implementation runs on a separate computation unit and is directly connected to the vehicle's Controller Area Network. Acceleration requests are applied through the vehicle's ACC interface. Chapter 5 details the vehicle-specific requirements to enact TOSCo.

4.1.5 HMI

The HMI plays an integral part within the TOSCo architecture to interact with the driver. The driver always needs to be in control of the vehicle and therefore needs to be informed about the current and planned actions of the vehicle controller. The system also needs to actively prompt the driver to enable the TOSCo system.

4.2 Software Architecture

The software components of the *TOSCo Control Unit* are implemented using the Automotive Data and Time-Triggered Framework (ADTF)[1] and runs on a Windows 7 embedded operating system. All software components are implemented in C++11, using MSVC10 compiler environments. Interaction with other software modules is realized by means of the ADTF message bus, TCP and UDP interfaces. The implemented software modules of the *TOSCo Control Unit* are split up into smaller stand-alone modules, called “filter” within ADTF. Each filter defines its required input and provides manipulated or generated output data based on the implemented filter-criteria.



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

Figure 23: Software Components of the TOSCo Control Unit

Figure 23 depicts a high-level representation of the software modules within the *TOSCo Control Unit*, constituting the entire TOSCo system and control logic. As mentioned in Section 4.1, the TOSCo Project leverages the existing CAMP CACC architecture by extending the CACC logic with a parallel TOSCo logic, as depicted. Whenever active, each logic computes a requested acceleration independently from each other. The appropriate applied acceleration, which is then used as an input to the *Longitudinal Controller*, is selected by the merging element *Minimum Acceleration Determination*, as detailed in Section 4.2.4.

All software components within the *TOSCo Control Unit* are triggered at a rate of $50\ Hz$.

4.2.1 Vehicle Interface

The vehicle interface filter is responsible for gathering all required input data for the TOSCo system by interacting with the vehicle’s CAN, onboard radar sensor, DSRC radio, etc. It handles the communication with the onboard GNSS device, therefore, serving as the single time-source for the entire logic. The module translates incoming data from different sources into pre-defined data structures which are utilized by consecutive TOSCo filter elements.

It should be noted that this module exists in two different types. In case the TOSCo system is used in the context of a simulation environment, the component is exchanged with a *Simulation Interface* implementation to interface with a connected simulation environment rather than with an actual vehicle. This enables the

[1] Digitalwerk GmbH, "Automotive Data and Time-triggered Framework. Accessed 12/19/2018. (https://www.digitalwerk.net/adtf/)."

utilization of the same software implementation of TOSCo's core logic in both simulation and vehicle environments.

4.2.2 CACC Logic

As mentioned above, the *CACC Logic* has been developed as part of the preceding CAMP CACC Project.[2]

As for the *TOSCo Logic*, the *CACC Logic* is only active if the driver provided clearance, i.e., actively passed on the longitudinal control of the vehicle within system limits to the TOSCo system. The computed requested acceleration command for the current execution cycle is provided to the *Minimum Acceleration Determination* filter, as outlined in Subsection 4.2.4.

4.2.3 TOSCo Logic

The *TOSCo Logic* represents a parallel computation track alongside the *CACC Logic*. As for the former, the module can only be activated in case the driver provides clearance, i.e., actively hands over the longitudinal control task to the TOSCo system. In addition, the *TOSCo Logic* is activated only when valid TOSCo information is received from the infrastructure component, thereby indicating an approach to an intersection.

4.2.3.1 Approach Determination

This module validates all input data provided to the *TOSCo Logic* and assesses the need for activation of the *TOSCo Logic*. It ensures input data contains valid timestamps by comparing the input data timestamps to the current time. A configurable time window can be set to allow for input data with slight timestamp deviations. The module provides a *TOSCo Approach Clearance Flag* that is used by subsequent modules for activation.

4.2.3.2 Cruise Speed Determination

As long as the vehicle is under CACC-only control, the driver's set speed is maintained as long as a preceding vehicle is not causing the host vehicle to slow down. Even if a preceding vehicle accelerates past the driver's set speed, the CACC maintains the set speed of the host vehicle. As soon as a vehicle receives valid TOSCo data from the infrastructure, it is allowed to speed up to the lane speed limit, potentially speeding up to a speed greater than the driver's set speed. The driver will be able to override this speed adaptation, if required. The *Cruise Speed Determination* module ensures that as long as a vehicle is following a *CSC* profile, the cruise speed fed to the longitudinal controller can be adapted to the lane speed limit, if required.

4.2.3.3 Clearance Check

This module determines if all required input data exists (e.g., TOSCo data is received from the infrastructure) and the driver did not deactivate the clearance for the TOSCo system. The module checks if the driver provided confirmation to start moving when the vehicle is stopped and sets the *Takeoff Clearance*. Clearance is maintained for an adjustable duration before reverting clearance.

[2] J.-N. Meier, Kailas, Aravind, Adla, Rawa, Bitar, George, Moradi-Pari, Ehsan, Abuchaar, Oubada, Ali, Mahdi, Abubakr, Maher, Deering, Richard, Ibrahim, Umair, Kelkar, Paritosh, Vijaya Kumar, Vivek, Parikh, Jay, Rajab, Samer, Sakakida, Masafumi and Yamamoto, Masashi, "Implementation and evaluation of cooperative adaptive cruise control functionalities," in *IET Intelligent Transport Systems*, 2018

In conjunction with the *Approach Determination* module, the *Clearance Check* module ensures that the TOSCo system may be activated.

4.2.3.4 Mode Selection Logic

A detailed description of the operation logic of the *Mode Selection* is provided in Section 4.3. The following subsections represent a short description of the software modules constituting the Mode S*election* logic.

4.2.3.4.1 Mode Verification

Within the *Mode Verification* module, pre-checks before re-evaluating new TOSCo modes are performed. This module covers the logic described in Subsection 4.3.1. The output of this module is a flag to determine if the currently active mode and corresponding speed profiles are valid.

4.2.3.4.2 Mode Selection

A detailed description of the logic of this module is provided in Subsection 4.3.2.1. In case valid profiles were computed by the *Mode Verification* component, further computation within this module is skipped. Otherwise, the *Mode Selection* module determines if the *STOP, CLAUNCH* or *CREEP* modes need to be entered, as detailed below. In case any of these modes is selected, a corresponding speed profile is determined and passed on to the Module *Speed Profile Determination,* which is responsible for computing profiles for coordinated speed control and coordinated stopping modes. Otherwise, existing profiles will be marked as invalid.

4.2.3.4.3 Speed Profile Determination

Within this module, in case invalid profiles prevail, new speed profiles are computed as detailed in Subsections 4.3.2.2 to 4.3.2.4. If the previous module has already determined a valid speed profile, further computation is skipped.

4.2.3.4.4 Mode Transition

This module filters the previously selected TOSCo system state transition to reduce jitter in case of too frequent transitions (e.g., toggling between states). A configurable number of identical transitions need to be confirmed by the previous modules before switching to the desired state.

Note: This module is currently deactivated and allows immediate transitions.

4.2.3.5 Speed Profile Selection

As detailed in Subsection 4.3.1.6, a *best*- and *worst-case* speed profile is computed for every TOSCo mode requiring a speed profile. This module selects the default profile that is provided as an input to the *TOSCo Longitudinal Controller* which is currently set to the *best-cast* profile.

4.2.3.6 TOSCo Longitudinal Controller

Whereas the *Longitudinal Controller* outlined in Subsection 4.2.5 performs the longitudinal control of the vehicle, this controller receives the reference speed and acceleration as well as distance error from the current speed profile and computes a corresponding desired acceleration to follow a selected speed profile. The controller consists of three separate control modules for distance, velocity and acceleration control. The distance control module is implemented as a PD controller, eliminating the distance tracking error corresponding to the active speed profile. The velocity control module is implemented as a PI controller to achieve fast tracking behavior of the active speed profile. The acceleration feed-forward control is limited by the defined system limits.

A more detailed description of the *TOSCo Longitudinal Controller* is out of the scope of this document.

4.2.4 Minimum Acceleration Determination

In case of both control logics being active, two separate acceleration commands are computed. Within the operating scope of *TOSCo*, the most conservative computed acceleration value is provided to the *Longitudinal Controller*. Hence, this module determines the most conservative, i.e., minimal acceleration value from all provided input values.

For a lead vehicle within a TOSCo string without any preceding vehicles, the *TOSCo Logic* computes an appropriate acceleration command corresponding to the generated speed profile as detailed in Section 4.3. The *CACC Logic* will always aim at maintaining the driver’s set speed and might, therefore, compute an acceleration request exceeding the *TOSCo Logic*’s acceleration request constrained by the currently active speed profile. As the *CACC Logic* is responsible for maintaining a safe time gap to a potentially preceding vehicle, the requested acceleration command from the CACC logic can also cause a deviation from the *TOSCo Logic*’s requested acceleration, e.g., in situations where a host vehicle would need to accelerate to pass the intersection on green, but a slower vehicle in front hinders the host vehicle’s acceleration.

In line with the functional safety assessment of the TOSCo system, this module therefore provides the most conservative acceleration request.

4.2.5 Longitudinal Controller

The *Longitudinal Controller* has been adapted from the CAMP CACC Project and essentially represents an implementation of an ACC system [2]. The detailed description of this module is out of the scope of this document.

4.3 TOSCo Core: Mode Selection

Depending on the TOSCo mode, as detailed in Chapter 2, different actions are taken. The *Mode Selection* component within the software architecture presented in Section 4.2 is responsible for selecting the appropriate operating mode with respect to the provided input data.

In correspondence with all other software modules, the *Mode Selection* is triggered at a rate of $50\ \mathrm{Hz}$. Upon updated input data, different TOSCo operating modes will be selected. As outlined below, there are some interdependencies built into the *Mode Selection* ensuring that only allowed and valid consecutive mode selections may occur, as detailed in Section 2.

It should be noted that the TOSCo *Mode Selection* resembles the operations of a state machine. As such, in the following, *transitions* are referred to as changes from one TOSCo operating mode to another operating mode.

The following subsections detail the operations of the TOSCo *Mode Selection* based on a flow chart which is provided in APPENDIX B.

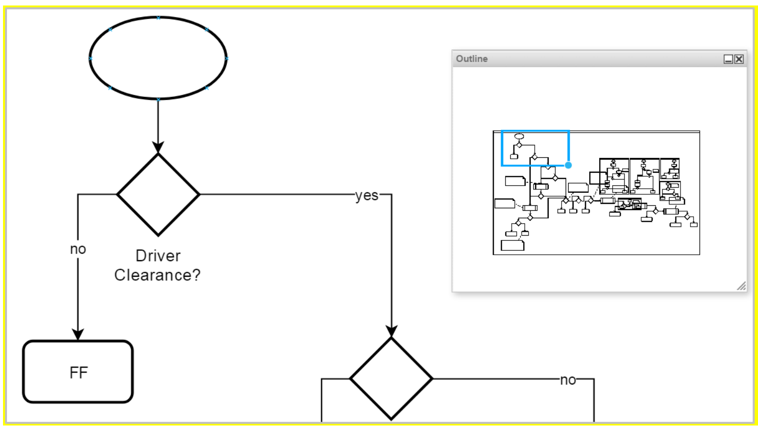
4.3.1 Mode Selection Pre-checks

For every cycle the *Mode Selection* is triggered, the entire decision logic as outlined in APPENDIX B will be assessed. The flow chart consists of a main flow as well as of several sub-processes, such as the figures that are outlined below.

