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Truck CACC Implementation, Field Test and Data Analysis Results

**PATH Research Report for
FHWA Exploratory Advanced Research Program
Cooperative Agreement DTFH61-13-H00012**

**Task 2.4 – Implement CACC Control on Trucks and Test to Verify Proper
Performance**

Xiao-Yun Lu

June 2018

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Table of Acronyms

ACC – Adaptive Cruise Control

CACC – Cooperative Adaptive Cruise Control

California PATH – Partners for Advanced Technologies

CAV – Connected Automated Vehicle

CC – Cruise Control

CV – Connected Vehicle

D-Gap – Distance Gap between two consecutive vehicles

DSRC – Dedicated Short Range Communication

DVI – Driver Vehicle Interface

GPS – Global Positioning System

I-80 – Interstate Freeway 80

LA – Los Angeles

PC – Personal Computer

Std Dev – Standard Deviation in Statistics

T-Gap – Time Gap between two consecutive vehicles

UDP - User Datagram Protocol, one of the core members of the Internet protocol suite

Vehicle ID – Vehicle Identification, i.e. vehicle position number in a platoon or CACC string

1. Introduction

This report documents the CACC implementation and field tests for Class-8 trucks. The CACC system design for this implementation has been documented in a separate report.

The field tests include two types: some limited freeway tests for control system tuning and development purposes, and extensive tests of fuel consumption at Transport Canada's Motor Vehicle Test Centre near Montreal. Although the objective of the latter test was for fuel economy analysis of CACC operations, the data have been used for CACC performance analysis in this report since most of the fundamental scenarios have been tested systematically.

The three-truck CACC system underwent fuel-economy testing during October 2016 at Transport Canada's Motor Vehicle Test Centre in Blainville, Quebec, Canada. A 6.5 km (4.0 mile) high-speed track was used for testing, consisting of two straight 1.6 km (1.0 mile) sections, and two 1.6 km (1.0 mile) constant-curvature banked sections. A test program was devised to examine the influence of four parameters on the fuel-savings potential of the three-truck CACC string:

- Separation Distance/Time: 17 m (57 ft) to 43 m (142 ft), equivalent to 0.6 s to 1.5 s at 65 mph (105 km/h).
- Truck configuration: standard trailer vs. aerodynamic trailer (side-skirts + boat-tail).
- Vehicle speed: 89 km/h (55 mph) and 105 km/h (65 mph).
- Vehicle weight (tractor + trailer): 14,000 kg (31,000 lbs) and 29,400 kg (65,000 lbs).

2 CACC Implementation

This section describes how the CACC system has been implemented. The implementation includes the following aspects:

- Hardware development
- Software development
- Driver-Vehicle-Interface (DVI) development
- Driver operation of CACC system apart from DVI

Since hardware, software and DVI development parts are documented in other reports, the CACC implementation in this report will only briefly report a high-level overall system implementation and driver operation.

2.1 Overall Picture of CACC Implementation

The following Figure 2-1 depicts the overall physical implementation of the CACC system, which includes the following main components:

- PC-104 computer: mounted in a cabinet behind the driver's seat

- Emergency disengage switch: mounted on the right-hand-side of the driver's seat for the convenience of driver access
- DVI: mounted on the dashboard in front of the driver for convenience of access
- Dual DSRC antennas: mounted on both side mirrors
- 5 Hz GPS: mounted inside of the tractor cab roof
- Video camera and Doppler radar were Volvo mounted components

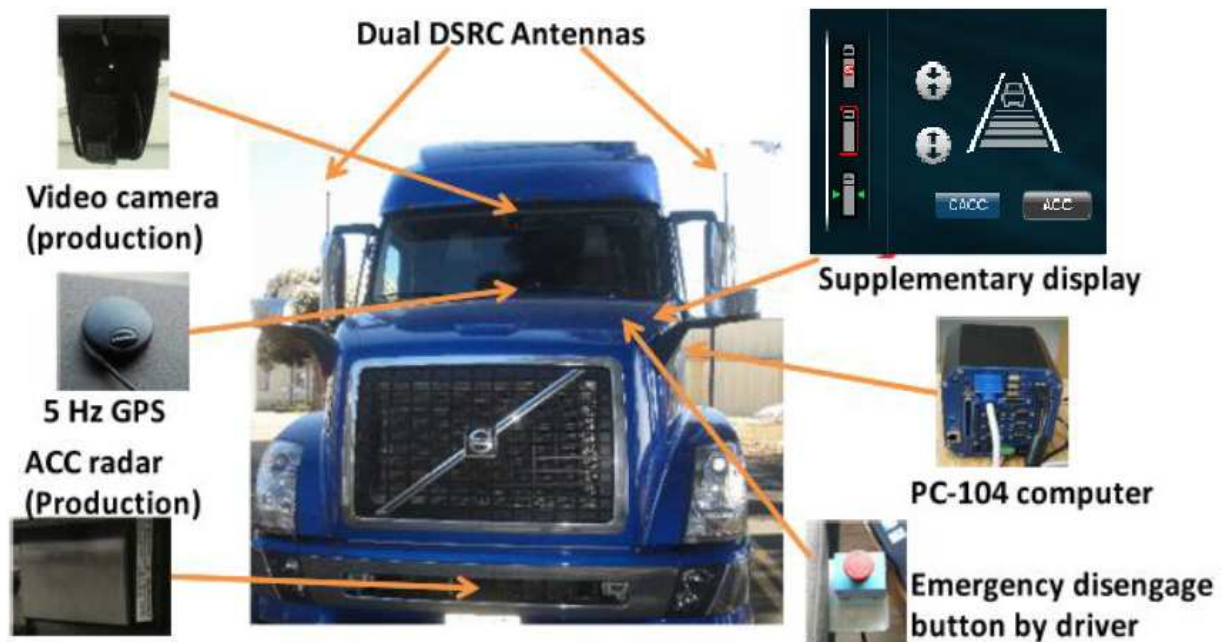


Figure 2-1 Overall picture of CACC Implementation

2.2 Control Activation

The default ACC built-in by Volvo was purposely deactivated so that the operation switch on the steering column (Figure 2-2) could be used for CACC operation. The ACC system was also PATH developed for easier integration with CACC and for better performance of the system when it is necessary to switch between different driving modes: manual, CC, ACC and CACC. All the following functions for the original ACC operation were kept for driver's easy adaptation:

- ACC/CACC ON
- ACC/CACC OFF (going to manual)
- Resume: going back to ACC/CAC mode if the control has been deactivated for any reason

Such implementation is feasible due to the real-time access of the operation switch signal information from J-1939 data bus.



Figure 2-2. Automatic Control Activation

2.3 Automatic Control Deactivation

The driver can deactivate the automatic control in any driving mode (CC, ACC and CACC) in any of the following three ways in case it becomes necessary:

- Switching off the operation switch on the steering column (Figure 2-2) (turn off the CACC from the vehicle control system but CACC software is still running after deactivation)
- Pressing the service brake pedal (turn off the CACC from the control system but CACC software is still running after deactivation)
- Pressing down the emergency switch (Figure 2-3) (physically cutting off the connection between the central control PC-104 computer and the J-1939 Bus; as a result, all the interface with J-1939 including data reading and command sending are deactivated; by default, it will return to manual mode.)



Figure 2-3. Control Deactivation

2.4 Driving Mode and Time Gap Selection

The following Figure 2-4 and Figure 2-5 is a screen shot of the supplementary Driver Vehicle Interface (DVI). Its main functions include: (a) for the driver to observe the current status of several critical items such as vehicle position in the platoon, driving mode (manual, CC ACC or CACC), DSRC health, service brake use of all the vehicles in the platoon; and (b) for the driver to select driving mode between ACC or CACC (for the following trucks since the lead truck is always in CC or ACC) and Time-Gap for ACC and CACC driving mode. A more detailed DVI description is presented in the separate report on Task 2.2. UDP messaging is used to send/receive messages from/to the control algorithm. The two sets of arrows on the DVI are used to send time gap requests, and the CACC/ACC radio button sends CACC or ACC control mode requests. The current status of the control system is contained in UDP messages received from the control computer.

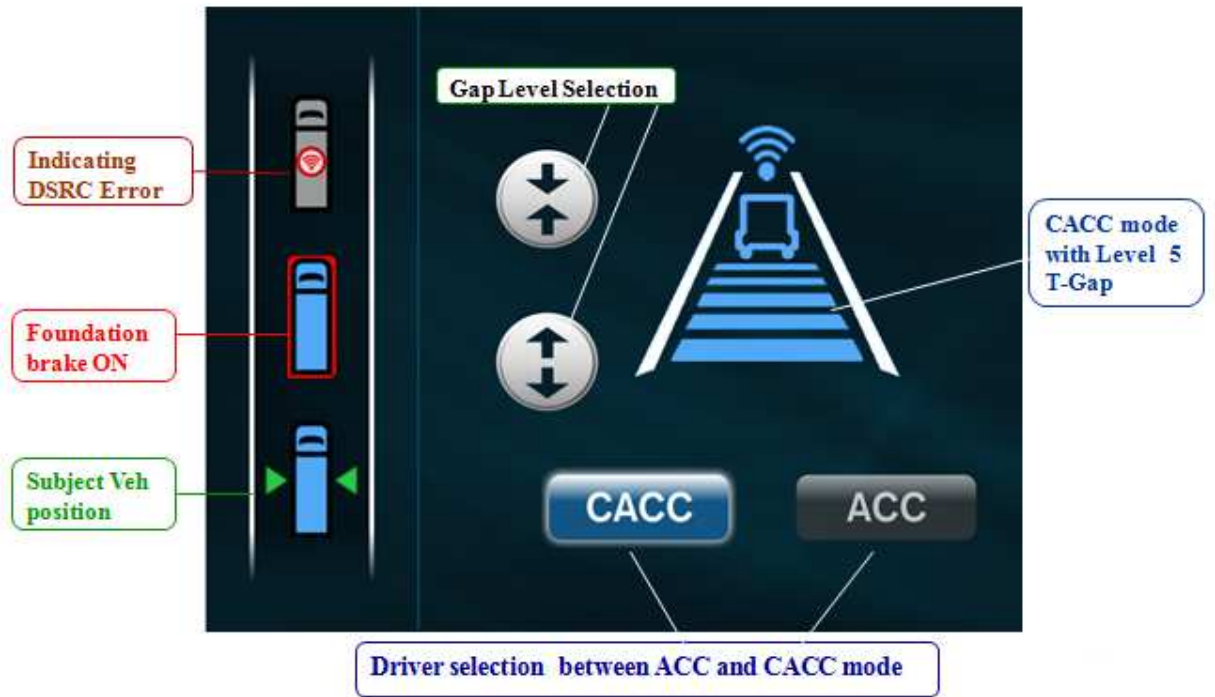


Figure 2-4. Driving Mode and Time Gap Selection: CACC



Figure 2-5. Driving Mode and Time Gap Selection: ACC

The following Table 2.1. Available Time Gaps Implemented for ACC and CACC respectively. Those numbers have been selected based on previous work in this field and field tests that the PATH team has conducted.

Table 2.1. Available Time Gaps Implemented

ACC Level	ACC Time Gap [s]		CACC Level	CACC Time Gap [s]
1	1.1		1	0.6
2	1.3		2	0.9
3	1.5		3	1.2
4	1.7		4	1.5
5	1.9		5	1.8

3 Truck CACC Performance Analysis

Three truck CACC has been tested on freeways with other public traffic as well as on a closed test track without public traffic. Although the real performance will need to be tested on freeways with other public traffic since the system is designed for that, it would require extensive tests for long periods of time with multiple drivers since each scenario cannot be repeated for multiple times under similar, if not exactly the same, traffic/road situation. This is obviously out of the scope of the project. Therefore, we used some freeway test data to show qualitatively the control system response. For the tests on the closed track, on the other hand, the test scenarios were repeated many times under the same or similar conditions for a long period of time. The data from those tests can be used for quantitative analysis of the performance. Such control performance evaluation is under simpler traffic situations. The following performance parameters are used in the quantitative analysis:

- Maximum positive and negative speed tracking errors
- Standard deviation of speed tracking error
- Maximum positive and negative distance tracking errors
- Standard deviation of distance tracking error

Since CACC is designed for both speed and distance tracking, it is believed that the above parameters quantitatively represent the control system performance.

The following terms are used throughout the discussion for convenience:

- Maneuver: means the test scenarios
- D-Gap: Distance Gap, speed dependent

- T-Gap: Time Gap, speed independent
- Vehicle ID: Truck position in the string

3.1 Truck CACC Following at Constant Speed on Freeways

Field testing of 3-truck CACC in public traffic has been conducted in California on several freeway sections/corridors including: Interstate 580 (or I-580), I-80, I-880, I-205, I-680, I-505, I-205, and State Routes 24, 4, and 110 (LA). Those freeway sections/corridors have different types of road geometry – curves and road grades (ascending and descending). Tested scenarios for three truck CACC included:

- truck one following other vehicles in ACC mode
- grading up/down as a CACC string
- cut-in and cut-out at different positions; the cut-in vehicles include those of public traffic and a confederate vehicle; the cut-ins included long space, short distance, and medium distance cut-in.

The following Figure 3-1 and Figure 3-7 are vehicle speed and road grade data for long distance round-trip driving on Interstate 80 and Interstate 505, which lasted over one and half hours in each direction. Those plots show a large scope qualitative observation of the performance for 3-truck CACC following. On I-80, the traffic volume was medium to high. Figure 3-1 is for Eastbound and **Error! Reference source not found.** is for Westbound. Besides, the road grade on I-80 Eastbound is also over 5% in some locations, which is significant for heavy-duty trucks. The traffic speed had some significant drops due to congestion on the I-80 section, which was reflected in truck 1 speed drop. It, in turn, caused speed drops of the two following trucks. Due to low traffic volume on I-505, there were not many cut-ins by other vehicles along the trips. Therefore, the speeds of the three trucks were almost constant in that section for both outbound (Figure 3-1) and inbound (Figure 3-7) trips. Figure 3-2 ~ Figure 3-6 are zoomed on Figure 3-1 to show more details of speed trajectories of the three truck – how they responded in vehicle following with respect to different road grade. Figure 3-8 ~ Figure 3-10 are zoomed on Figure 3-7 for the same reason. It can be observed that, in general, speed tracking error will be larger as road grade changes.