4.3.1.1 Driver Clearance

In each cycle, driver clearance as shown in Figure 24 needs to be available. If the driver operates the brake-pedal or disengages the system otherwise, TOSCo will default back to *Free Flow.*

Only if driver clearance is available, the next check will be performed.



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

Figure 24: Mode Selection Pre-checks - Driver Clearance

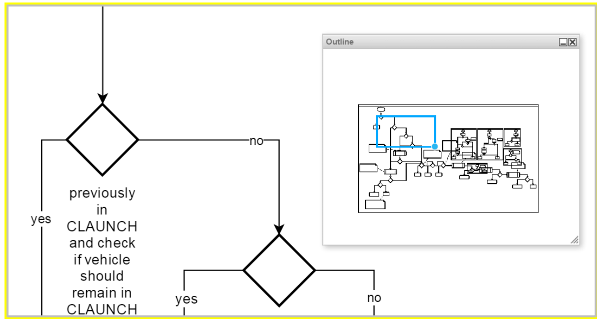
4.3.1.2 Previously in CLAUNCH Check

Before proceeding to further checks, several pre-existing conditions and former TOSCo modes have to be checked that might result in a specific behavior.

As outlined in Chapter 2, whenever a vehicle is currently in *Coordinated Launch (CLAUNCH)* mode, it will remain in this mode until it is clear to default back to CACC operations (*Free Flow).* This check is required as the conditions for *CLAUNCH* are not mutually exclusive with other prevailing conditions such as the *STOP* mode (e.g., When a vehicle is just about to launch, its speed profile starts at a velocity close to $0\ km/h$. The condition to enter *STOP* would then also be satisfied in the next cycle).

If the vehicle has just entered *CLAUNCH* in the previous cycle or has been in *CLAUNCH* previously, it should consider remaining in *CLAUNCH* and proceed to the sub-process *Deviation Check* (see Section 4.3.1.5).

Otherwise, proceed to the next check (see Subsection 4.3.1.3). See Figure 25.

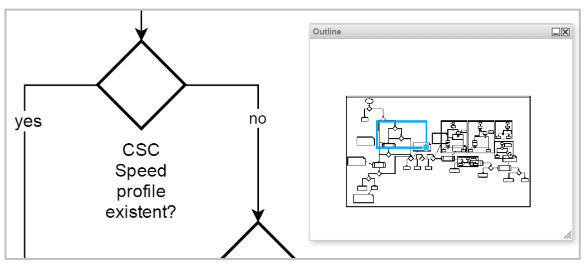


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 25: Mode Selection Pre-checks – Previously in CLAUNCH Check

4.3.1.3 Check for Existing Coordinated Speed Control Speed Profile

In case a vehicle is already following a valid coordinated speed control (*CSC)* profile (*CSC_UP* or *CSC_DOWN*), it might not be necessary to compute a new profile. In this case, it will be advanced to the sub-process *Deviation Check*, as detailed in Subsection 4.3.1.6. If, however, no *CSC* profile has been computed in the last cycle, the next check will be performed as outlined in Subsection 4.3.1.4. See Figure 26.



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

Figure 26: Mode Selection Pre-checks - Check for Existing Coordinated Speed Control Speed Profile

4.3.1.4 Check for Existing Coordinated Stop Speed Profile

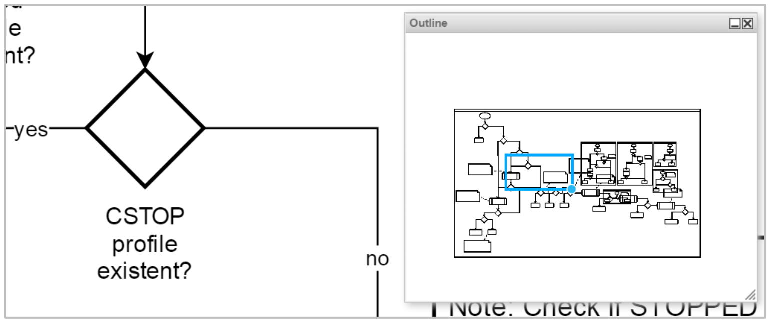
This check will only be entered if no other valid speed profile (*CSC, CLAUNCH)* prevails.

Since stopping is the least preferred option (i.e., the *Mode Selection* aims at keeping the vehicle in motion for reasons of traffic flow optimization and fuel economy), this is the last check before computing entirely new profiles.

In case a valid *Coordinated Stop (CSTOP)* speed profile has been computed before and is currently being followed, the vehicle will assess if the existing profile can still be followed and proceeds to the external conditions check sub-process (see Subsection 4.3.1.6).

If, however, no valid speed *CSTOP* profile exists, the main *Mode Selection* is triggered, as detailed in Subsection 4.3.2. See Figure 27.

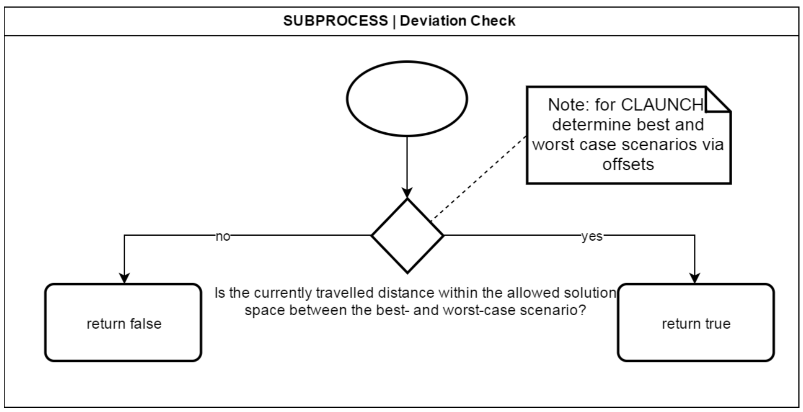
.



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

Figure 27: Mode Selection Pre-checks - Check for Existing Coordinated Stop Speed Profile

4.3.1.5 Sub-process Deviation Check



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

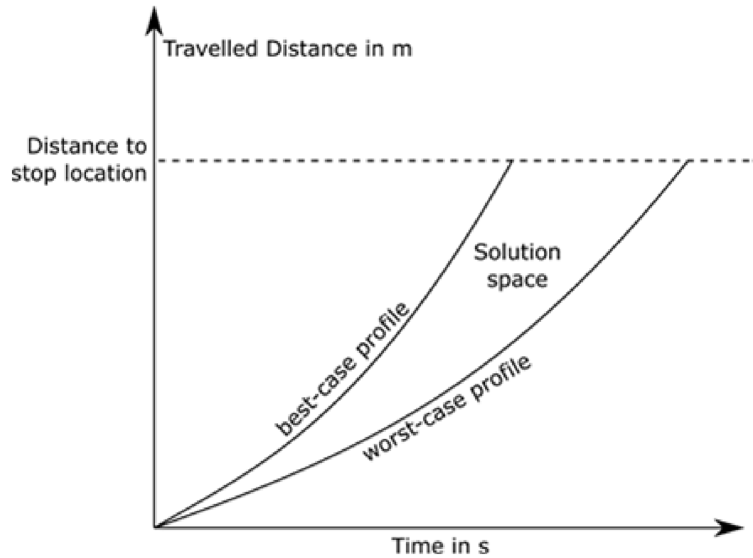
Figure 28: Sub-process “Deviation Check”

This sub-process is entered whenever a valid speed profile has been computed in one of the last iteration cycles of the *Mode Selection* and is visualized in Figure 28.

As outlined in Subsection 4.3.2, whenever a mode is selected, a corresponding set of speed profiles is computed. This set consists of a so-called *best*- and *worst-case* speed profile.

The *best-case* profile resembles a valid profile that enables a vehicle to cross the stop location as early as possible, i.e., as close as possible to the start of the green window. This is in line with the basic idea of TOSCo to improve traffic efficiency by increasing the throughput at an intersection by means of clearing as many vehicles as possible.

The *worst-case* profile resembles a valid profile that enables a vehicle to just pass the intersection at a green light, i.e., as late as possible.



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

Figure 29: Best and Worst Case Speed Profiles (Generalization, Depicts Speed Up Case)

Figure 29 depicts this concept and the corresponding basic logic in more detail for any speed profile. In both cases, the total distance travelled must be equal to the distance to the stop location at the time the speed profile is computed. This sub-process determines if the total distance travelled is within the solution space created by the corresponding *best*- and *worst*-case speed profile.

Even though the system is designed in a way that a vehicle will always aim at following the *best-case* profile, there will be traffic situations in which a vehicle might have to deviate from this profile, e.g., in case of a preceding traffic participant slowing down unexpectedly or because of another traffic participant changing onto the same lane as the host vehicle's. However, these situations might not always require a re-computation of the existing speed profiles. As long as the vehicle can continue to follow a preceding traffic participant at a speed that results in sufficient distance travelled within the solution space indicated in Figure 29**,** a re-computation is not required.

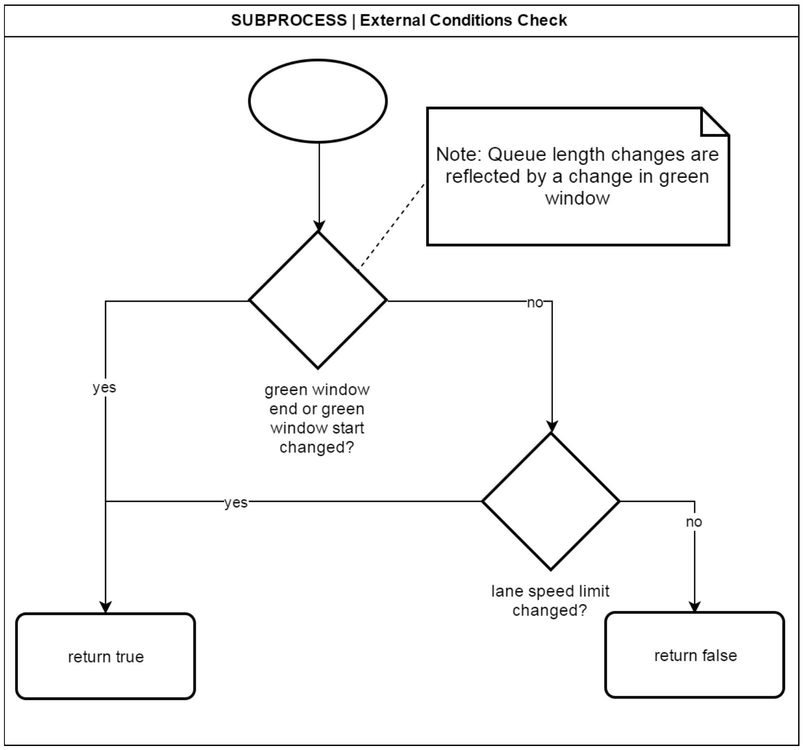
Note: In case of an active *CLAUNCH* profile that is currently being followed, only one optimal speed profile exists. However, due to controller inaccuracies and external factors, deviation from the speed profile will occur. Hence, a guard band is computed around the original computed *CLAUNCH* profile, thus resulting in an equivalent set of a *best*- and *worst-case* profiles.