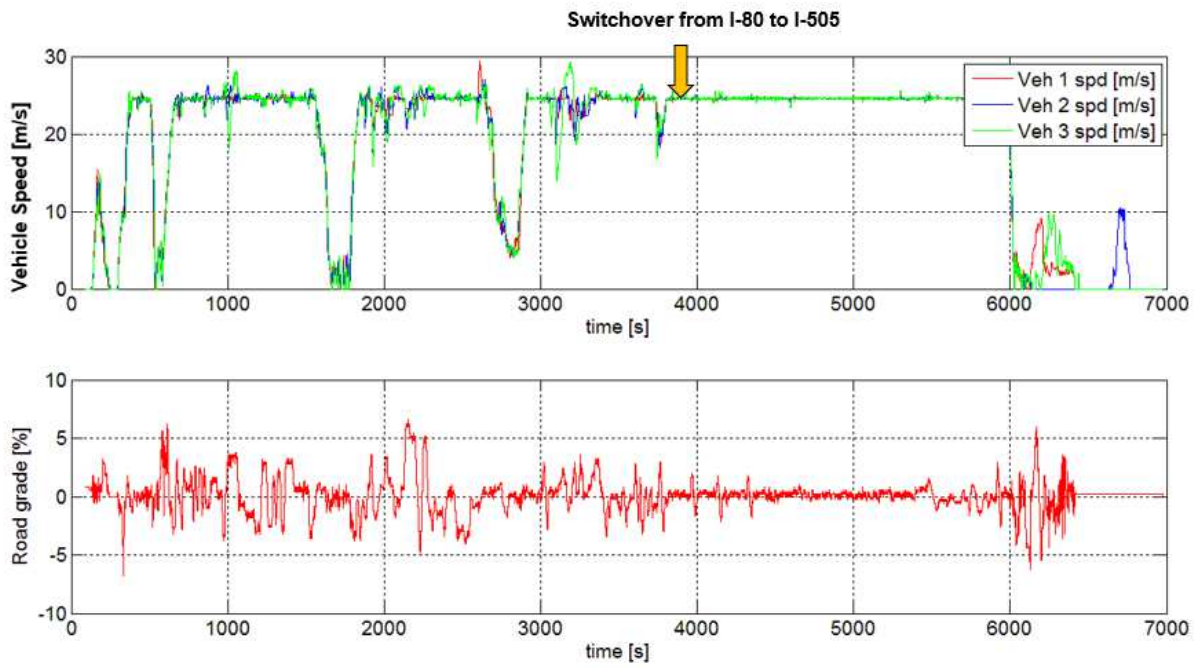


Figure 3-1. Three truck CACC speed trajectories (upper) on I-80 Wets Bound and I-505 with road grade measurement on truck 1 (lower)

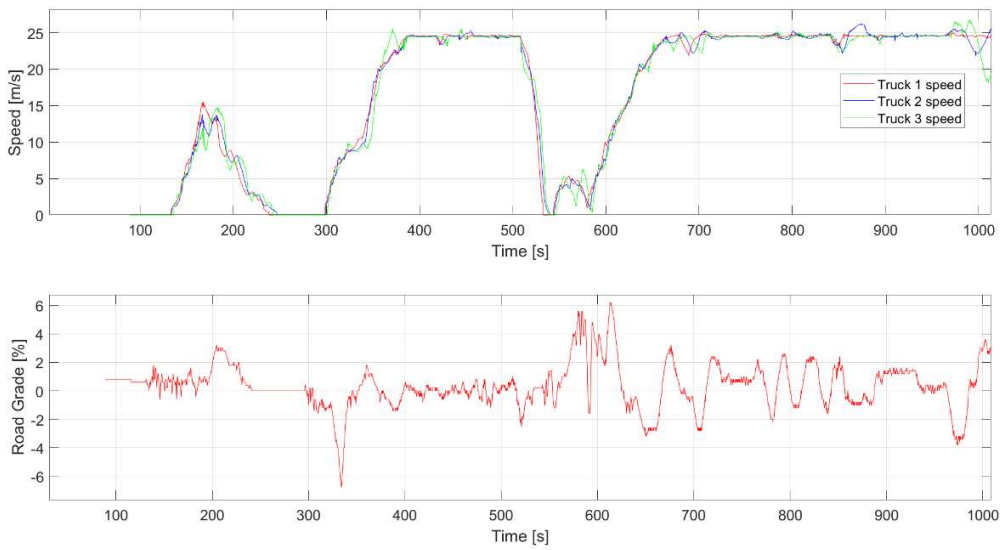


Figure 3-2 Three truck CACC speed (upper) on I-80 Wets Bound and I-505 (Zoomed)

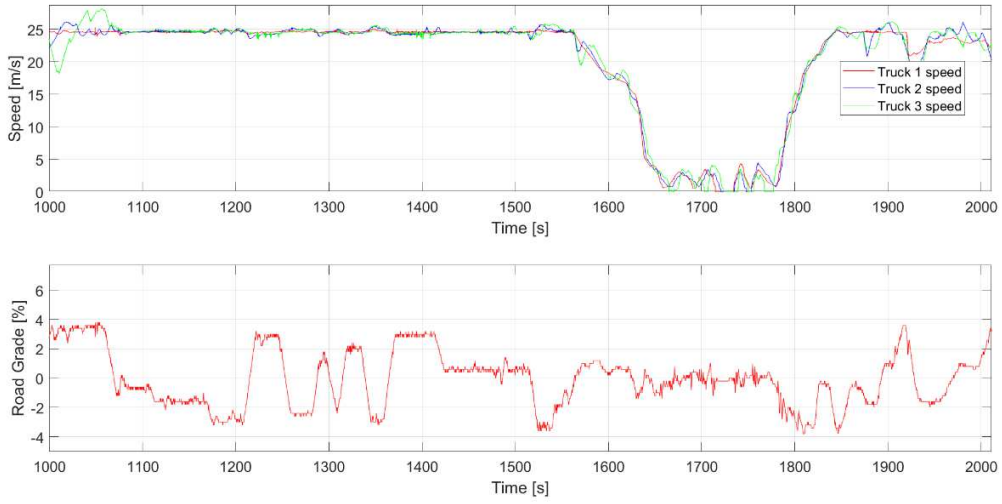


Figure 3-3 Three truck CACC speed (upper) on I-80 Wets Bound and I-505 (Zoomed)

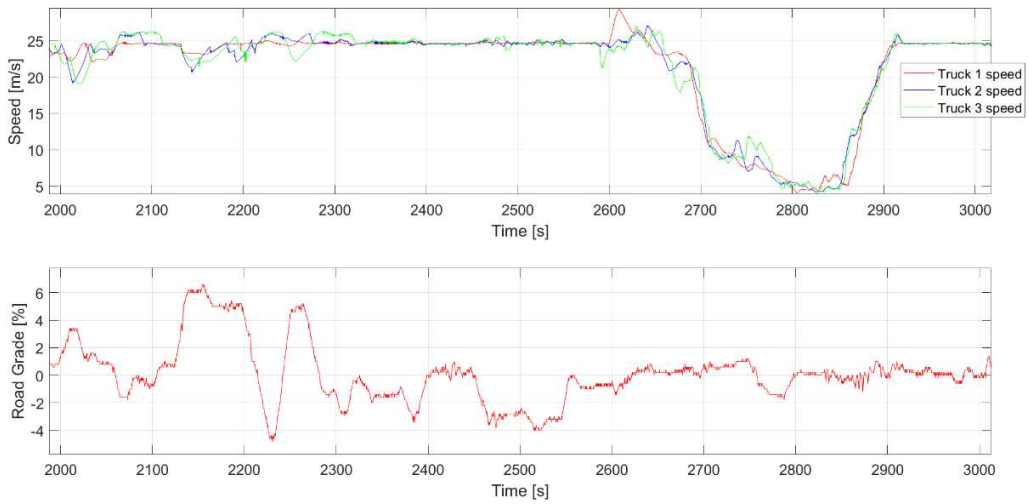


Figure 3-4 Three truck CACC speed (upper) on I-80 Wets Bound and I-505 (Zoomed)

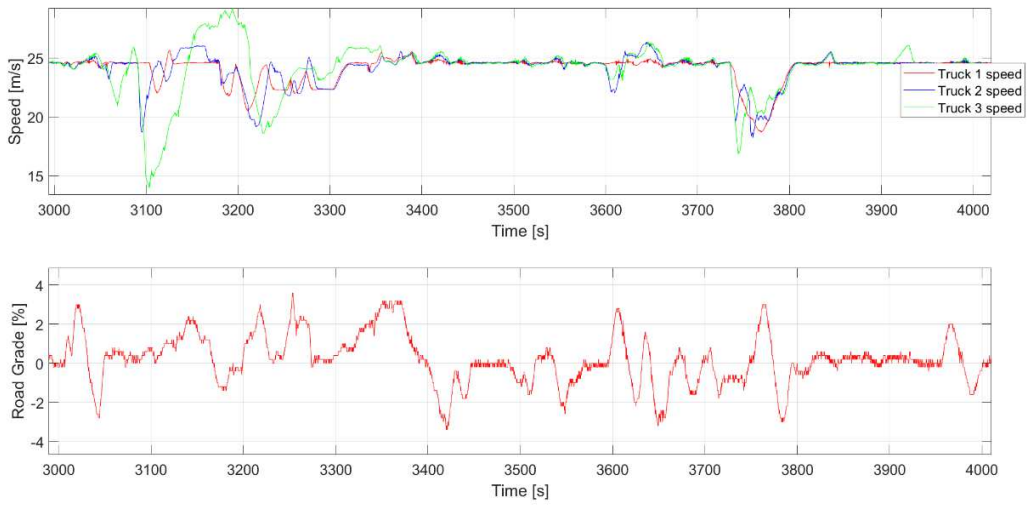


Figure 3-5 Three truck CACC speed (upper) on I-80 Wets Bound and I-505 (Zoomed)

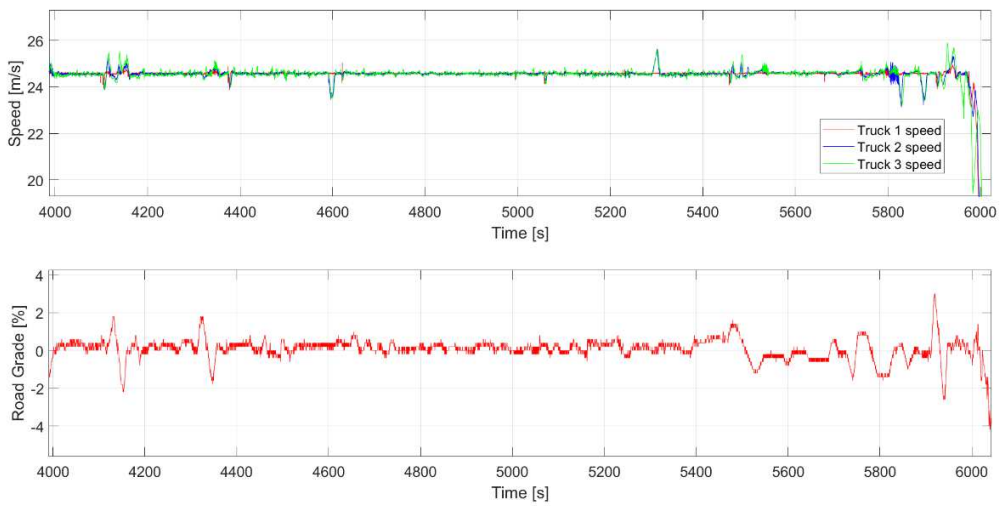


Figure 3-6 Three truck CACC speed (upper) on I-80 Wets Bound and I-505 (Zoomed)

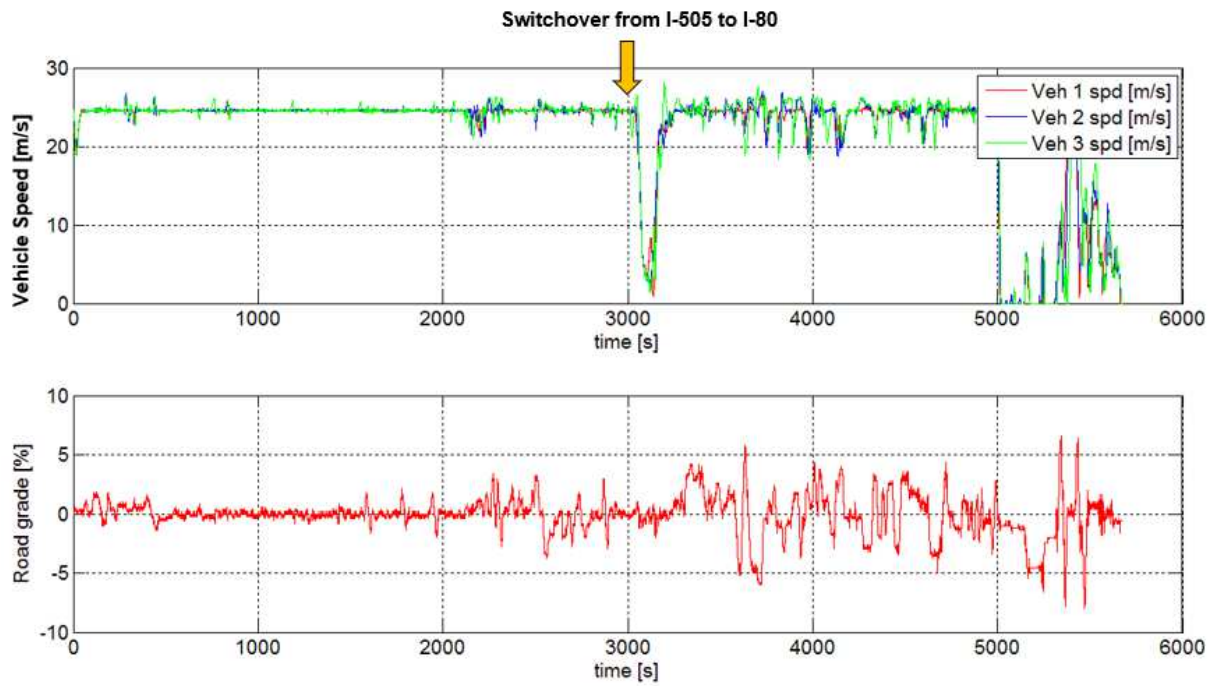


Figure 3-7. Three Truck CACC speed trajectories (upper) on I-505 and I-80 East Bound with road grade measurement on truck 1 (lower)