Consequentially, the sub-process *Deviation Check* determines if a re-computation of an existing set of speed profiles is required. As long as the current distance travelled is within the boundary given by the maximum allowed distance travelled (governed by the corresponding *best-case* profile) and the minimum allowed distance travelled (governed by the corresponding *worst-case* profile), this module returns *true* and the next checks according to Subsection 4.3.1.7 can be assessed.

The module returns *false* otherwise, thus causing a re-computation of the speed profiles as outlined in Subsection 4.3.2.

4.3.1.6 Sub-process External Conditions Check

Whenever a *CSC* or *CSTOP* speed profile exists, it is consecutively checked if a re-computation needs to be triggered as external conditions may have changed that render an existing profile invalid. The sub-process *External Conditions Check* takes care of validating potential external factors that may render the current speed profile obsolete. Figure 30 depicts the checks performed by this sub-process. Whenever a vehicle approaches an intersection, the timespan of the green window may change, e.g., in case of a queue built up or in case of actuated traffic signals. Whenever the green window changes, the sub-process returns *true*, since external conditions have changed, and a new profile needs to be selected, as outlined in Subsection 4.3.2.



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

Figure 30: Sub-process "External Conditions Check"

Even if the green window does not change, the vehicle might already operate in a TOSCo mode, but the lane speed limit might change, e.g., in case of a rather long approach with different speed limits or programmable speed limit signs along the way to the intersection. In this case, external conditions have also changed, and a new speed profile needs to be determined for an applicable TOSCo mode, as outlined in Subsection 4.3.2. In this scenario, the sub-process *External Conditions Check* returns *true* as well.

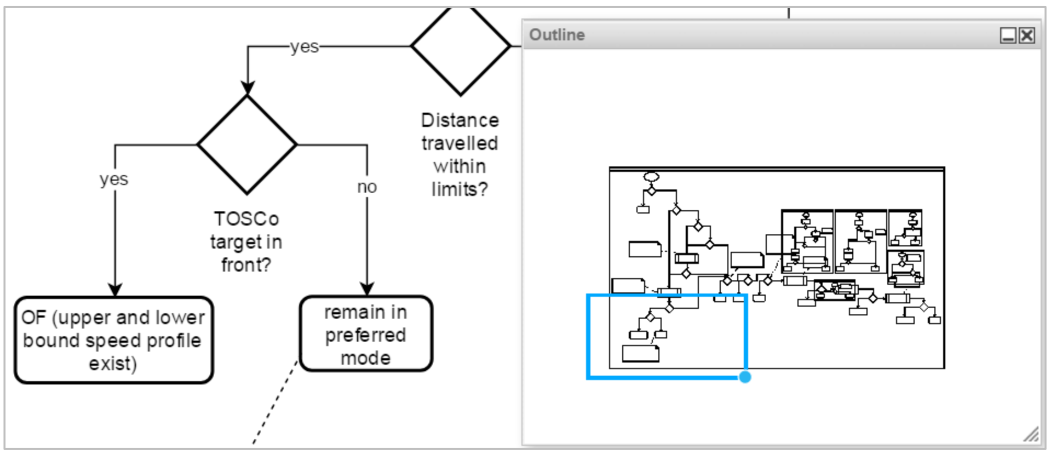
False is returned whenever external conditions did not change for the current cycle. Consequentially, the existing speed profile remains valid and can be assessed further in the sub-process *Deviation Check* as detailed in Subsection 4.3.1.5.

4.3.1.7 Check for Existing TOSCo Target

If previous checks have resulted in an assessment that the existing speed profile is valid, the algorithm has determined which TOSCo mode is selected if the subject vehicle is the lead vehicle of a string, i.e., the preceding vehicle is not TOSCo-enabled.

If the immediately preceding vehicle does not transmit TOSCo-relevant information (or is a non-communicating vehicle altogether), the subject vehicle is considered the lead vehicle and the mode corresponding to the existing speed profile is selected. This results in the current speed profile being fed to the TOSCo longitudinal controller, as outlined in Section 4.2.

If the preceding vehicle is equipped with TOSCo functionality, it is assumed that the lead vehicle is also optimizing its speed profile. Consequentially, the subject vehicle can switch to Optimized Follow. See Figure 31.



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

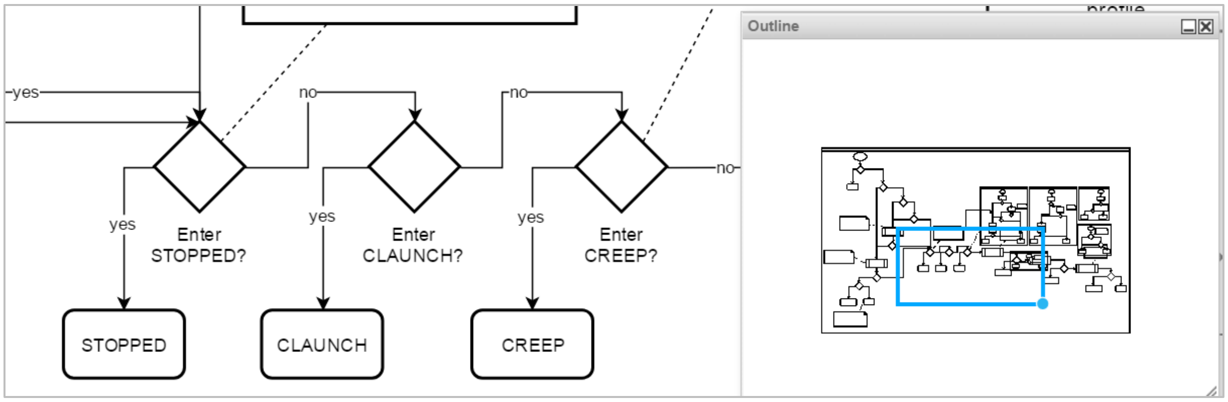
Figure 31: Mode Selection Pre-checks - Check for Existing TOSCo Target

4.3.2 Mode Selection Operations

The following stages of the *Mode Selection* flow chart are only entered in case a valid speed profile has not been computed before or is rendered invalid either because of a change of external conditions (see Subsection 4.3.1.6) or because the distance travelled is no longer within the allowed solution space, given a set of *best*- and *worst-case* speed profiles (see Subsection 4.3.1.5).

4.3.2.1 Check for Modes Valid at Low Speed

Before computing any of the profiles for higher speed, the *Mode Selection* consecutively checks the behavior at lower speeds. See Figure 32.



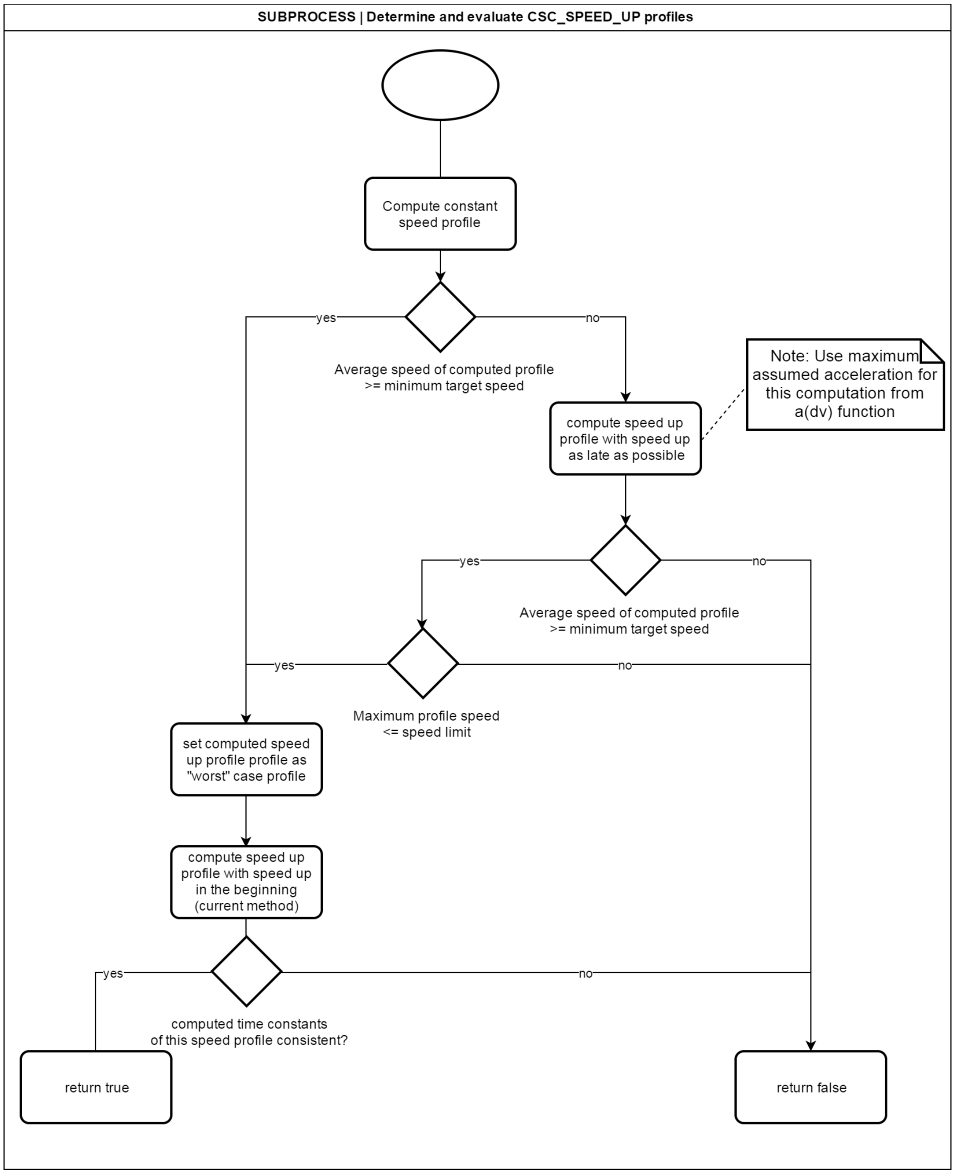
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 32: Check for Modes Valid at Low Speed

In case the vehicle's speed is below the standstill speed threshold, the *Stopped* mode is entered. The vehicle remains stopped until it receives the takeoff-clearance from the driver (e.g., by pushing a button on the steering wheel) and a valid *CLAUNCH* profile can be computed. Refer to Chapter 2 for more information on the *STOP* mode.

Upon a traffic light turning green, a stopped vehicle will not re-enter the *Stop* mode in the next iteration cycle, since a valid green window exists. This check will be activated by the sub-process *External Conditions Check*, as detailed in Subsection 4.3.1.6. Upon entering the *CLAUNCH* state, a new launch speed profile is computed, as detailed in Chapter 2. Every stopped vehicle within a string is computing a *CLAUNCH* profile. In case of a host vehicle receiving a *CLAUNCH-Flag* from the preceding vehicle, it will immediately start to follow the computed *CLAUNCH* profile to enable a simultaneous launch of all vehicles for the purpose of clearing the intersection as quickly as possible. Vehicles receiving a *CLAUNCH-Flag* from a preceding vehicle will switch their state to *OPTIMIZED FOLLOW* afterwards.

As long as a vehicle is waiting in front of a red traffic light, preceding vehicles might move and clear the lane, e.g., in case of a vehicle turning right at a red traffic light. In these scenarios, the host vehicle can move up to either the stop location or decrease the distance to another preceding vehicle moving forward by creeping forward. The *CREEP* mode is only entered whenever the host vehicle is not at the stop location whilst located in front of a red traffic light and a preceding vehicle starts to move, thereby allowing a host vehicle to get closer to the stop location. In these scenarios, a vehicle computes a creep profile which consists of a phase to speed up to creep speed, a phase to maintain creep speed until shortly before the stop location and a deceleration phase to bring the vehicle to a full stop again. It should be noted that because of a decelerating preceding vehicle, the underlying CACC algorithm will cause the vehicle to come to a stop if required, thus causing a re-computation of a new mode within the *Mode Selection*.



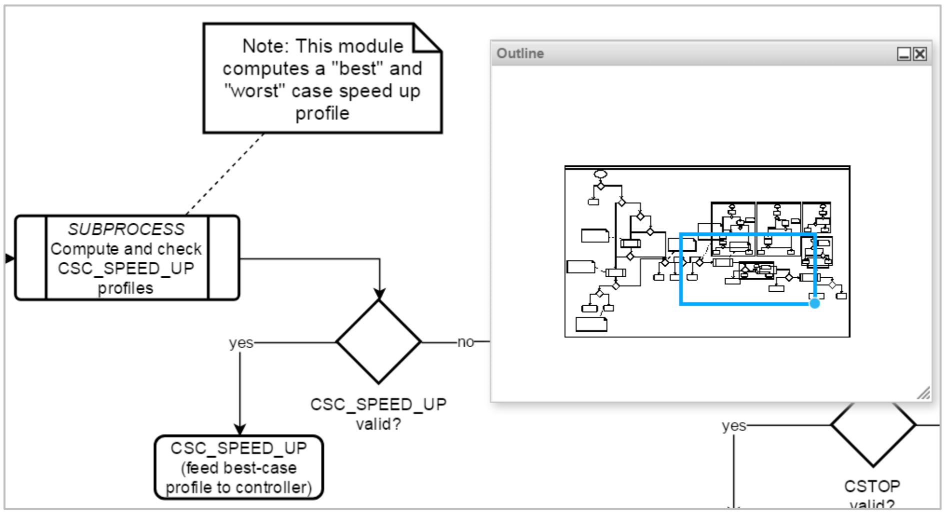
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 33: Sub-process “Determine and Evaluate CSC_SPEED_UP Profiles”

If none of these three modes can be entered, e.g., because of a vehicle driving at higher speeds, the mode *CSC_SPEED_UP* is assessed, as outlined in Subsection 4.3.2.2.

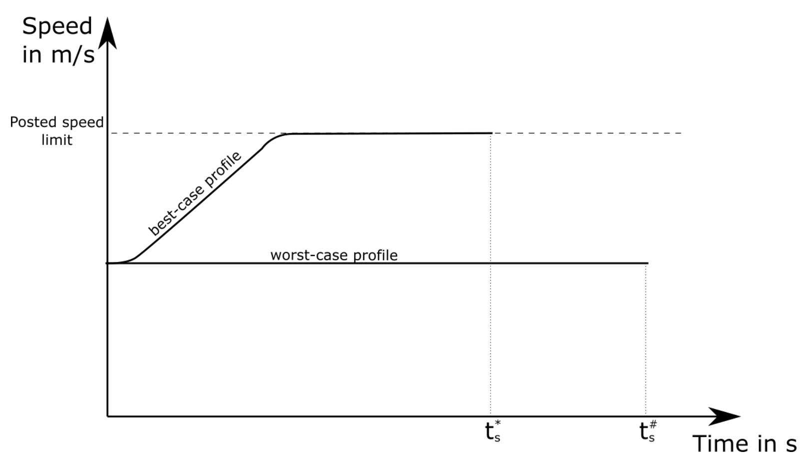
4.3.2.2 Coordinated Speed Control Speed Up

The objective of the TOSCo algorithm is to improve traffic flow. As such, its foremost objective is to increase the average speed of a particular road section. Hence, a host vehicle driving at any speed above the creep speed, determines if there exists a pair of *best*- and *worst-case* speed profiles that allow a vehicle to speed up to speed limit (or some other speed above the maximum speed of the *worst-case* profile) to pass the intersection within the green window as early as possible.



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

Figure 34: Coordinated Speed Control Mode - Speed Up



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

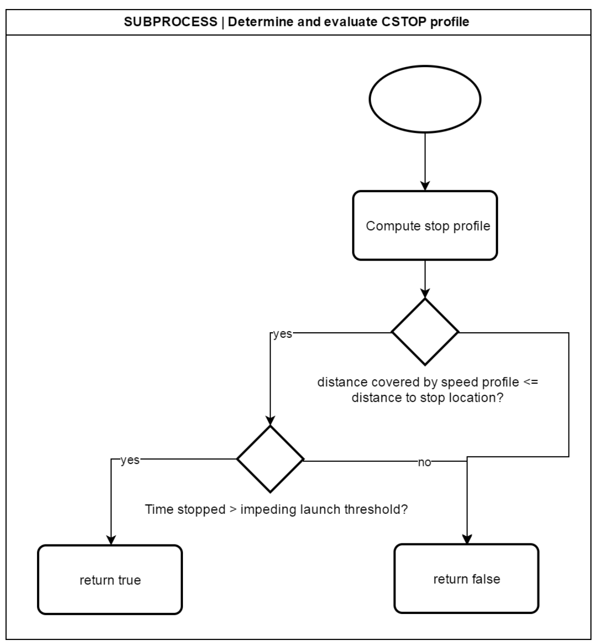
Figure 35: Best- and Worst-case Speed Profile for Speed-up

The sub-process *Determine and evaluate CSC_SPEED_UP profiles* is responsible for computing and evaluating these profiles, as depicted in Figure 36.

In case of a host vehicle trying to speed up to pass the intersection as early as possible within the green window, the *worst*-case scenario is to not speed up at all. As long as the average speed of the computed constant speed profile exceeds the minimum target speed, which is the minimum average speed a vehicle needs to travel at the time the profile is computed to pass the intersection when the light is about to turn red at $\boldsymbol{t_s^{\#}}$ (i.e., at the end of the green window), it can be adopted as the *worst-case* profile (see Figure 35). If this check fails, the algorithm proceeds to compute a profile which includes a speed up to some target speed as late as possible, to pass the intersection at the end of the green window. This procedure ensures that a vehicle takes as much time as possible to reach the stop location within the green window and thus resembles a valid *worst-case CSC_SPEED_UP* profile.

If the average speed of a computed *worst-case CSC_SPEED_UP* profile does not exceed the minimum target speed or the maximum allowed speed on the current lane is exceeded at any point in time of the computed profile, a valid *CSC_SPEED_UP* profile cannot be computed. The *Mode Selection* will hence proceed to computing a *CSTOP* profile, as outlined in Subsection 4.3.2.3.

Upon existence of a valid *worst-case* profile, a *best-case* speed up profile is created by computing a profile which enables a host vehicle to pass the intersection as early as possible, without exceeding the posted speed limit. The profile aims at speeding up as early as possible to a speed ensuring the host vehicle passes the intersection as early as possible at t_s^* without violating the posted speed limit. The algorithm ensures that all time constants of the speed profile are valid[3] (i.e., larger than 0) before returning a valid pair of *CSC_SPEED_UP* profiles.



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

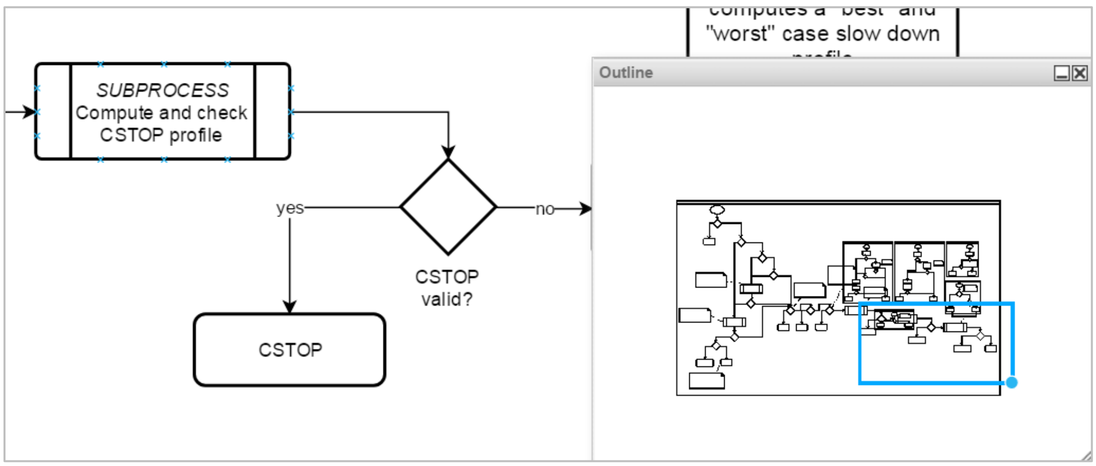
Figure 36: Sub-process "Determine and Evaluate CSTOP Profile"

[3] Invalid profiles might result in case the difference between the current vehicle's speed and the maximum speed of the computed speed profile is too small, given the jerk limits of the computation process.

A valid pair of *CSC_SPEED_UP* profiles causes the *Mode Selection* to activate the corresponding *CSC_SPEED_UP* mode. The *best-case* profile will be fed to the controller.

4.3.2.3 Coordinated Stop

If speeding up is not possible, the least preferred option from the perspective of the TOSCo algorithm is for the host vehicle to come to a stop. Instead, slowing down to some speed lower than the current cruising speed is preferable. However, the objective of checking if coming to a stop is feasible before assessing *CSC_SLOW_DOWN* is to ensure that a valid (and more importantly logical) *CSTOP* profile exists and should be followed instead. A *CSTOP* profile might seem illogical from an external, i.e., other traffic participant's perspective, if a vehicle comes to a stop for a very short time only, prior to accelerating. In these situations, a valid *CSC_SLOW_DOWN* profile will exist.