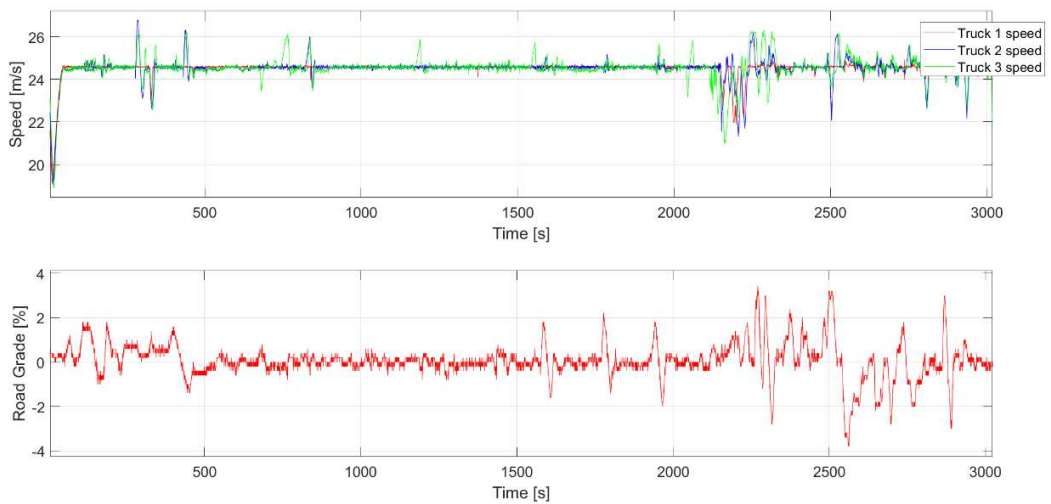


Figure 3-8 Three Truck CACC speed (upper) on I-505 and I-80 East Bound (Zoomed)

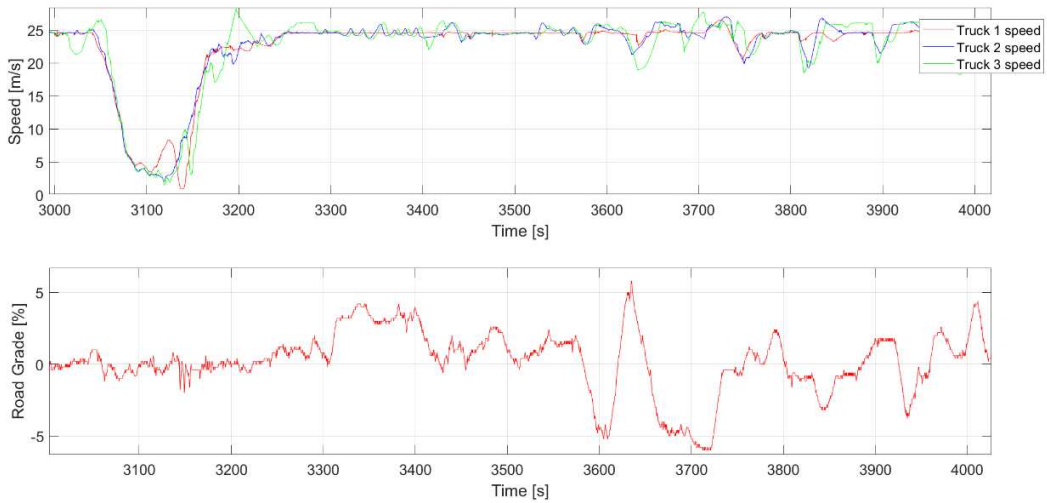


Figure 3-9 Three Truck CACC speed (upper) on I-505 and I-80 East Bound (Zoomed)

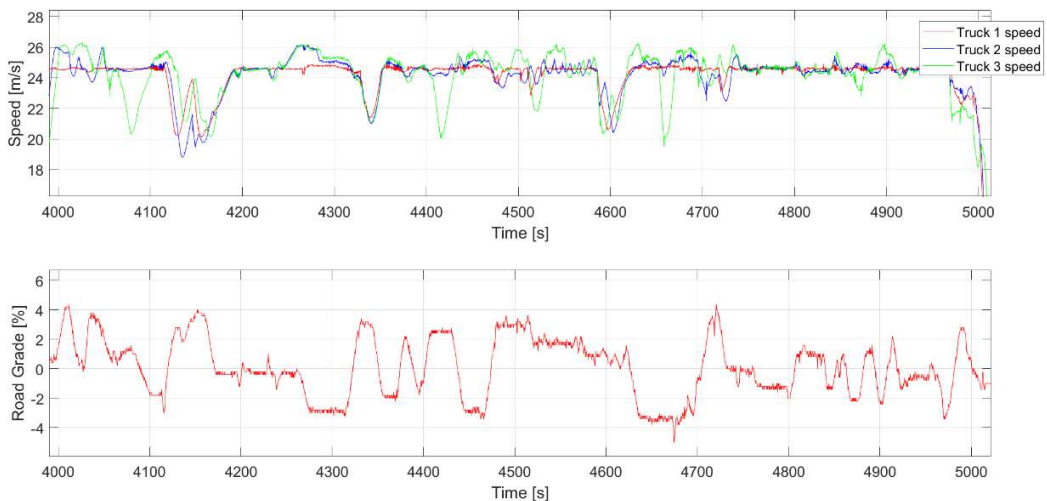


Figure 3-10 Three Truck CACC speed (upper) on I-505 and I-80 East Bound (Zoomed)

It is noted that some of the differences among the three trajectories were caused by cut-in and cut-out movements of other vehicles, which will be described in more detail in **Error! Reference source not found.**, but some of the differences were caused by road grade. In general, significant road grade ($> 5\%$) for class 8 would cause larger distance and speed tracking errors. Otherwise, the feedback control for individual vehicles and the overall string stability are reasonably robust in practice as could be observed from those plots.

3.2 Truck CACC Following for Cut-in and Cut-out Scenarios on Freeways

The cut-in and cut-out maneuvers are very important for such a truck driven on a freeway with other public traffic. It needs to be able to handle other vehicles' cut-in and cut-out maneuvers. Those interactions are dynamic and impromptu. The cut-in vehicle could be conservative or very aggressive with very short cut-in distance as we observed in tests on freeways, particularly in the case when some drivers have to leave the freeway from the off-ramps and to merge into the freeway from onramps.

The following are cut-in and cut-out maneuvers during the 3-truck CACC demo on I-66 near Washington D. C. on September 15 2017. Figure 3-11 the speed and front range (target distance in [m]) of three trucks vs. time in [s].

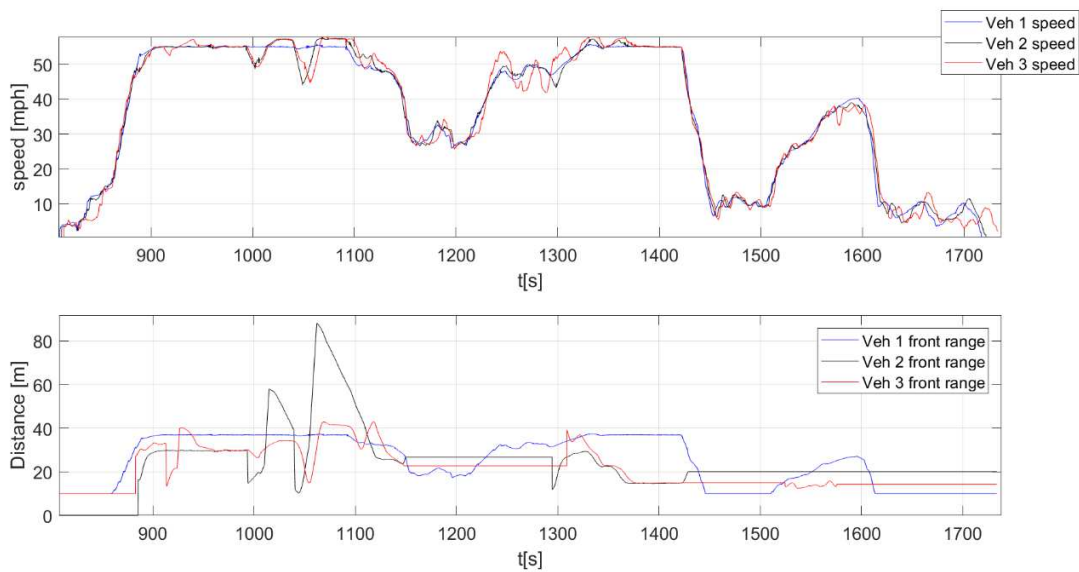


Figure 3-11 3-truck CACC at 55 mph on I-66 with cut-in and cut-out maneuvers by a confederate vehicle

Figure 3-12 is zoomed in from Figure 3-11 for more detailed observation of speed and distance trajectory for cut-in and cut-out maneuvers between truck 1 & 2, and between truck 2 & 3. Vehicle 1 range is the target vehicle in front of the Vehicle 1.

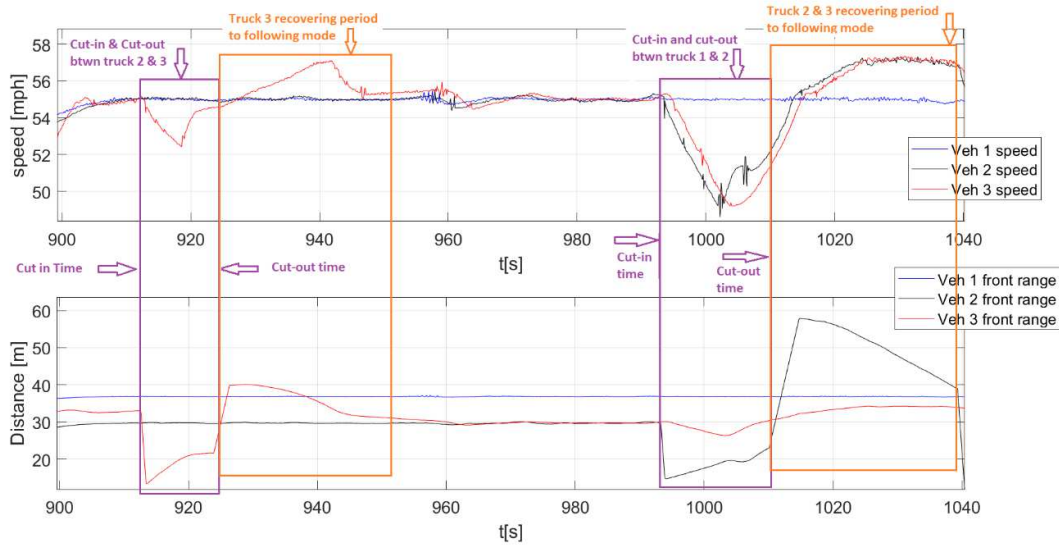


Figure 3-12. A closer look at 3-truck CACC at 55 mph on I-66 with cut-in and cut-out maneuvers by a confederate vehicle

In Figure 3-12 the purple rectangle marks the cut-in and cut-out maneuver time period. The orange rectangle marks the recovering period of the subject vehicle after cut-out to the CACC following mode with desired (driver selected) time gap. The first pair of purple and orange rectangles marks the cut-in between truck 2 & 3, while the second pair of orange rectangles marks the cut-in between truck 1 & 2. It is noted that, for the former, the cut-in vehicle would affect only truck 3, while for the latter, the cut-in vehicle would affect both truck 2 and truck 3. It can be observed that the cut-in between truck 2 & 3 caused the front range measurement of truck 3 to significantly reduce from about 35 m to about 18 m. As a response, the CACC control of this truck reduced its speed and the front range starts to increase to about 23 m. Then the cut-in vehicle started to cut-out, which caused the front range of truck 3 to increase to about 40 m, which is larger than the desired D-gap (determined based on the selected T-Gap). It can be observed that, after cut-out, the subject vehicle, and its follower, if applicable, will take about 30 s to recover, characterized by speed increasing and distance decreasing to the default CACC following mode at the driver selected T-Gap. This time is usually determined by two factors: (a) the cut-in vehicle speed and position in front of the subject vehicle: the closer in distance and/or the lower speed relative to the subject vehicle, the more speed reduction will be incurred by the subject vehicle, leading to longer D-Gap to the preceding truck, and therefore it will take longer time to catch up (recover) with the preceding truck after cut-out; and (b) control design for smoothness for driver's comfort: it is intuitive that a smoother control response will take a longer time to recover after disturbance.

Truck CACC following or platooning on graded roads is another test of control performance since the demand for acceleration capability in uphill and for deceleration capability in downhill will be much higher, particularly for fully loaded trucks. Due to the problem of automatic control of service brake deactivating the overall control system including engine control and the service brake

control itself, the control performance evaluation in this respect will need to be conducted extensively on freeways with significant road grades such as I-80 in a future project after the service brake problem has been resolved.

3.3 Three Truck CACC Following on Test Track at Transport Canada's Motor Vehicle Test Centre

This subsection will focus on the test data analysis for performance of three-truck CACC following, in particular, for three following distances: 18 m, 6 m and 4 m.

The tests were conducted on Transport Canada's Motor Vehicle Test Centre test track as shown in Figure 3-13 near Montreal Canada. Each lap is 4 miles long, with 2 miles of track being straight-lined and 2 miles being curved.



Figure 3-13. Map of test track with radar checkpoints and weather station location.

The following are the data analysis of three truck CACC test results on this track with D-Gap of 18 m (T-Gap = 0.6 s).

Speed Error [m/s]; the speed tracking error of each truck in meters per second; it is defined as the difference between the reference speed and the measured truck speed, which is quantified as: Root Mean Square (RMS) error, maximum value and standard deviation;

Distance Error [m]; the distance tracking error of each truck in meters; it is defined as the difference between the reference distance and the measured front gap in meters, which is quantified as: Root Mean Square (RMS) error, maximum value and standard deviation;

The following tables (Table 3.1–Table 3.2) show the speed and distance tracking errors for three T-Gaps (D-Gaps): 0.6 s (18 m), 0.21 s (6 m), and 0.14 s (4 m) respectively. Each scenario has been tested on the track for 16 laps, which is 64 miles. The maximum speed is 65 mph.

Table 3.1. Root Mean Square, Max and Standard Deviation of tracking errors, D-Gap [18m]

Maneuver	D_Gap [m]	T-Gap [s]	Veh ID	Speed Error [m/s]			Distance Error [m]		
				RMS	Max	Std Dev	RMS	Max	Std Dev
ACC	18m	No target	1	0.051999	0.531	0.052	0.28903	0.53	0.147249
CACC	18m	0.6	2	0.079383	1.113	0.079369	0.19305	0.844	0.162807
CACC	18m	0.6	3	0.087115	0.967	0.082824	0.231323	1.194	0.160698

The following Table 3.2 is the data analysis of three truck CACC on the track with D-Gap of 6 m (T-Gap = 0.21 s).

Table 3.2. Root Mean Square, Max and Standard Deviation of tracking errors, D-Gap [6m]

Maneuver	D_Gap [m]	T-Gap [s]	Veh ID	Speed Error [m/s]			Distance Error [m]		
				RMS	Max	Std Dev	RMS	Max	Std Dev
ACC	6m	No target	1	0.052791	0.553	0.052792	0.185494	0.446	0.141293
CACC	6m	0.21	2	0.084628	1	0.084627	0.170691	0.537	0.156544
CACC	6m	0.21	3	0.092889	1.013	0.089512	0.254495	0.638	0.157895

The following Table 3.3 is the data analysis of three truck CACC on the track with D-Gap of 4 m (T-Gap = 0.14 s).