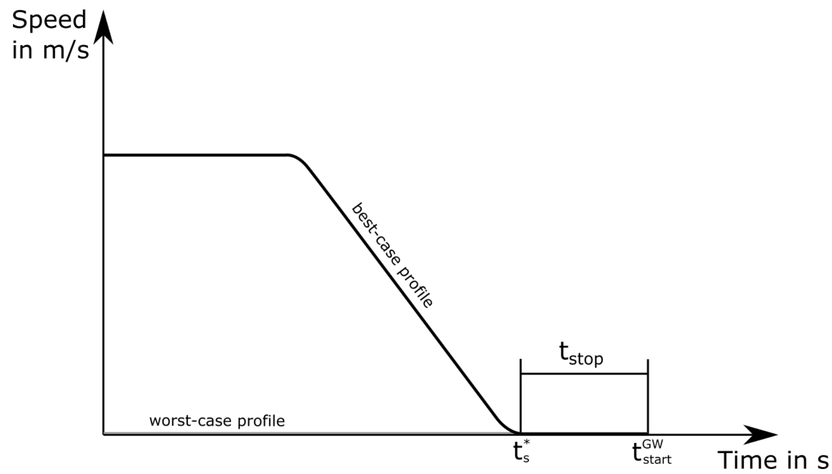


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 37: Coordinated Stop

The sub-process *Determine and evaluate CSTOP profile*, as depicted in Figure 37, details the computation of a valid *CSTOP* speed profile.

As outlined in Chapter2, a valid *CSTOP* profile aims at ensuring that a host vehicle approaches the stop location at its current speed as long as possible, prior to decelerating within a constraining parameter set to ensure the vehicle stops at the stop location provided by the infrastructure component. A *CSTOP* profile is considered a valid profile if the time a vehicle remains stopped exceeds a configurable minimum stop-time t_{stop}, referred to as the *impeding launch threshold*. This parameter ensures that if a vehicle comes to a stop following the guidelines above, it has to remain stopped for some minimum time between stopping at t_s^* and the beginning of the green window t_{start}^{GW} before accelerating again.



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

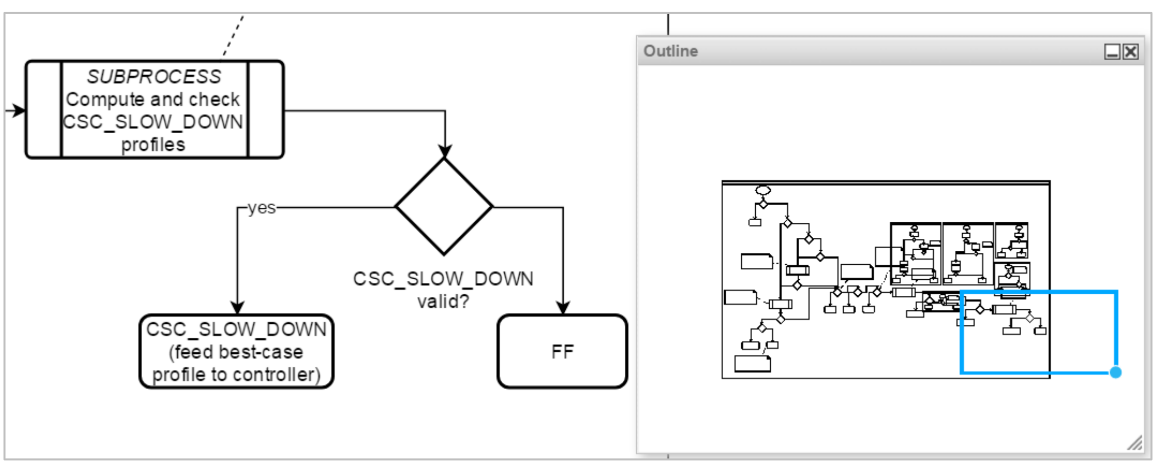
Figure 38: Coordinated Stop Speed Profile

A valid *CSTOP* profile represents the *best-case* profile while the *worst-case* profile is represented by a zero-speed profile.

In case the time stopped t_{stop} given the computed profile is shorter than this threshold, this profile will be perceived as unreasonable from the perspective of any other traffic participant. However, in this scenario, there exists another speed profile that will allow the vehicle to pass the intersection merely by reducing its current speed (i.e., follow a *CSC_SLOW_DOWN* profile). Consequently, a valid *CSTOP* cannot be computed and the module returns *false*, continuing by assessing a *CSC_SLOW_DOWN* profile as outline in Subsection 4.3.2.4.

A valid pair of *CSTOP* profiles causes the *Mode Selection* to activate the corresponding *CSTOP* mode. The *best-case* profile will be fed to the controller.

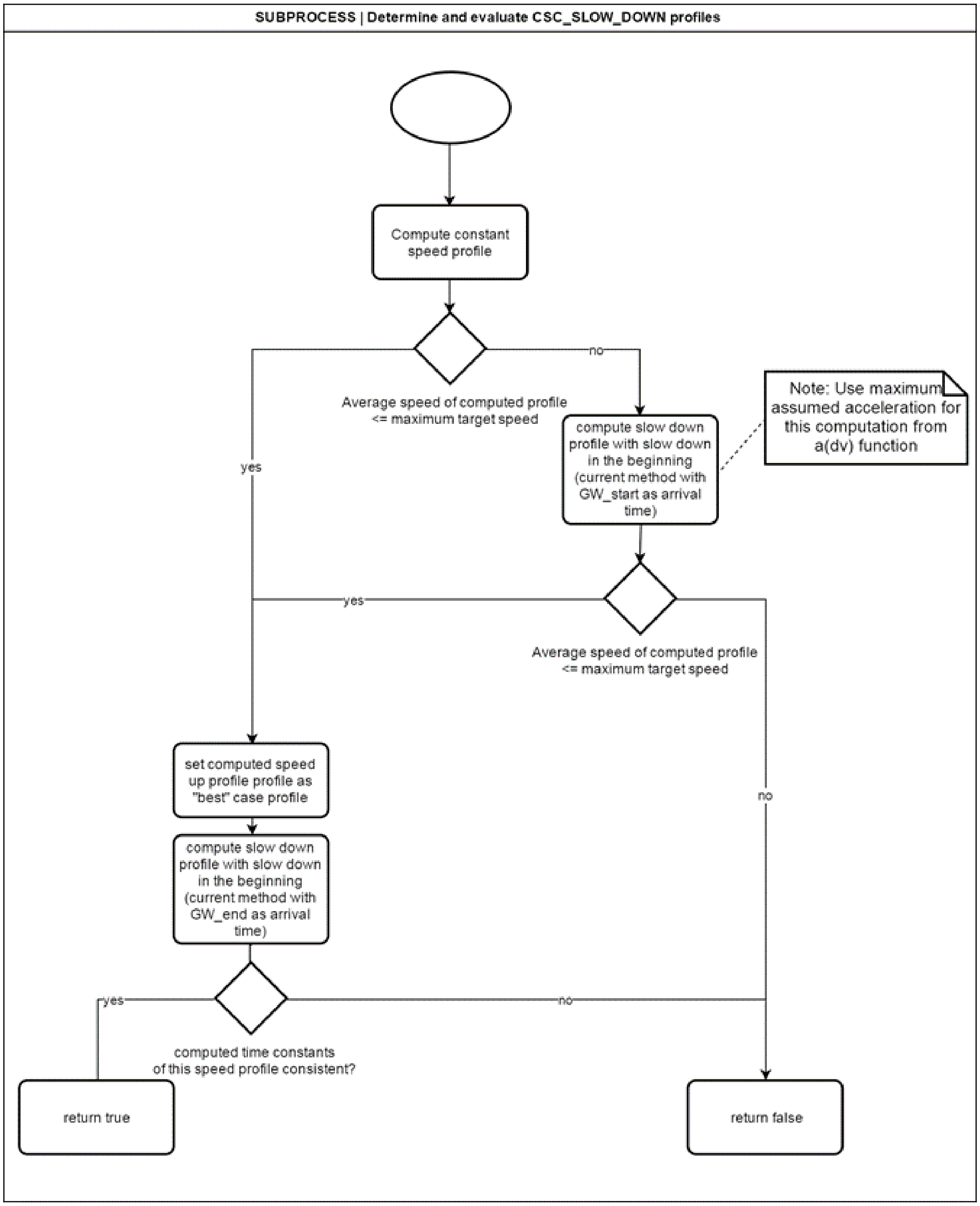
4.3.2.4 Coordinated Speed Control Slow Down



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

Figure 39: Coordinated Speed Control - Slow Down

In case stopping is unfeasible, there exists a valid slow down profile which ensures that a vehicle can reach the beginning of a green window as early as possible by slowing down without coming to a full stop, thus increasing fuel efficiency. In close resemblance to *CSC_SPEED_UP*, the sub-process *Determine and evaluate CSC_SLOW_DOWN profiles,* as depicted in Figure 40, computes a pair of valid *best*- and *worst-case* slow-down profiles.

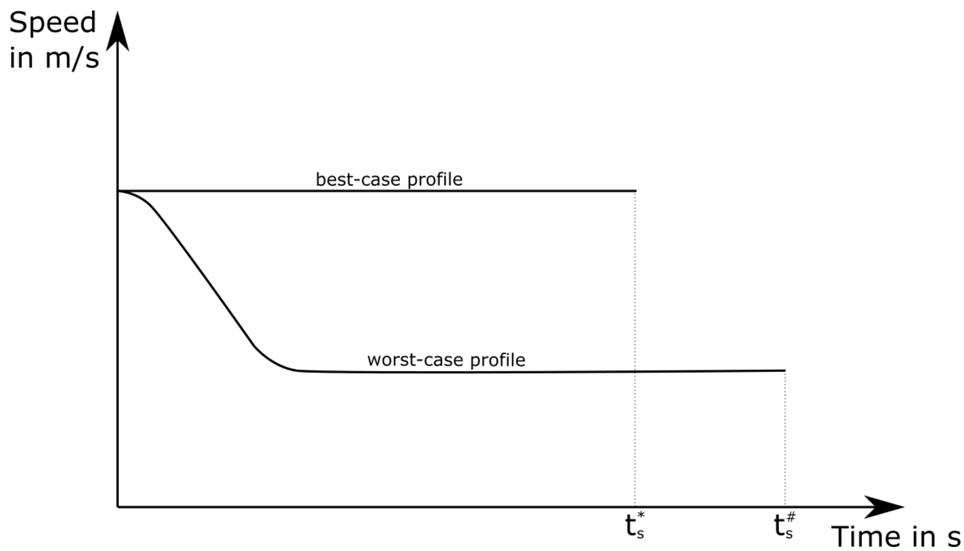


Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 40: Sub Process "Determine and Evaluate CSC_SLOW_DOWN Profile"

In the case of a host vehicle trying to slow down to pass the intersection as early as possible within the green window, the *best*-case scenario is to not slow-down at all. As long as the average speed of the computed constant speed profile exceeds the maximum target speed, which is the maximum average speed a vehicle needs to travel at the time the profile is computed to pass the intersection when the light is about to turn green at t_s^* (i.e., at the beginning of the green window), it can be adopted as the *best-case* profile (see Figure 41). If this check fails, the algorithm proceeds to compute a profile which includes a slow-down to some target speed as early as possible, to pass the intersection in the beginning of the green window. This procedure ensures that a vehicle takes as little time as possible to reach the stop location as close to the beginning of the green window as possible and thus resembles a valid *best-case CSC_SLOW_DOWN* profile.