Table 3.3. Root Mean Square, Max and Standard Deviation of tracking errors, D-Gap [4m]

Maneuver	D_Gap [m]	T-Gap [s]	Veh ID	Speed Error [m/s]			Distance Error [m]		
				RMS	Max	Std Dev	RMS	Max	Std Dev
ACC	4m	No target	1	0.057547	0.703	0.057548	0.208934	2.086	0.169429
CACC	4m	0.14	2	0.084418	0.84	0.084411	0.182147	1.076	0.172765
CACC	4m	0.14	3	0.095612	0.76	0.091309	0.281005	1.409	0.174174

It can be observed from Table 3.1, Table 3.2, and Table 3.3 that the maximum distance following error for truck 3 is about 1.4 m, which causes concern for a 4 m distance following. To investigate the cause of such significant distance error with respect to the desired short following distance, driving modes and distance tracking errors of the three trucks have been analyzed. Two causes have been identified that caused the large distance tracking error:

- Transition from manual to automatic mode at the beginning of the run, which is the case for the 18 m and 6 m following respectively in Table 3.1 and Table 3.2;
- Driver accidentally switched off the automatic control for the case in Table 3.3.

It can be observed from Table 3.1, Table 3.2, and Table 3.3 that CACC tracking errors are generally larger than ACC tracking errors which seem unreasonable. In fact, since the CACC following scenarios were tested without any vehicle in front of the lead truck, the leader was actually under CC (Cruise Control) mode. In this mode, the reference trajectory is internally planned for smooth acceleration and deceleration. This is why it has less tracking error in CC mode than in CACC mode.

The following Figure 3-14 and Figure 3-14 (zoomed from Figure 3-14) shows the differences and the distance tracking errors at the time instants when the three drivers switched from manual to automatic modes. The maximum distance tracking error was actually caused jointly by unsynchronized switching and time delays in control responses, so these are essentially artifacts of the testing procedure that was used rather than representing situations that are likely in normal real-world operations.

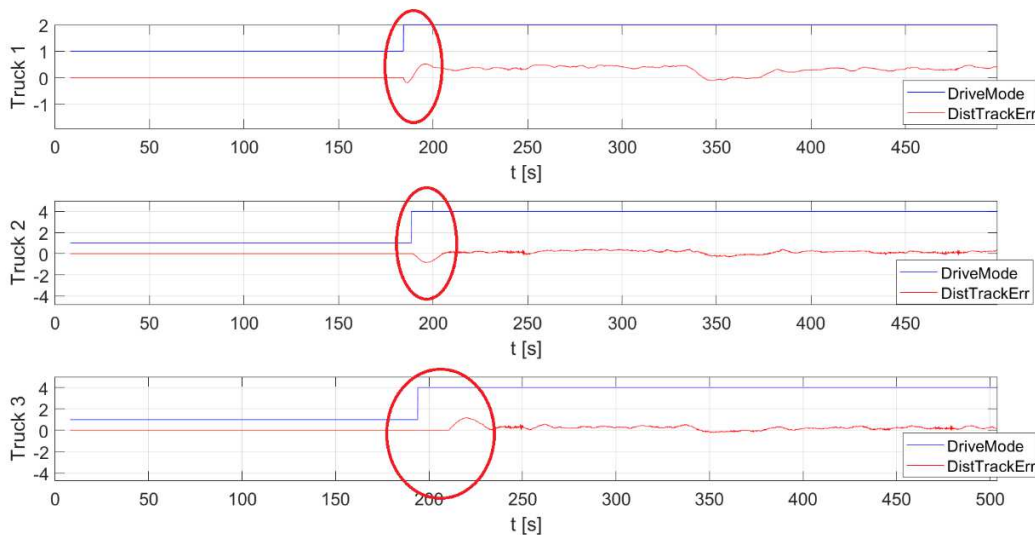


Figure 3-14. Max distance tracking error analysis for 18 m CACC following

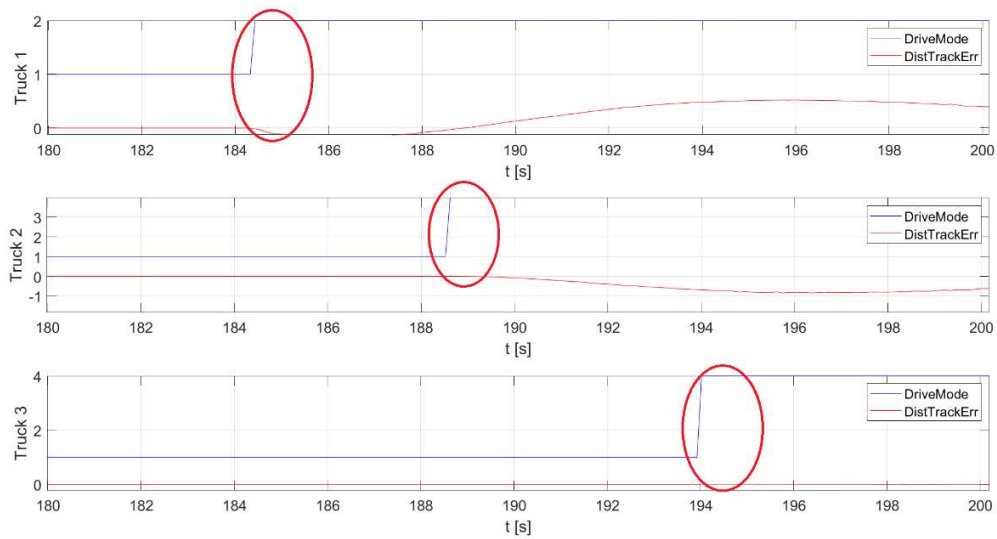


Figure 3-15. Max distance tracking error analysis for 18 m CACC following (Zoomed)

Figure 3-16 and Figure 3-17 are driving modes, speed tracking error and distance tracking errors of three trucks for the second case – the driver accidentally switched to manual mode for a short period of time. It can be observed that:

- The large distance tracking error of truck 2 and truck 3 at about 650 s was caused by a spike in distance tracking of truck 1;
- Since truck 1 is under speed control (CC mode without front target), the distance tracking error was an integral of the speed tracking error; therefore, a large distance tracking error should not happen to truck 1 in CC mode in principle; further observations showed that such a distance tracking error was eventually caused by the driving mode suddenly changing from automatic (Drive Mode = 3) to manual mode (Drive Mode =2); this might be caused by the driver behavior – accidentally switched off the automatic control then turned it on again after a short period of time;
- Apart from the incident-caused significant errors, the distance tracking errors at other times and the speed tracking errors are small.

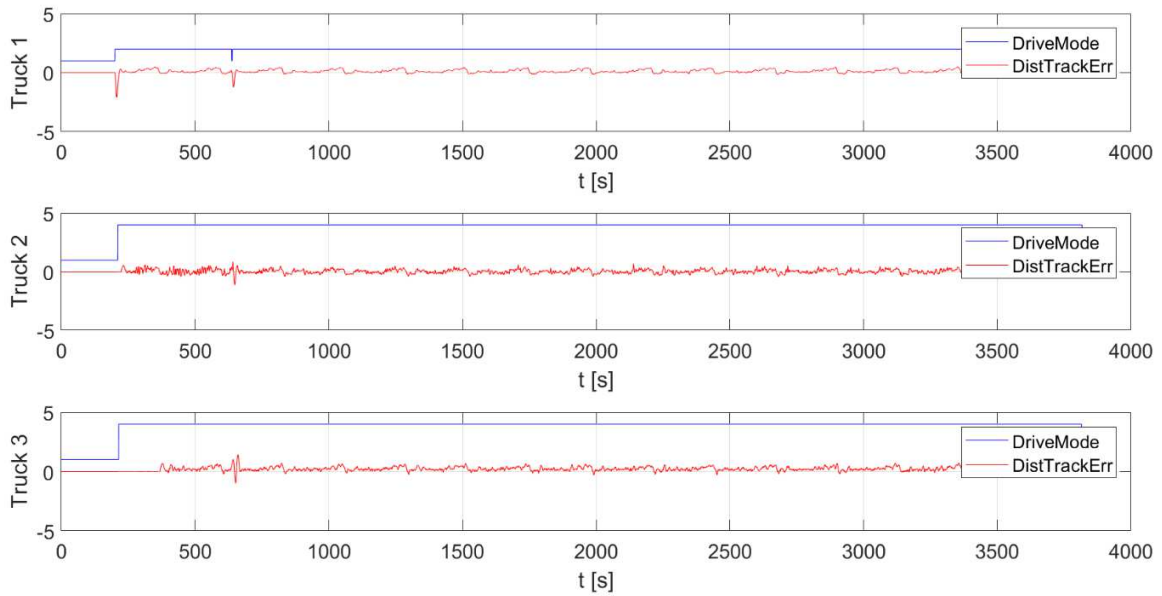


Figure 3-16 Max distance tracking error analysis for 4 m CACC following

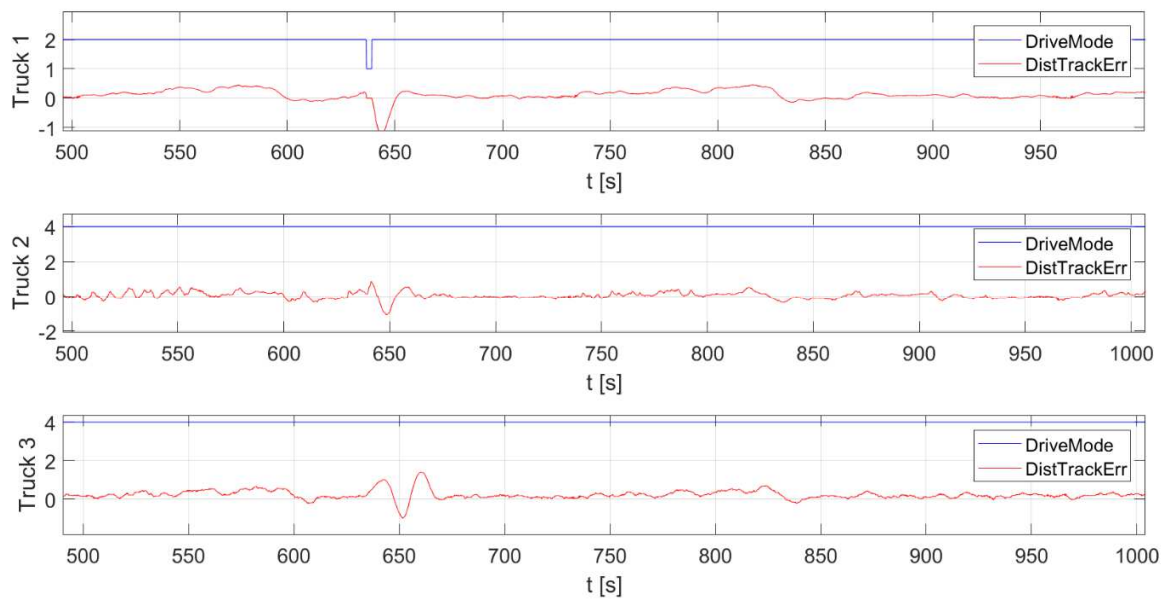


Figure 3-17 Max distance tracking error analysis for 4 m CACC following; zoomed from Figure 3-16 for higher resolution

3.4 Single Truck with Double Fully Loaded Trailers (Long Combination Vehicle)

It is noted that the loads were doubled in this scenario. The distance tracking error is obtained assuming there is a virtual vehicle (defined as a vehicle running exactly with the reference trajectory) in the front although it is actually in CC mode instead of ACC mode. However, we did not have the data for such an over-loaded truck following another truck in the front. The performance for CC mode is comparable with other test cases for single trucks or for the front (truck 1) of a CACC string. The following Table 3.4 lists the speed and distance tracking errors at cruise speed 65 mph.

Table 3.4. Single Truck Pulling Two Loaded Trailers: Root Mean Square, Max and Standard Deviation of tracking errors

Maneuver	D_Gap [m]	T-Gap [s]	Veh ID	Speed Error [m/s]			Distance Error [m]		
				RMS	Max	Std Dev	RMS	Max	Std Dev
Double Trailers	No target	No target	No target	-0.000314	0.701	0.050235	0.799699	1.281	0.362201

3.5 Three Truck Cut-in and Cut-Out Between Truck 1 & 2 on Test Track

Since the cut-in maneuver was between the truck 1 and truck 2, truck 1 (in CC mode) speed and distance tracking would not be affected, which is therefore ignored. The following Figure 3-18, Figure 3-19 and Figure 3-20 and Figure 3-21 show the speed and distance tracking error of truck 2 respectively. It can be observed from Figure 3-18 that the cut-in performance is similar for all the 16 laps (each lap has two cut-in maneuvers on the two straight track sections). It can also be observed from the zoomed plots in Figure 3-18 the following behaviors: front target distance sudden drop (cut-in happened) → the subject truck (truck 2) speed drop → speed and distance intended to resume to the desired values → front target distance suddenly increased (cut-out happened) → truck 2 speed increasing to close the gap until the desired distance gap was reached → both speed and distance tracking resumed to steady-state tracking. It is noted that the distance tracking error is about 2 m, which is different from (much smaller than) the actual distance changes as a vehicle cut-in. This is due to the reference distance trajectory planning while taking into account the characteristics of the cut-in maneuver. Otherwise, the distance tracking error would be significantly larger, which would cause large speed tracking error. As a result, it would cause spikes in feedback control action and truck 2 would jerk significantly.

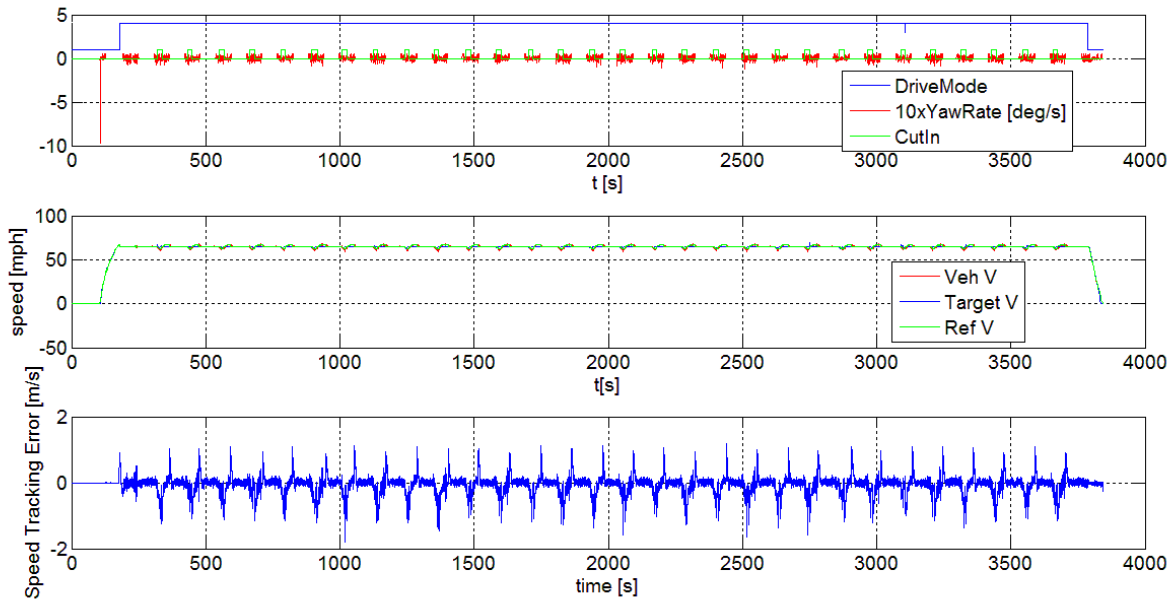


Figure 3-18 Cut-ins (repeated 30 times) Between Truck 1 & 2: Vehicle 2 Speed tracking error

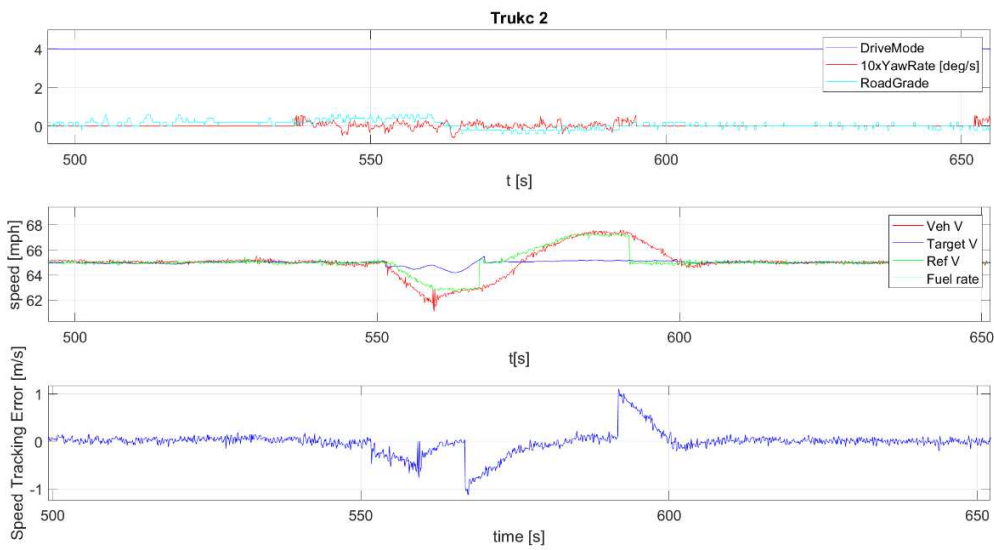


Figure 3-19. Cut-ins Between Truck 1 & 2: Vehicle 2 Speed tracking error (zoomed)

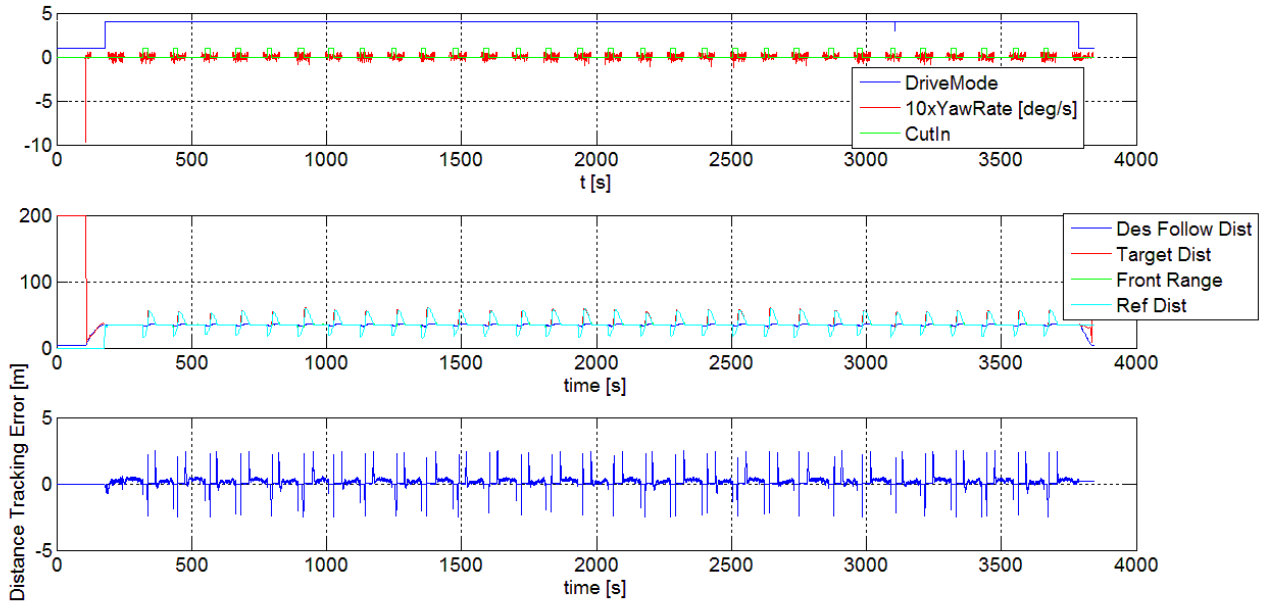


Figure 3-20. Cut-ins (repeated 30 times) Between Truck 1 & 2: Vehicle 2 Distance tracking error

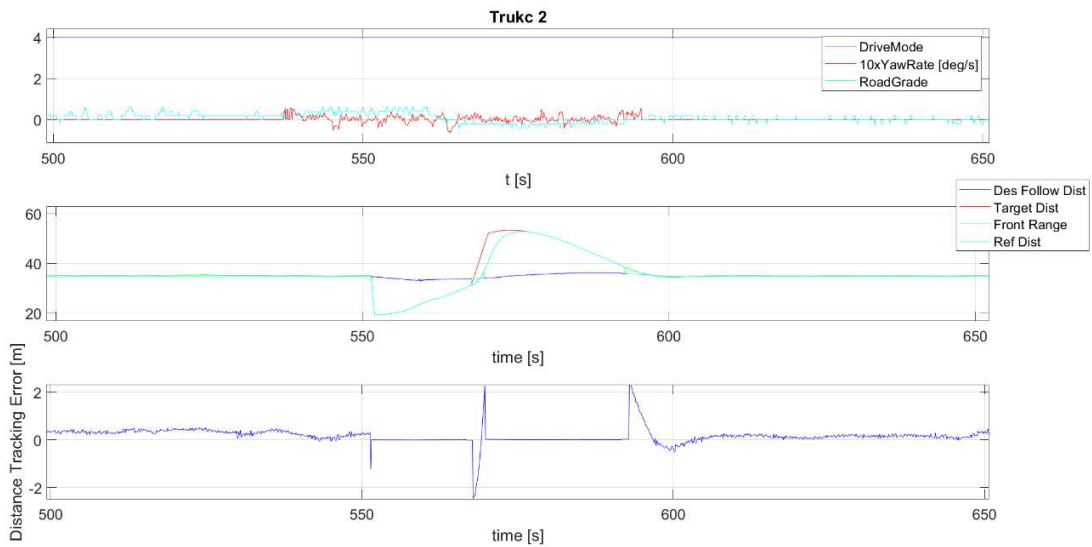


Figure 3-21. Cut-in Between Truck 1 & 2: Vehicle 2 Distance tracking error (zoomed)

Figure 3-22, Figure 3-23 and Figure 3-24 and Figure 3-25 show the speed and distance tracking error of truck 3 respectively. Since the cut-in happened between truck 1 and truck 2, the following behavior of truck 3 was directly affected by truck 2 and indirectly affected by the cut-in vehicle.

As a result, the speed tracking errors are smaller than those of truck 2; and the distance tracking errors are also smaller on average. However, the speed and distance tracking error changing logics are very much similar to that of truck 2.

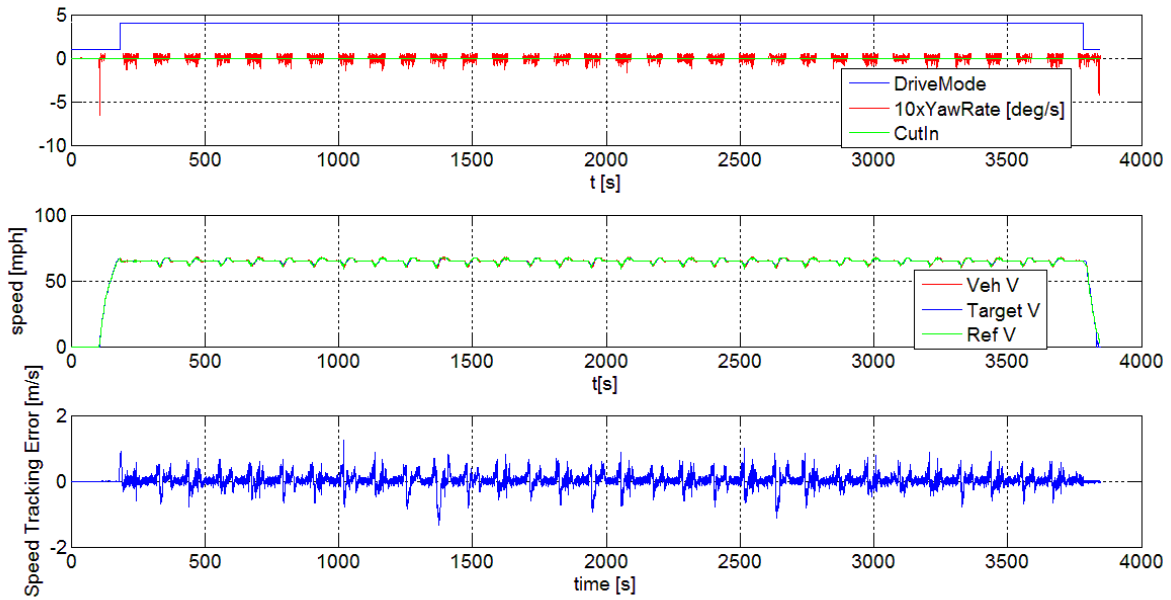


Figure 3-22. Cut-ins Between Truck 1 & 2: Vehicle 3 Speed tracking error

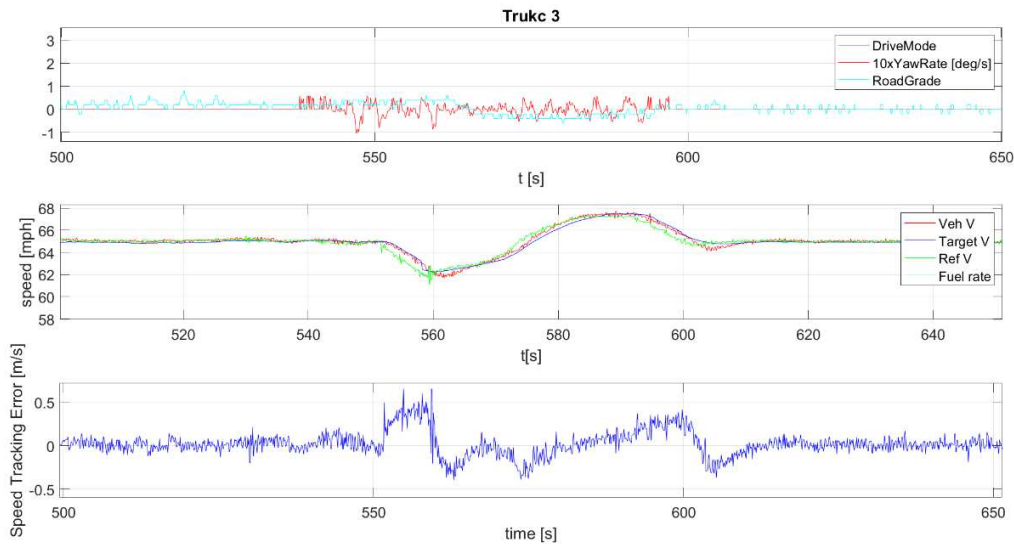


Figure 3-23. Cut-ins Between Truck 1 & 2: Vehicle 3 Speed tracking error (zoomed)

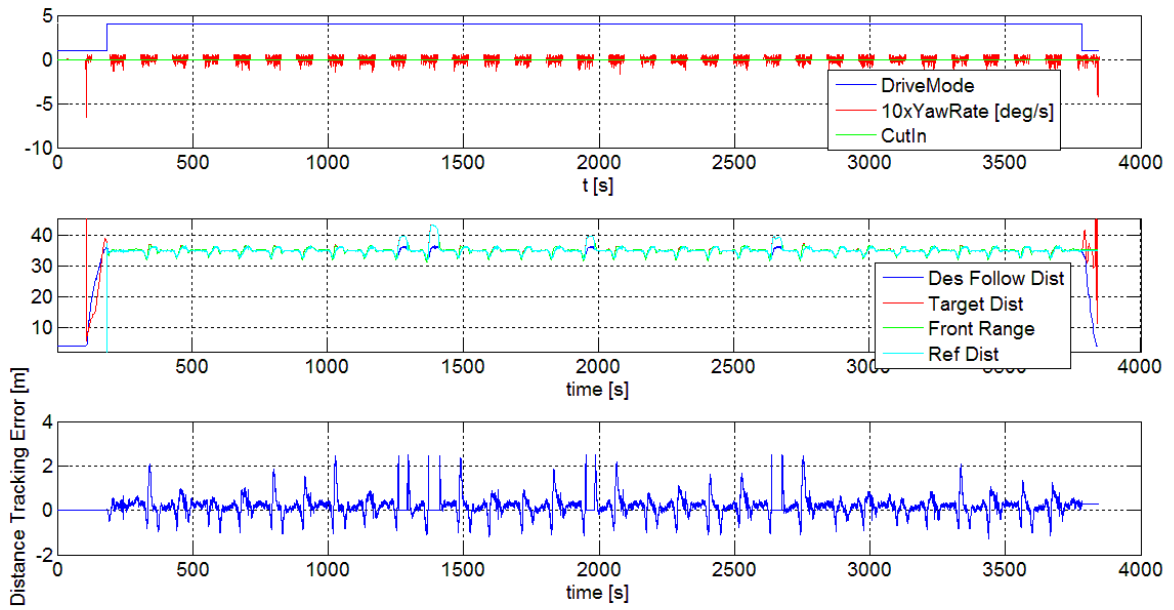


Figure 3-24. Cut-ins Between Truck 1 & 2: Vehicle 3 Distance tracking error

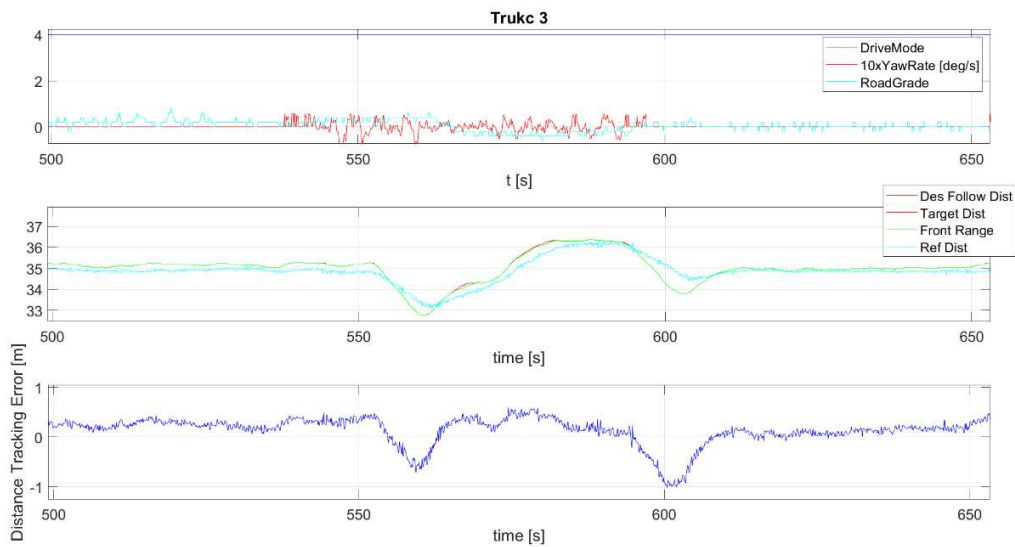


Figure 3-25. Cut-in Between Truck 1 & 2: Vehicle 3 Distance tracking error (zoomed)

The following Table 3.5 lists the speed and distance tracking errors of the three trucks. It can be observed that the maximum distance tracking error is nearly 2.5 m, even with trajectory planning

for both desired speed and desired distance. This was due to the delay in driveline caused by large mass and inertia. Practical ride of the subject truck during cut-in maneuver still showed smoothness in performance, which is desirable.