If the average speed of a computed *best-case CSC_SLOW_DOWN* profile exceeds the maximum target speed, a valid *CSC_DLOW_DOWN* profile cannot be computed. The *Mode Selection* will hence fall back to *FREE_FLOW* mode. It should be noted that in this case, there exists not a single valid speed profile within the TOSCo optimization range. This will likely be the case if the TOSCo algorithm gets activated if the vehicle is too close to the intersection, e.g., because of a short communication range.



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

Figure 41: Best- and Worst-case Slow-down Profile

Upon existence of a valid *best-case* profile, a *worst-case* speed up profile is created by computing a profile which enables a host vehicle to pass the intersection at the latest possible time $t_s^\#$. The *worst-case* profile aims at slowing down to a target speed as early as possible to a speed ensuring the host vehicle passes the intersection as late as possible within the green window. The algorithm ensures that all time constants of the speed profile are valid (i.e., larger than 0) before returning a valid pair of *CSC_SLOW_DOWN* profiles.

A valid pair of CSC_SLOW_DOWN profiles causes the *Mode Selection* to activate the corresponding CSC_SLOW_DOWN mode. The *best-case* profile will be fed to the controller.

5 Requirements Needed to Enact TOSCo

This chapter introduces high-level system requirements that are needed for vehicle and infrastructure side to enact TOSCo functionality. Based on the simulation results, objective values are defined for requirements that are listed in the following tables.

5.1 TOSCo Vehicle-side Requirements

In order to deploy a TOSCo system, a number of requirements need to be met by the vehicle. Those requirements are listed in the table below.

Table 12: Vehicle-side Requirements

Summary	Description
Adherence to CACC (Ref : CACC Final Report)	• Vehicle shall comply with performance requirements defined in CACC Project. The vehicle shall use the more conservative acceleration command
Reception of SPaT/MAP (Ref : J2735 – Appendix H : MAP and SPaT Message Use and Operation)	• Vehicle shall be capable of receiving SPaT • Vehicle shall be capable of decoding SPaT • Vehicle shall be capable of receiving MAP • Vehicle shall be capable of decoding MAP
Information Tracking	• Vehicle shall be capable of tracking the information decoded from SPaT/MAP • Vehicle shall be capable of matching the information decoded from SPaT/MAP
Differentiating Intersections (Ref : J2735 – Appendix H : MAP and SPaT Message Use and Operation)	• Vehicle shall be capable of using message ID to differentiate intersections • Vehicle shall be capable of using intersection ID to differentiate intersections • Vehicle shall be capable of using MAP message to differentiate intersections
MAP matching (Ref : V2I-SA Final Report Chapter 6.2)	• Vehicle shall comply with MAP matching requirements

Summary	Description
Speed Profile Determination	• Vehicle shall be capable of generating its own set of available speed profiles and determine which speed profile to follow (See Chapter 4)
Traffic Situation Determination	• Vehicle shall be capable of generating traffic conditions data, such as queue formation, discharge rates
Control Brake/Accelerator	• Vehicle shall be capable of controlling brake when waiting at a red signal • Vehicle shall be capable of controlling accelerator when it is necessary
Coordinated Stop	• Vehicle shall be capable of adjusting speed profile to come to a stop • Vehicle shall be capable of stopping without deactivating its ACC/CACC/TOSCo system
Optimized Trajectory Planning	• Vehicle shall be capable of estimating its emission and fuel economy performance for its trajectory planning • Vehicle shall be capable of following generated speed profile with a deviation of less than x.x% from acceleration/velocity/distance
CACC w/ TOSCo Optimization	• Vehicle shall be capable of determining vehicle performance (speed, acceleration, power-train currently out of scope) profile with the objective of promoting a time- and energy-efficient driving style that lowers vehicle emissions and fuel consumption
Position with the String Determination	• The vehicle shall be capable of determining if it is the head of the string or within the string
Transmission of TOSCo State	• The TOSCo/CACC state data element shall be set to the current state that the longitudinal control system is operating in (enumeration shall cover both CACC and TOSCo states)
Coordinated Launch / Stop Flag	• The vehicle will be able to send a coordinated launch / stop flag to other vehicles in the string if it determines itself to be the head of the string and it is in either CSTOP or CLAUNCH.
Impending Launch/Creep Forward	• Vehicle shall be capable of determining that the signal is about to transition to green • Vehicle shall be capable of notifying the driver of an impending launch • Vehicle shall be capable of notifying the driver that the vehicle will move forward while in a queue • Vehicle shall be capable of providing means for driver to indicate readiness for launch • Vehicle shall be capable of interpreting that the driver is ready for launch • Vehicle shall be capable of notifying the driver to release brake during impeding launch
Vehicle in Motion	• Vehicle shall be capable of determining if vehicle speed is above a defined stationary speed threshold
Transmission of BSM with TOSCo Extension	• Vehicle shall be capable of decoding BSM with TOSCo extension

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

5.2 TOSCo Infrastructure-side Requirements

In order to deploy a TOSCo system, a number of requirements need to be met by the infrastructure. Those requirements are listed in Table 13 below.

Table 13: TOSCo Infrastructure-side Requirements

Summary	Description
Transmission of SPaT/MAP (J2735 – Appendix H : MAP and SPaT Message Use and Operation)	• Every intersection in a corridor defined as TOSCo-enabled shall transmit SPaT and MAP through DSRC • Each intersection in the corridor shall transmit the Intersection ID and the approaching LaneIDs of the next downstream intersection in each direction • The MAP message shall contain grade data for the approach to the current intersection
TOSCo Supported Locations	• Each TOSCo supported approach at an intersection shall have the ability to measure actual queue lengths in real-time
Reception and Decoding of BSM	The infrastructure shall be able to receive and decode the BSM (including the BSM extension which contains a flag indicating that a vehicle is TOSCo enabled) • The infrastructure shall be able to distinguish TOSCo-equipped vehicles from CACC-enabled vehicles or regular Connected Vehicles (CVs) • The infrastructure shall be able to identify whether the BSMs are within the geo-fence range of current intersection • The infrastructure shall be able to identify whether the received BSMs are originating from vehicles traveling on the TOSCo-equipped corridor • The infrastructure shall be able to locate each received BSM on the map and calculate additional information such as distance to stop bar, estimated time of arrival, requested SPaT, and approach states (approaching current intersection, leaving current intersection)
Sensor Requirements for Queue Determination	The infrastructure shall be equipped with vehicle detectors that provide lane-level traffic data such as volume and occupancy • The infrastructure shall be able to identify the status of each detector • The vehicle detectors shall be able to provide data every 1 second
Adjusting Signal Phase	• If appropriate, the infrastructure may use information from vehicles to adjust its signal phase (sequence) and timing parameters to accommodate TOSCo-equipped vehicles approaching the intersection
Generation and Transmission of Target Window Information for each Lane	The infrastructure shall provide the TOSCo-equipped vehicle a target window of time • The beginning of the green window shall be the time when current queue is estimated to clear at the stop bar of the approaching intersection • The end of the green window shall be the end of the current green phase • The infrastructure shall update the target green window data every second (1Hz)
Generation and Transmission of Queue Information	The infrastructure shall be able to provide approaching TOSCo-equipped vehicles with information related to the location of the queues present at the intersection. A TOSCo-equipped vehicle is defined to be in a “queued” state when its distance to

Summary	Description
	the preceding vehicle is less than or equal to 6.1 meters (20 ft) AND when its speed is less than or equal to 2.24 m/s (5 mph). • The infrastructure shall have the capability of providing queue information by lane for each approach to support TOSCo • The infrastructure shall provide the TOSCo-equipped vehicle with updated queue information every second • The infrastructure shall provide the TOSCo-equipped vehicle the current location of the back of the queue relative to the stop bar of the intersection, measured in meters • The infrastructure may provide the TOSCo-equipped vehicle with an estimate of the time when the predicted maximum length of queue (in meters) will clear the intersection • If the infrastructure is unable to estimate the queue, the infrastructure shall not broadcast SPaT and MAP messages • The infrastructure shall be capable of fusing information from vehicle BSM data with information obtained from the infrastructure-based detection systems to determine the location of the back of queue
Advanced Traffic Signal Controller	• The traffic signal controller shall provide the TOSCo system with status of each phase at a frequency of 10 Hz • The infrastructure shall have the capability of providing the time to change in phase state for each phase at a frequency of 10 Hz
Road-side Unit (RSU)	• The RSU shall be able to receive the signal data and broadcast in SAE J2735 SPaT format • RSU shall be able to read a local map description file and broadcast in SAE J2735 MAP format • RSU shall be able to receive, and decode, BSMs from connected vehicles (including TOSCo vehicles) • The RSU shall be able to make any received BSMs available to the TOSCo System • RSU shall be able to broadcast customized DSRC messages (e.g., SPaT regional extension)
Road-side Processor (RSP)	RSP holds the infrastructure algorithms • RSP shall be able to estimate queue length and calculate green window based on received BSMs

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

List of Acronyms

Acronym	Meaning
ACC	Adaptive Cruise Control
ADTF	Automotive Data and Time-Triggered Framework
BSM	Basic Safety Message
CACC	Cooperative Adaptive Cruise Control
CAMP	Crash Avoidance Metrics Partners LLC
HMI	Human Machine Interface
DSRC	Dedicated Short Range Communication
HV	Host Vehicle
LV	Lead Vehicle
RSM	Road Safety Message
RSU	Roadside Units
SPaT	Signal Phase and Timing
TOSCo	Traffic Optimization for Signalized Corridors
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
VISSIM	Verkehr In Städten - SIMulationsmodell

APPENDIX A. Theoretical Analysis of Simultaneous Launch

A key potential benefit of TOSCo is having a large number of vehicles move simultaneously and cooperatively. This section focuses on the theoretical benefits of vehicles launching simultaneously from a Stop upon a phase transition from red to green for a single intersection. Mathematical expressions for acceleration, speed and displacement are first defined then applied to individual vehicles in a queue to determine the overall time required for them to individually clear the stop bar. By varying various parameters of the movement profile, launch type (i.e., simultaneous or driver-based), the number of vehicles in the queue and the distance between vehicles, changes in system performance (i.e., clearing time) can be observed. The clearing time is defined as the time it takes for the rear-end of the last vehicle in the queue to cross the stop bar.