Table 3.5. Cut-in Between Truck 1 & 2: Root Mean Square, Max and Standard Deviation of tracking errors

Maneuver	D_Gap [m]	T-Gap [s]	Veh ID	Speed Error [m/s]			Distance Error [m]		
				RMS	Max	Std Dev	RMS	Max	Std Dev
Cut in between 1 & 2	35	1.2	1	0.052319	0.542	0.05232	0.303378	0.554	0.168854
Cut in between 1 & 2	35	1.2	2	0.299402	1.812	0.292205	0.37078	2.497	0.343633
Cut in between 1 & 2	35	1.2	3	0.2012	1.342	0.200321	0.476924	2.499	0.437299

3.6 Three Truck Cut-in and Cut-Out Between Truck 2 & 3 on Test Track

Similar observations and conclusions can be made for the cut-in maneuver between truck 2 and truck 3. In this case, truck 1 and truck 2 would not be affected by the cut-in vehicle with the current control configuration. Truck 3 during the cut-in and cut-out should behave similarly as the truck 2 in the previous maneuver, i.e., cut-in between truck 1 and truck 2. Observations of Figure 3-26, Figure 3-27, Figure 3-28 and Figure 3-29 show that this is actually the case.

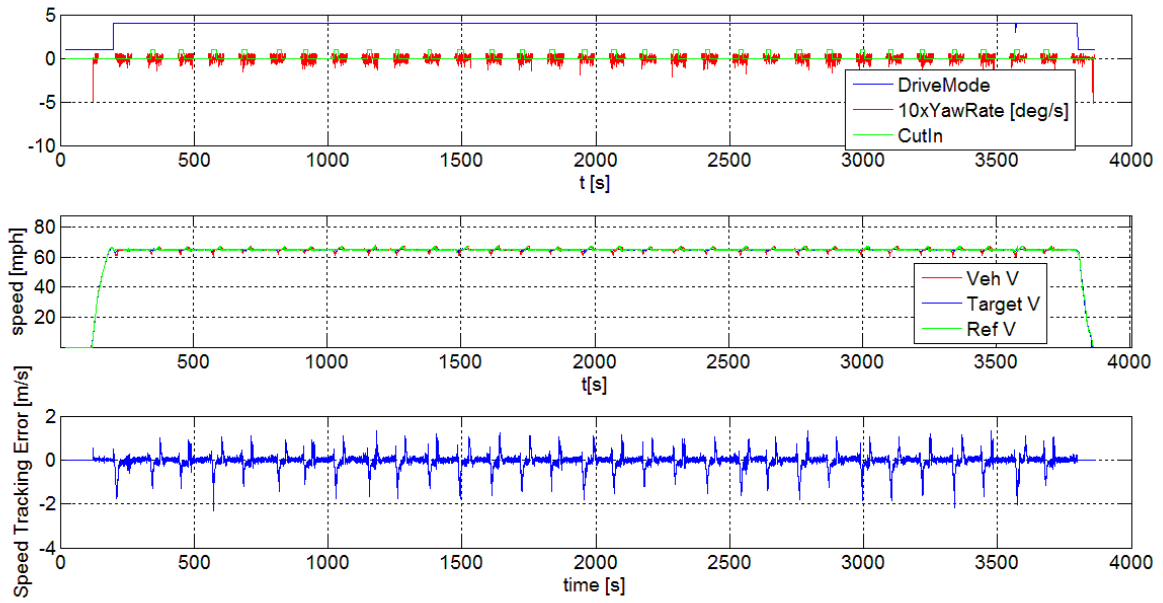


Figure 3-26. Cut-ins Between Truck 2 & 3: Vehicle 3 Speed tracking error

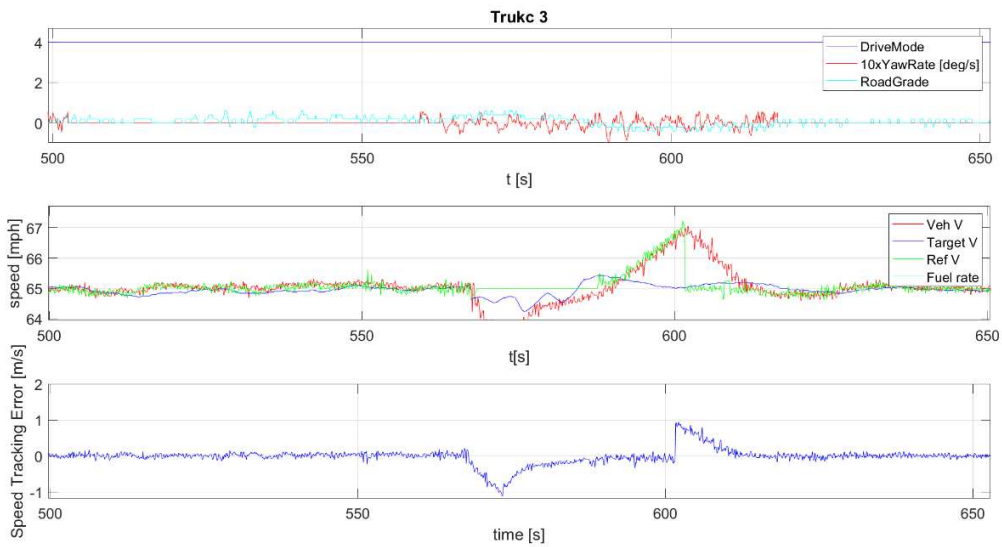


Figure 3-27. Cut-in Between Truck 2 & 3: Vehicle 3 Speed tracking error (zoomed)

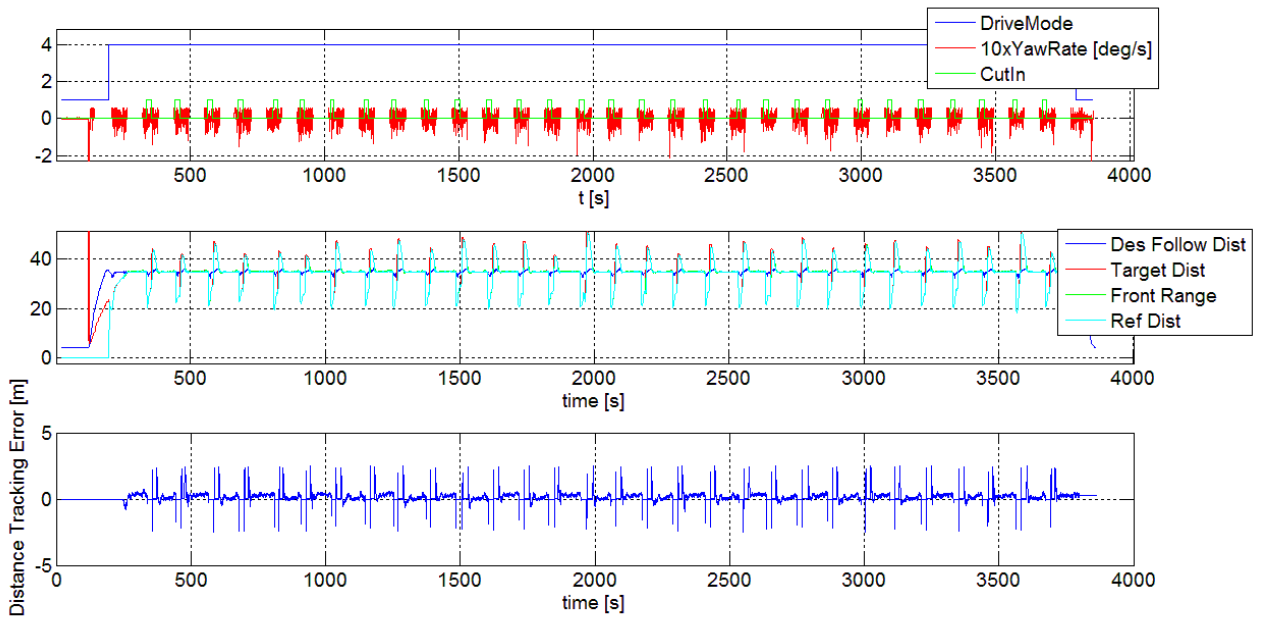


Figure 3-28. Cut-ins Between Truck 2 & 3: Vehicle 3 Distance tracking error

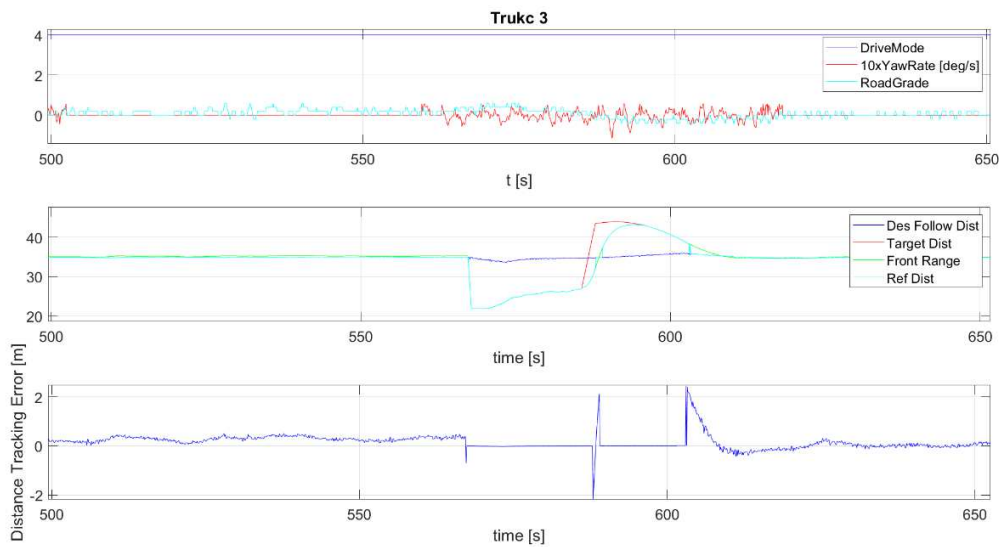


Figure 3-29. Cut-in Between Truck 2 & 3: Vehicle 3 Distance tracking error (zoomed)

The following

Table 3.6 show the speed and distance tracking error of cut-in maneuvers between truck 2 and truck 3. It is noted that the maximum distance tracking error is 2.5 m for truck 3 which implies the

latency of response for the third truck in the CACC string. It also shows that the practical string stability that could be achieved is ultimately bounded instead of asymptotic as designed in [1].

Table 3.6. Cut-ins Between Truck 2 & 3: Root Mean Square, Max and Standard Deviation of tracking errors

Maneuver	D_Gap [m]	T-Gap [s]	Veh ID	Speed Error [m/s]			Distance Error [m]		
				RMS	Max	Std Dev	RMS	Max	Std Dev
Cut in between 2 & 3	35	1.2	1	0.052968	0.579	0.052968	0.297751	0.595	0.166475
Cut in between 2 & 3	35	1.2	2	0.089018	1.031	0.089001	0.2216	0.821	0.182282
Cut in between 2 & 3	35	1.2	3	0.296129	1.835	0.293762	0.371268	2.5	0.337306

3.7 Three Truck CACC with Speed Variations

Lead truck speed variation is the test case for *string stability* for any multi-vehicle following strategy including platooning and CACC from a control viewpoint. The reason is that the overall system delays and control responses will be reflected in the speed variation scenarios. Admittedly, the response also depends on the reference trajectory planning of each truck and the information that is used from the front truck, particularly, the maximum acceleration and deceleration. The effect of maximum deceleration on the feedback control would not heavily depend on the current speed of the truck since the total braking torque of the truck would not change significantly with speed. The acceleration capability of a fully loaded truck is rather limited as truck speed increases. From a control point of view, the reachable set of the torque control at high speed range is rather small. However, for commercial trucks with engine braking, higher vehicle speed would correspond to higher engine speed, which will lead to larger available braking torque, while engine braking capability is rather low at low speed due to low engine speed. For the current truck, since the service brake control activation will deactivate the control of engine torque, engine braking torque and the service brake itself, we have deactivated the service brake control for most maneuvers except the coordinated braking control in emergency situation. Therefore, the deceleration needs to fully rely on the engine brake control since the truck does not have a transmission retarder. For those reasons, in the speed variation maneuver, the maximum deceleration is limited to 0.3 m/s^2 , and the maximum acceleration is below 0.1 m/s^2 . The following plots (Figure 3-30 ~ Figure 3-41) show the system's string stability related performance. The speed switching logic between minimum 55 mph and maximum 65 mph is as follows: once it reaches minimum or maximum, the CACC string will stay at that speed to cruise for 1 minute exactly, and then it starts to switch to the other.

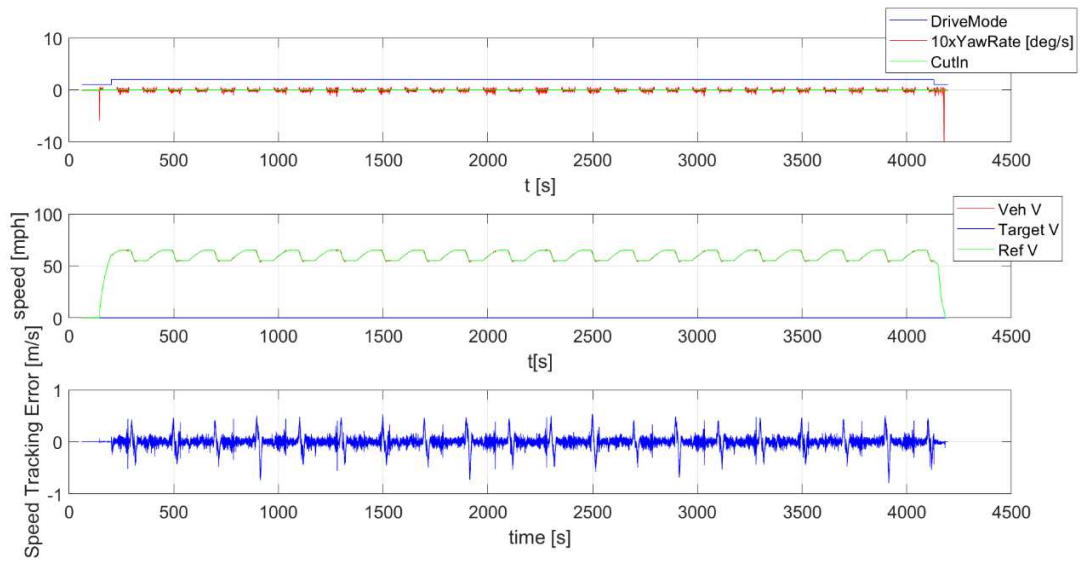


Figure 3-30. Three CACC Truck Speed Variation: Vehicle 1 Speed tracking error

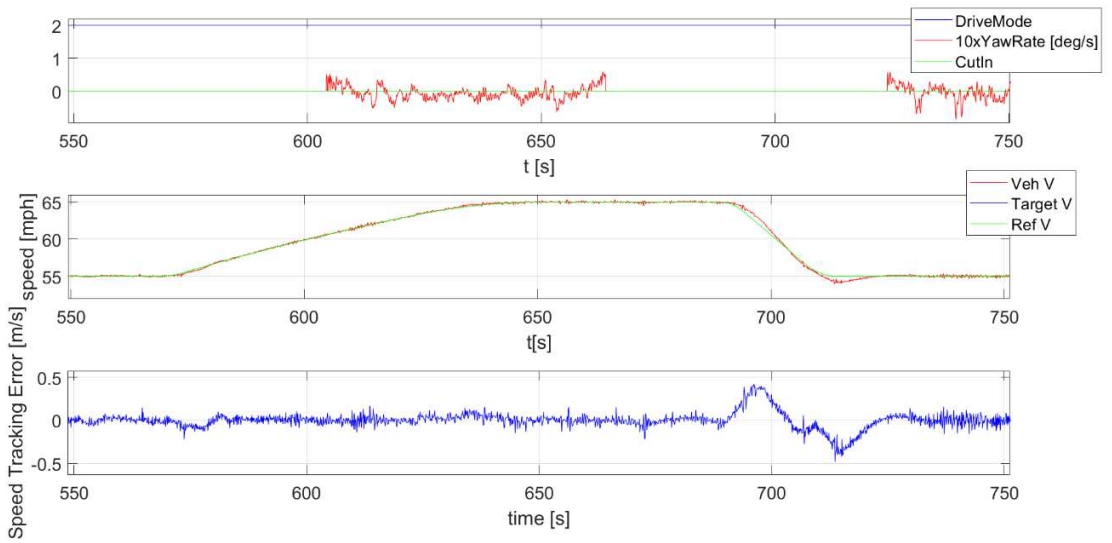


Figure 3-31. Three CACC Truck Speed Variation: Vehicle 1 Speed tracking error (zoomed)

Figure 3-31 and Figure 3-32 depict the speed tracking error of truck 1. Since truck 1 is in CC mode and there is a virtual vehicle (defined as a vehicle running exactly with the reference trajectory) in its front the reference trajectory planning is with respect to the virtual vehicle. Therefore, the control response is different from truck 2 and truck 3, which are in CACC mode. i.e. the two

following trucks used the information passed by the DSRC. Figure 3-33 is for distance tracking error of truck 1.

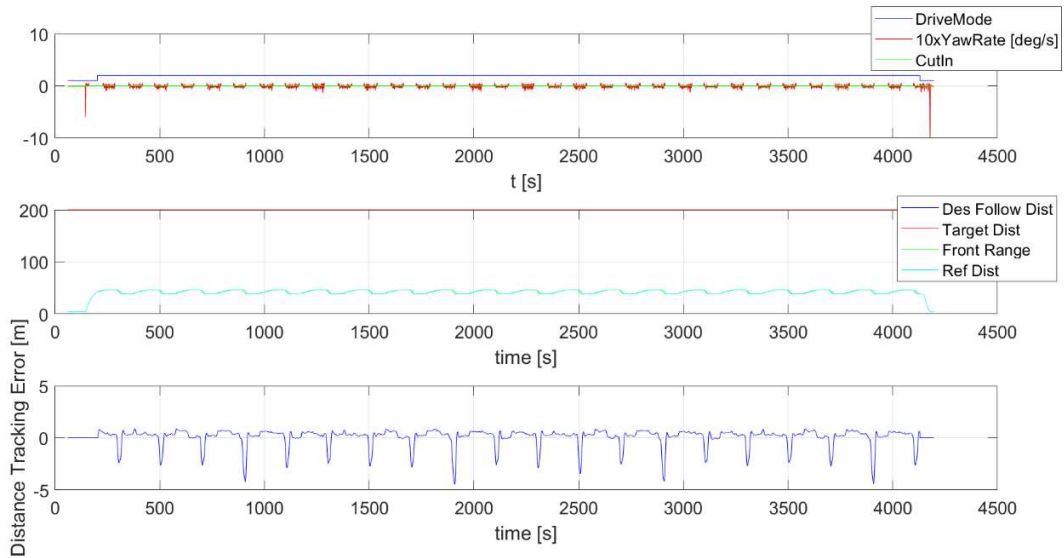


Figure 3-32. Three CACC Truck Speed Variation: Vehicle 1 Distance tracking error

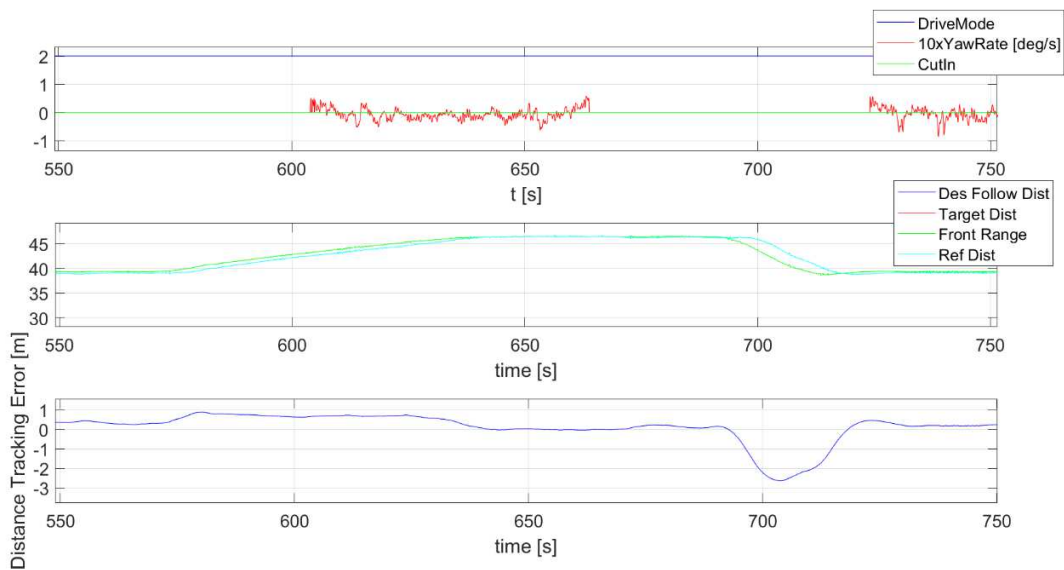


Figure 3-33. Three CACC Truck Speed Variation: Vehicle 1 Distance tracking error (zoomed)

Figure 3-34 and Figure 3-35 depict the distance tracking error of truck 1 for the speed variation scenario. Again, truck 1 is in CC mode and there is a virtual vehicle (defined as a vehicle running exactly with the reference trajectory) ahead of it. The reference distance trajectory planning is with

respect to the virtual vehicle. Therefore, the control response is different from truck 2 and truck 3 which are in CACC mode in distance tracking.

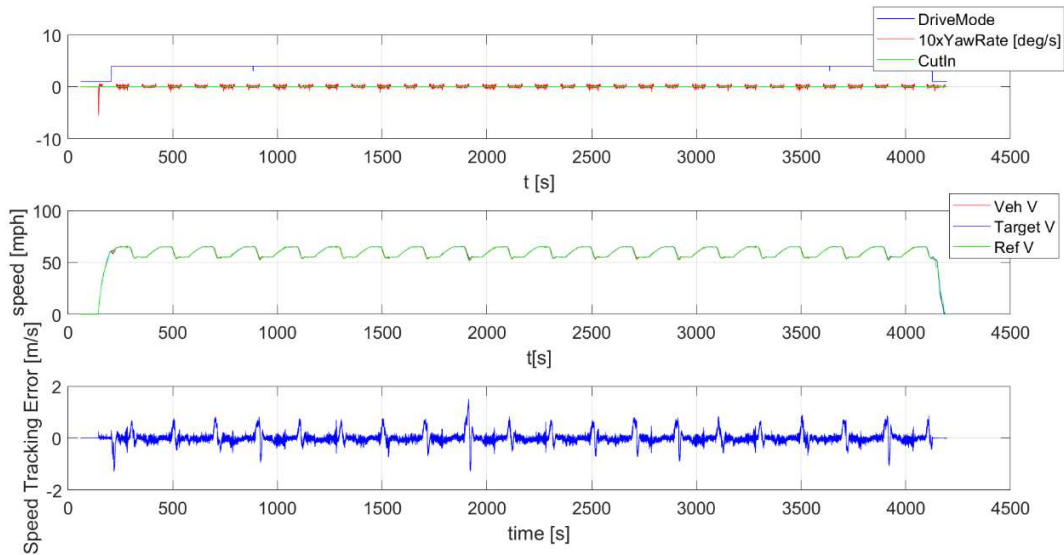


Figure 3-34. Three CACC Truck Speed Variation: Vehicle 2 Speed tracking error

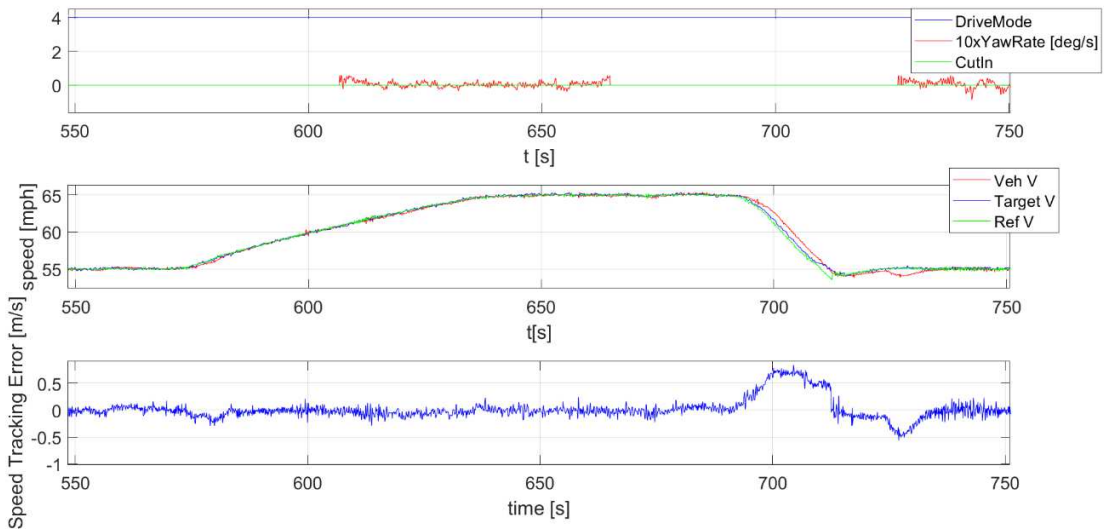


Figure 3-35. Three CACC Truck Speed Variation: Vehicle 2 Speed tracking error (zoomed)

Figure 3-36, Figure 3-37 depict the speed and distance tracking error of truck 2. The speed trajectory planning is with respect to the actual speed of the lead truck. Therefore, the control response is different from truck 1 in speed tracking error. Again, the delay in response with respect to truck 1 is observed.