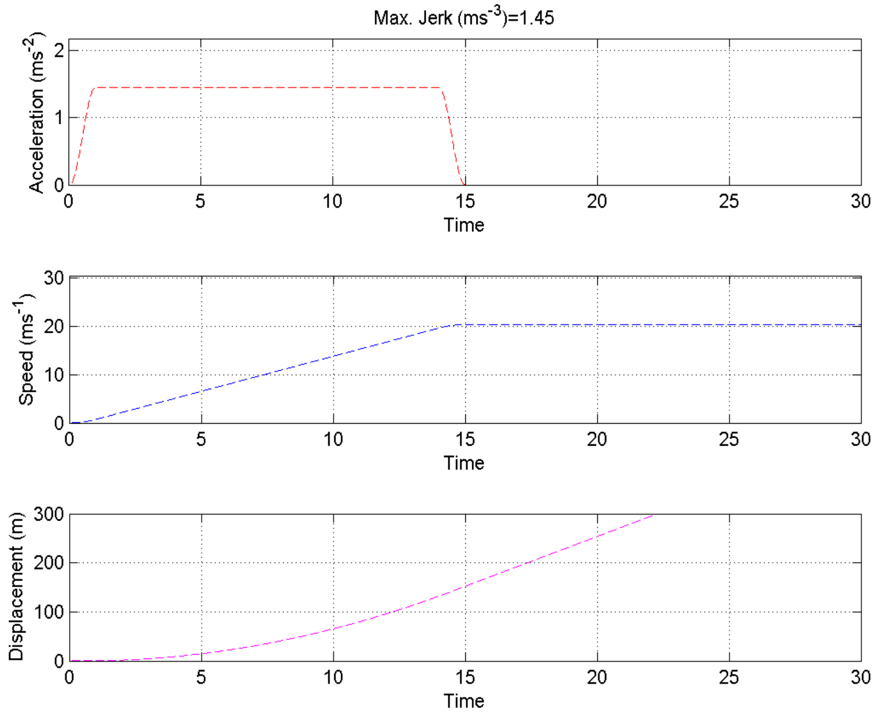
A.1 Vehicle Movement Profile

The acceleration profile is a vehicle's acceleration level (in m/s^2) as a function of time (s). The function itself is defined mathematically as a piecewise function as shown below. The inputs to this profile comprise the following variables shown as MATLAB pseudo-code:

```
t0 = 0 (start time (s) of accel.), t1 = 1 (peak accel. reach time (s))

t2= 14 (peak accel. fall time (s)), t3 = 15 (accel. end time (s)),

amax = 1.45 (max. accel. (m/s^2)), ainit = 0 (initial accel. (m/s^2) at t0),
afinal = 0 (final accel. (m/s^2) at t3),

V0 = 0 (initial speed (m/s) at t0)

S0 = 0 (initial displacement (m) at t0), Jerk = (amax-ainit)/(t1-t0);

A(t0<=t<=t1) = a1*sin(b1*(t+c1)) + d1; (initial accel. ramp-up phase)
A(t1<=t<=t2) = amax;                   (constant accel. phase)
A(t1<=t<=t2) = a2*sin(b2*(t+c2))+d2;   (terminal accel. phase)

V = V0 + cumsum(A*time_delta)  (speed profile)
S = [S0 S0+cumsum(0.5*(V(2:end)+V(1:end-1)))*time_delta] (displacement profile)
```

The acceleration profile is determined in three phases; (i) the ramp-up phase, where the acceleration value starts from some initial value `ainit` and then follows a sinusoidal function between `t0` and `t1` seconds to reach some constant threshold, (ii) the constant acceleration phase with a value `amax` phase between `t1` and `t2` seconds, and (iii) the terminal phase between `t3` and `t4` seconds, where it again follows a sinusoidal function to reach a final value `afinal`. The ramp-up and terminal phases can be configured to be symmetric with the appropriate level of maximum jerk (i.e., rate of change of acceleration).

Based on the acceleration profile defined above, provided some predefined initial speed `V0` and initial displacement value `S0`, the speed and the displacement profiles can be numerically or analytically computed which are again function of time. Plotted in Figure 42 below are the movement profiles of a vehicle accelerating from an initial speed of zero to nearly 45 mph in a 15 second interval, using some variables defined above.



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

Figure 42: Movement Profile of a Vehicle which Accelerates to 45 mph from a Stop.

A.2 Simulating Queue

In simulating a vehicle queue at the stop bar, the same exact movement profile (i.e., acceleration, speed and displacement) can be used for all vehicles by simply adjusting their initial displacements (i.e. `S0`). To reiterate, by having a common underlying profile for all vehicles, the relative impact of system-level variables such as inter-vehicle distance or the queue length on launch performance can be determined.

In our simulation of a queue of N vehicles, all vehicles are of the same length and have the same inter-vehicle distance between neighboring vehicles. The movement profile of the TOSCo-equipped HV (i.e., at the head of the queue at the stop bar) is as described in Figure 42. Time `t0` can be considered as the time when the light turns green and the TOSCo-equipped HV starts moving.

A.2.1 Distance Gap Control vs Time Gap Control

The successive vehicles behind the TOSCo-equipped HV will adopt the same movement profile except with two modifications: (i) they follow a distance gap control (i.e., maintain a minimum distance) at lower speeds, and (ii) time gap control (maintain a minimum time gap) at higher speeds with respect to the vehicle ahead. This adaptive behavior applies regardless of whether the vehicle is part of simultaneous launch or of conventional (driver) launch.

A.2.2 Driver (Conventional) Launch

In a deterministic driver launch, the inter-vehicle distance of the vehicles is set to a value smaller than the minimum safety distance. This setting is to imitate the real-world driver behavior where each vehicle may be positioned quite close to the vehicle ahead of them. Once the TOSCo-equipped HV launches, the second vehicle waits until the gap becomes larger than the minimum safety distance before moving. In this case, it has the same displacement/speed profile as the TOSCo-equipped HV except with an initial displacement offset with respect to the TOSCo-equipped HV and start time set when the minimum safety distance to the TOSCo-equipped HV is reached. Also, consequently, the time gap control does not kick in since the inter-vehicle distances always remains large. Using the same approach, the speed and displacement of all successive vehicles are iteratively determined with respect to the vehicle ahead of them.

A.2.3 Simultaneous Launch

In simultaneous launch, the inter-vehicle distance of the vehicles is set to exactly the minimum safety distance. This setting thus leads to a queue length that is longer than that in the driver launch scenario. Once the TOSCo-equipped HV launches, all vehicles can launch at the same time. In this case, all vehicles have the same initial speed profile as the TOSCo-equipped HV. However, their displacement profile has added displacement with respect to the vehicle ahead of them. Since all vehicles launch simultaneously while having the minimum safety distance, in the simulation they switch to a time gap control when the speeds exceed a threshold (i.e., a crossover speed threshold). The time gap control reflects a natural means to have a larger safety distance to the vehicle ahead proportional to the speed. In the simulation, once the speed of the TOSCo-equipped HV exceeds this crossover speed threshold while accelerating, the second vehicle either maintains its speed or may only accelerate if the actual time gap is larger than the target level. In the simulation, a given speed profile is adapted in such a way that at any time the vehicle's speed remains locked at the current level until the time gap constraint, with respect to the vehicle ahead, is satisfied. To reiterate, this speed lock only applies when the speeds are above the crossover threshold. The same approach is iteratively applied where the successive vehicles maintain distance gap or time gap control with respect to the vehicle ahead of them.

As an additional comparison, the impact of constant accumulative delay offset between vehicles is considered. For instance, the first vehicle may launch at 0 s, second at 0.5 s, third at 1.0 s and so on.

A.3 Results and Benefits

In the following simulation, a vehicle queue of N = 8 vehicles which accelerate from a stop to 45 mph is considered first. The time it takes for all the vehicles to depart the stop bar is evaluated. The following parameters have been selected for the simulation:

Acceleration profile parameters:

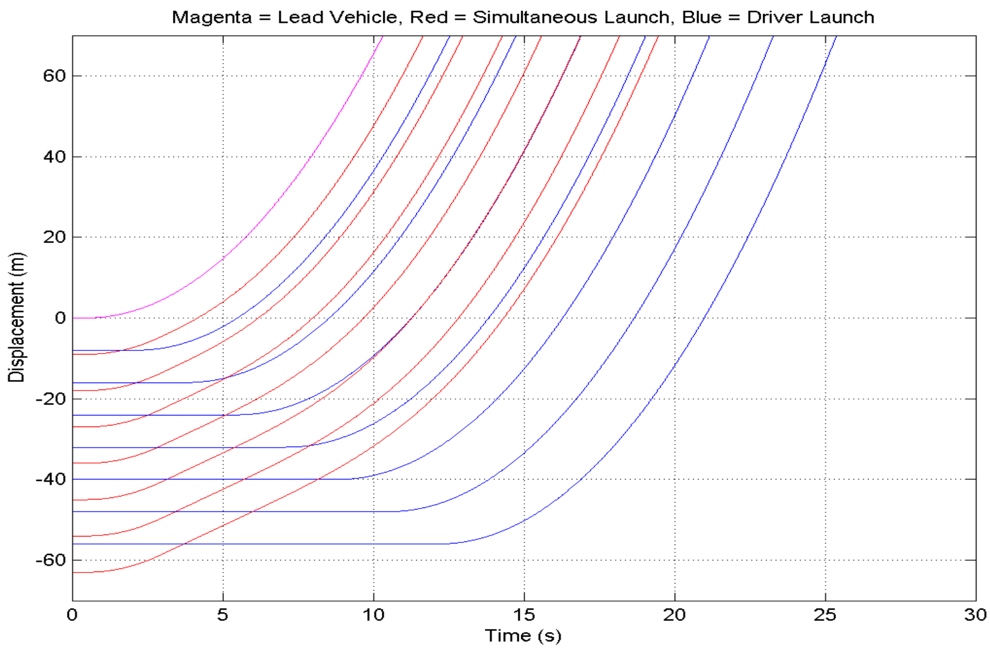
```
t0= 0; t1 = 1; t2= 14; t3=15; amax = 1.45; ainit = 0; afinal = 0; V0 = 0;
```

Miscellaneous parameters:

```
VehLen = 5.5; FrontToRearBumperGap = 2.5; min_safety_dist = 9;
optional_simultaneous_launch_delay = 0; time_gap = 1;
speed_transition_threshold = 3;
```

All vehicles are 5.5 m, where the distance from front-to-rear bumper for drive launches is set to 2.5 m, while that for simultaneous launches is kept at 3.5 m (i.e., a minimum safety distance of 9 m between the centers of neighboring vehicles each of 5.5 m). The target time gap is set at 1 s and the speed transition threshold to go from distance gap control to time gap control is 3 m/s.