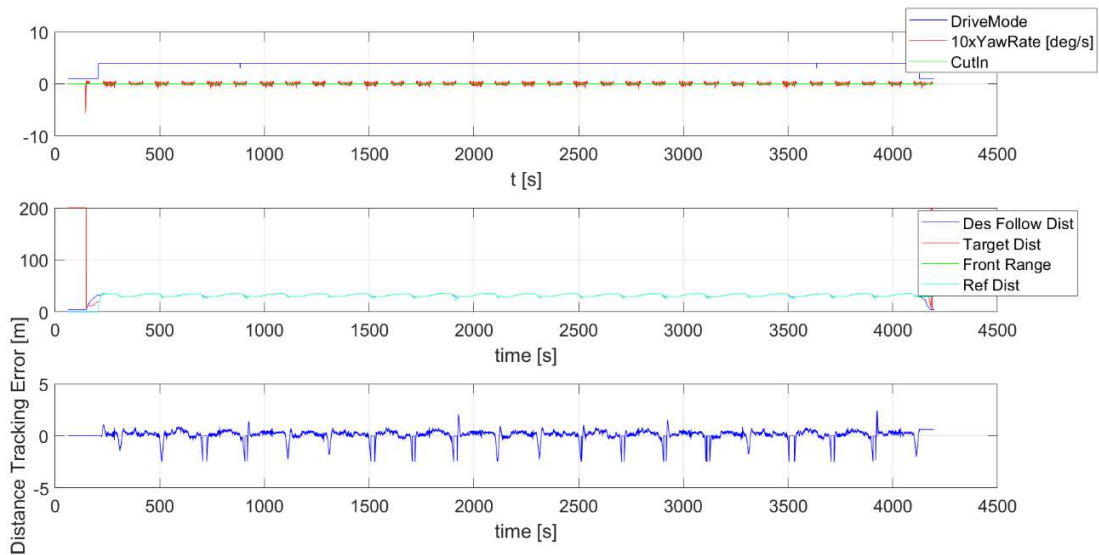


Figure 3-36. Three CACC Truck Speed Variation: Vehicle 2 Distance tracking error

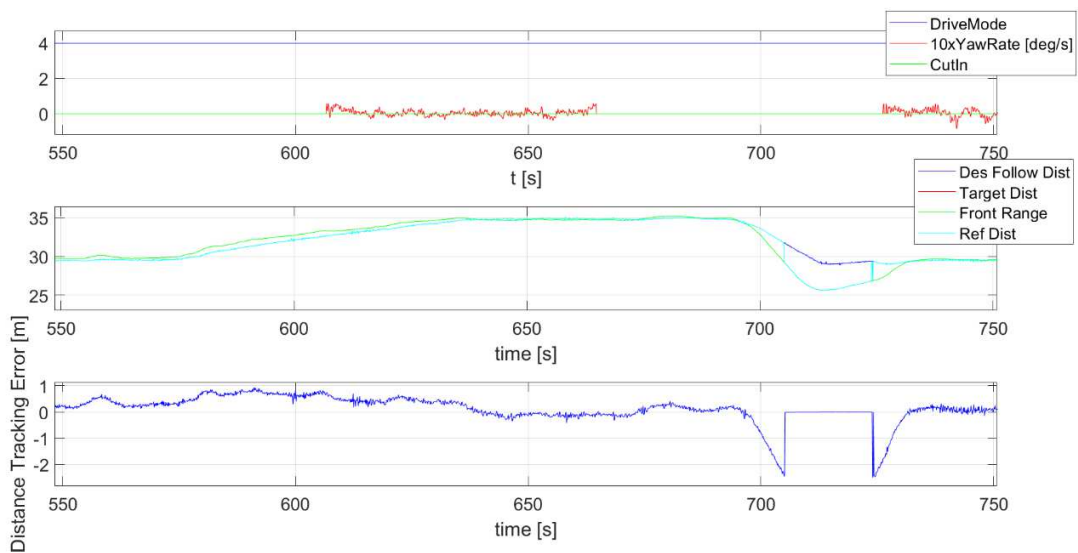


Figure 3-37. Three CACC Truck Speed Variation: Vehicle 2 Distance tracking error (zoomed)

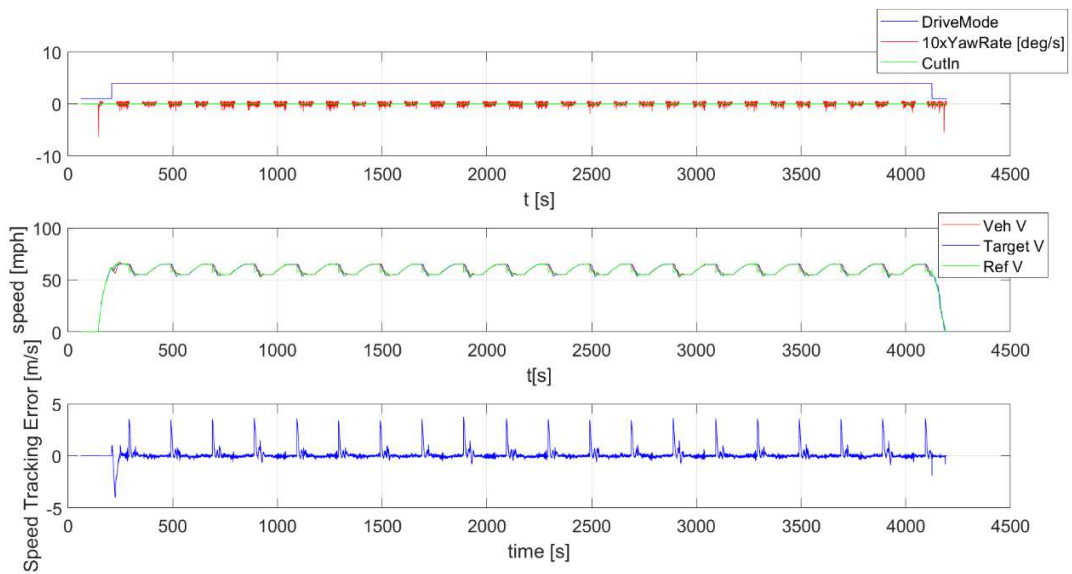


Figure 3-38. Three CACC Truck Speed Variation: Vehicle 3 Speed tracking error

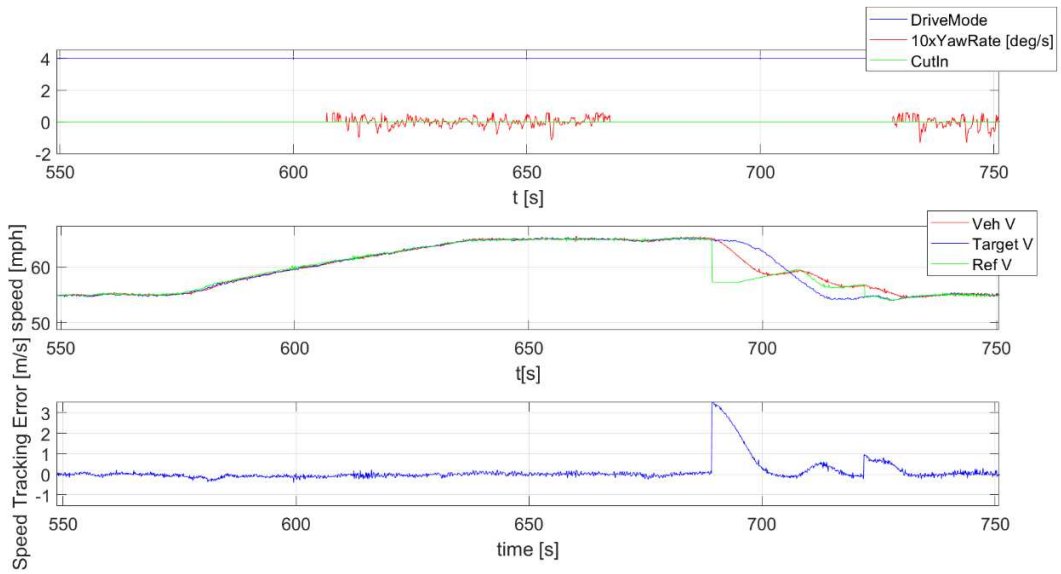


Figure 3-39. Three CACC Truck Speed Variation: Vehicle 3 Speed tracking error (zoomed)

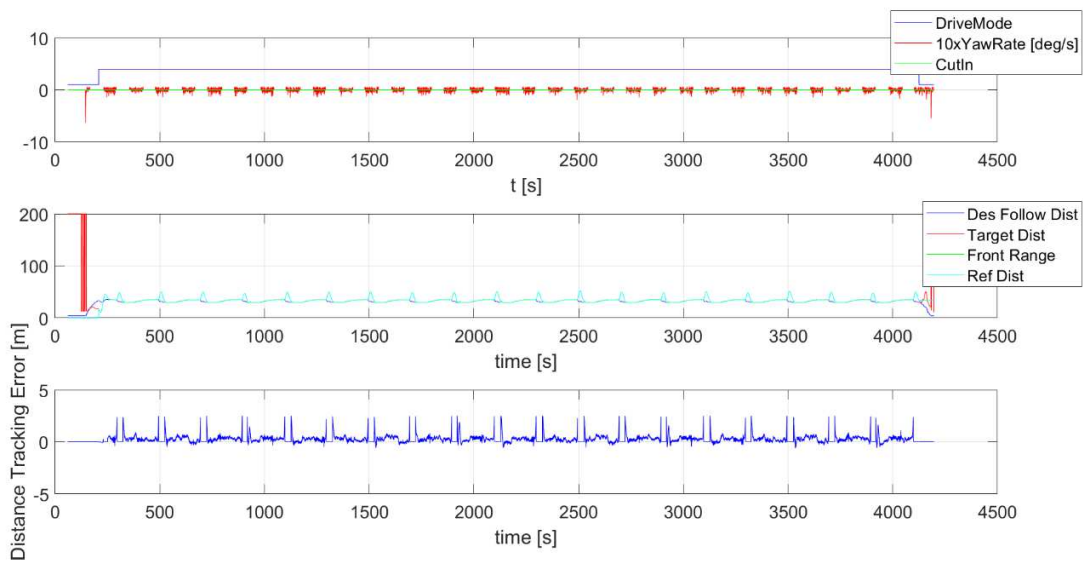


Figure 3-40. Three CACC Truck Speed Variation: Vehicle 3 Distance tracking error

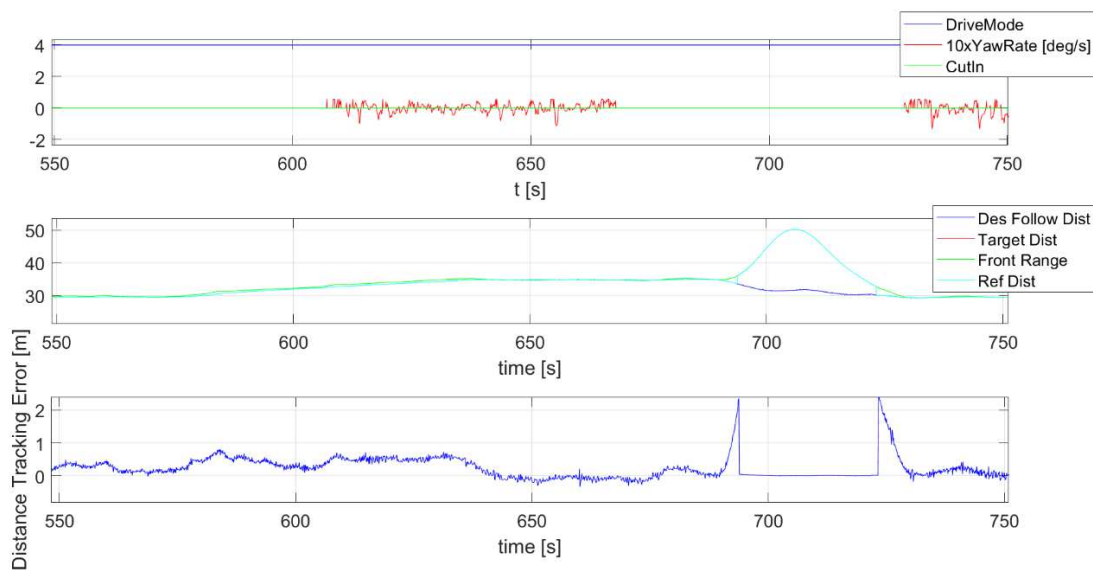


Figure 3-41. Three CACC Truck Speed Variation: Vehicle 3 Distance tracking error (zoomed)

Figure 3-38 through Figure 3-41 depict the speed and distance tracking error of truck 3. The speed trajectory planning is with respect to the actual speed of the lead truck and the second truck. Therefore, the control response is different from both trucks in speed tracking error. Again, the delays in response with respect to truck 1 and truck 2 are also observed.

The following Table 3.7 shows the maximum speed and distance tracking errors for 3-truck CACC speed variation maneuvers. It can be observed from the table that (a) the truck further behind has

larger speed and distance tracking errors, which reflect the weak string stability characteristics; and (b) the maximum distance tracking error is nearly 2.5 m, which means that for highway maneuvers with the maximum acceleration and deceleration listed before, the following distance should not be closer than 10 m for safety. This is similar to the maximum distance tracking error for cut-in maneuver observed before. However, the performance should be improved when the service brake automatic control deactivation problem can be resolved so that service brakes could be applied to provide a higher braking rate. Also, if the truck had a transmission retarder, the deceleration performance could be improved.

Table 3.7. Truck Speed Variations: Root Mean Square, Max and Standard Deviation of tracking errors

Maneuver	D_Gap [m]	T-Gap [s]	Veh ID	Speed Error [m/s]			Distance Error [m]		
				RMS	Max	Std Dev	RMS	Max	Std Dev
ACC Speed Variation	35	1.2	1	0.124694	0.979	0.124695	0.92154	5.725	0.918811
CACC Speed Variation	35	1.2	2	0.225755	1.532	0.225711	0.479321	2.499	0.469326
CACC Speed Variation	35	1.2	3	0.572691	4.346	0.557813	0.419433	2.498	0.328177

3.8 Conclusion

Truck CACC (Cooperative Adaptive Cruise Control) designed and developed in this project [2, 3] have been preliminarily tested with public traffic and extensively tested in a controlled traffic environment, i.e. Transport Canada Test Track near Montreal of Canada. The latter included most fundamental maneuvers such as constant speed following at different time gaps, cut-in and cut-out between truck 1 and truck 2, and between truck 2 and truck 3, long combination (one tractor towing two trailers), speed variation between 55 mph ~ 65 mph etc.. Fully loaded trucks were used for the tests. Since each run of a scenario was for 16 laps in total of was 64 miles, it is appropriate to use the repetitive test data for statistical analysis of the control performance with respect to those scenarios. The following parameters have been used for performance measures of both speed and distance tracking errors: Root Mean Square (RMS), the maximum, and standard deviation. The results showed that the performance of the CACC system is reasonably robust stable for constant speed following – the RMS error of the speed tracking error was well within 0.1 m/s and the that of the distance tracking error is well within 0.3 m. It has been found out that some larger maximum distance tracking error (about 2 m) was mainly caused by transitions between manual and automatic, which often happened at the very beginning or during the runs due to driver's accidentally switching OFF and then ON the CACC mode. Once the distance tracking error caused by switching OFF to certain level, it will take some time to recover to correct T-Gap or D-Gap following. This situation cannot be simply removed using the Drive Mode parameter in data. For

cut-in and cut-out maneuvers, the distance tracking error was reduced gradually for smoothness of the system. The rate for decreasing was proved to be reasonable as demonstrated in several demonstrations afterwards. As expected, CACC string speed variation was the indicator of the string stability. Due to truck internal delays in control actuation and large mass of fully loaded trucks, control response delays are unavoidable. The practical string stability [1] can only be ultimately bounded instead of asymptotic. Due to those delays, speed variation will cause larger speed and distance tracking errors which will take longer time to recover. This fact directly affects the string/platoon length and minimum T-Gap (or D-Gap) for safe operations of truck CACC.

The data analysis has shown that there are still spaces for CACC performance improvements, which include but not limited to: systematic fault detection and handling, reducing transients tracking errors for cut-in and cut-out maneuvers which involve sudden distance changes, and for speed variations which is avoidable when the CACC string is operated in real-world traffic.

4 References

- [1] X. Y. Lu, S.E. Shladover, 2017, Integrated ACC and CACC Development for Heavy-Duty Truck Partial Automation, 2017 American Control Conference, May 24-26, Seattle, WA, USA
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