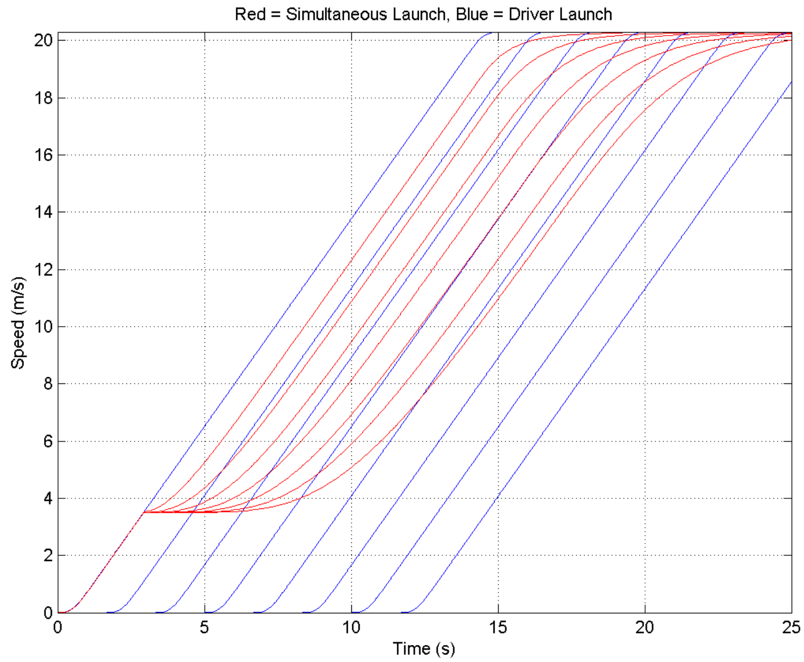
Plotted in Figure 43 are the displacement profiles of both the driver launch and the simultaneous launch. Notice that despite the fact that the initial queue length at time 0 s is longer for the latter (about 48 m vs 63 m), the time it takes for the last vehicle to cross the 0 m displacement (i.e., stop bar) is much shorter (about 15 s vs 22 s). The movement profile of the TOSCo-equipped HV is identical in both types of launches.



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

Figure 43: Displacement Profiles for Simultaneous and Driver Launches for N = 8 Vehicle

Plotted in Figure 44 are the corresponding speed profiles of the vehicles. For the simultaneous launches, the vehicles switch to a time gap control when their speeds are 3.5 m/s or more. There is, however, too large a distance gap in driver (conventional) launches for the time gap control to initiate.



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

Figure 44: The Speed Profiles for the Simultaneous and Driver Launches

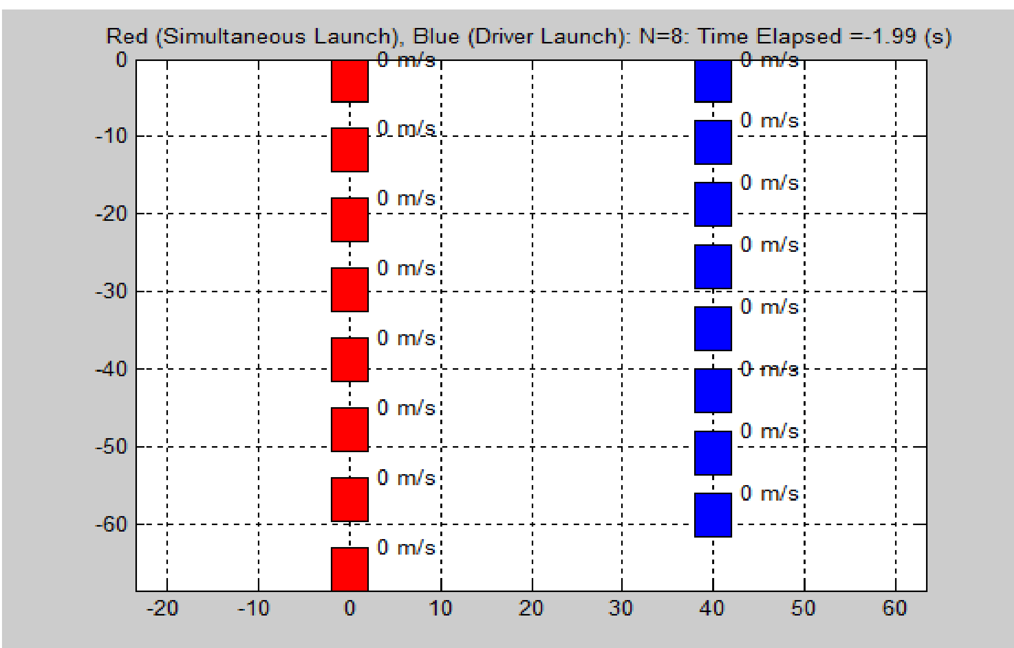
Plotted in Figure 45 is the time it takes for individual vehicles in the queue to cross the stop bar. The time difference between simultaneous and driver launches grows with the queue length. The request time is defined as the time it takes between successive vehicles to cross the stop bar. The mean request time of the two launches as numerically computed in the simulation is about 1.7 s (simultaneous) and 2.6 s (driver). Plotted in Figure 46 is a snapshot from a GIF that illustrates the temporal movement of the vehicles in both types of launches.

Plotted in Figure 45 and Figure 48 are results by setting `optional_simultaneous_launch_delay = 0.5` to imitate a situation where there is a half-second accumulative constant delay between for simultaneous launches. Even with the accumulative lags (i.e., 4 s for the eight vehicle), the clearing time for simultaneous launch is about the same (i.e., 15 s). This is because of the deceleration induced by the time gap control occurring much later due to the extra accumulative lag as shown in Figure 47.

The results in both Figure 45 and Figure 48 reinforces the benefits of simultaneous launches and which also show that this advantage scales with a longer queue length.

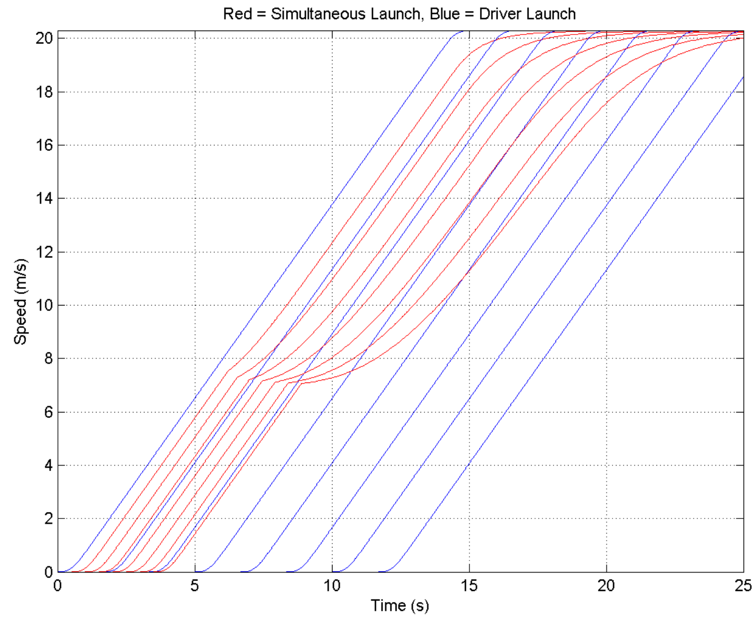
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 45: Clearing Time Comparison for Simultaneous and Driver Launches



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

Figure 46: A GIF Illustration of the Movement of Vehicles



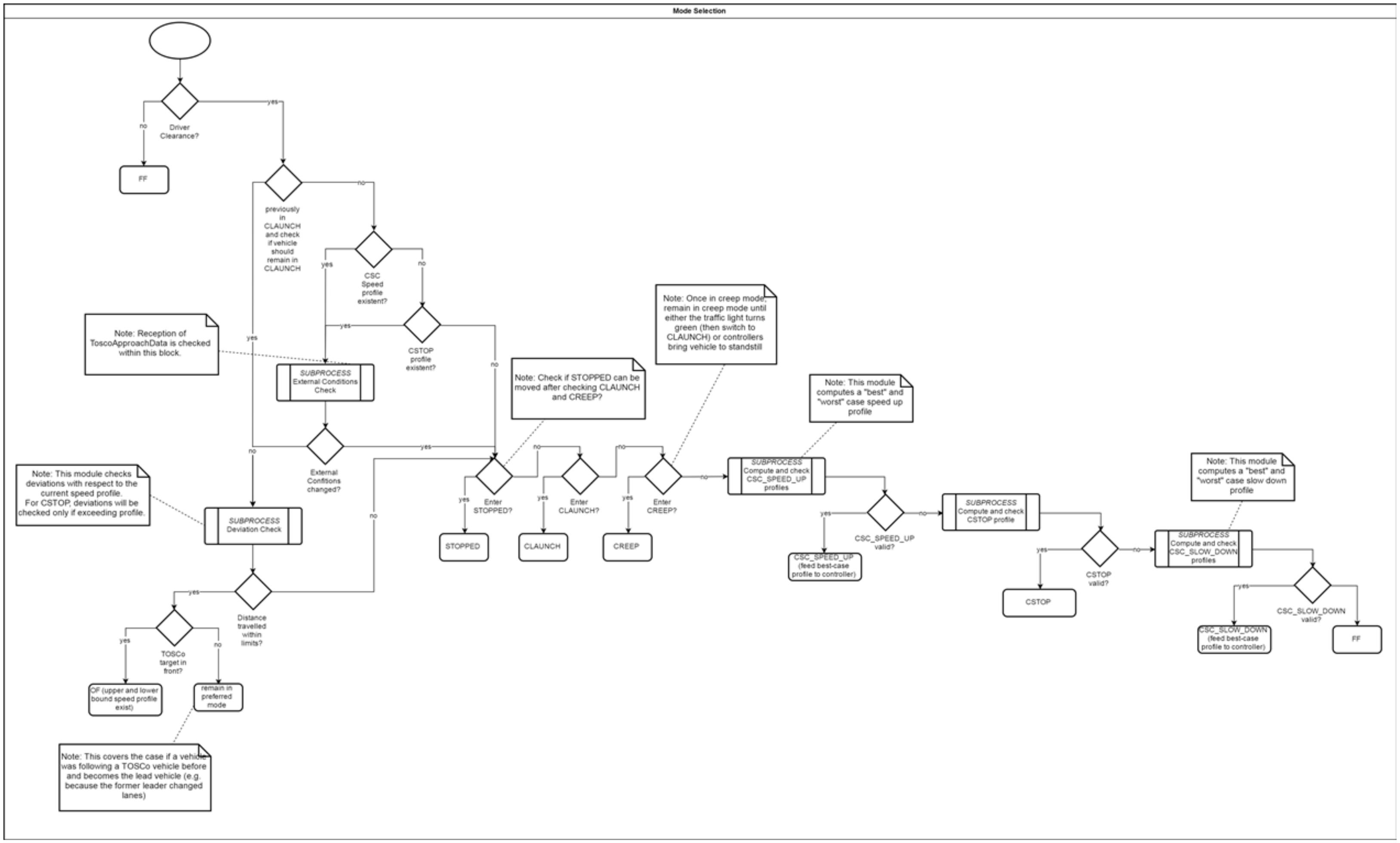
Source: Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 47: Time Gap Control in Simultaneous Launch

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

Figure 48: Impact of Constant Accumulative Delay in Simultaneous Launches

APPENDIX B. TOSCo Mode Selection Flow Chart



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

Figure 49: TOSCo Mode Selection Flow Chart

U.S. Department of Transportation
ITS Joint Program Office-HOIT
1200 New Jersey Avenue, SE
Washington, DC 20590

Toll-Free "Help Line" 866-367-7487
www.its.dot.gov

FHWA-JPO-20-793

U.S. Department of Transportation