INVESTIGATION INTO DYNAMIC ISSUES OF TRUCK PLATOONING SYSTEMS

S.P.S. PARKER
Lead Researcher in Transportation at FPInnovations in Vancouver, Canada
Graduate of University of BC in Forestry (1982) and Mechanical Engineering (1988)

Abstract
FPInnovations cooperated with Transport Canada and Auburn University to investigate platooning dynamics in 2019. A two-unit 5-axle tractor/semi-trailer platoon was instrumented and tested at moderate speeds to measure the yaw-rate rearward amplification. The tests showed that good overall dynamic performance was achieved for the test units, with overall rearward amplification of between 0.565 and 0.980. Further testing will be required to validate the platooning system at highway speeds. The test data was also used to refine simulation models to investigate alternative path following strategies and estimate dynamic performance at highway speeds. Modelling showed that the 5-axle tractor/semi-trailer performs well regardless of path following method used. However, B-trains loaded to maximum loads are very sensitive to path following methods and require a specialized path smoothing strategy to perform satisfactorily. Further testing and cooperation between platoon system developers and road transport stakeholders will be required to ensure optimal deployment of these systems.

Keywords: Simulation, Heavy Vehicle Testing, Rearward Amplification, Platoon, Dynamics

1. Background

Truck platooning systems have the potential to improve transportation efficiencies allowing one driver to control two to three truck units. This multi-truck platoon combination essentially becomes an electronically coupled multi-trailer combination which is subject to complex dynamic interactions, particularly when undertaking emergency manoeuvres. A potential safety issue was highlighted in a recent paper presented at the previous Heavy Vehicle Truck Technology (HVTT15) conference (de Pont, 2018), where simulations showed high levels of rearward amplification on two-unit tractor/semi-trailer platoons during standard lane change manoeuvres when the following unit follows the path of the lead unit's rear trailer.

Much research has been conducted to date on the need to consider dynamics in the implementation of truck platooning systems. Guanetti et. al. (2018) surveyed existing literature to determine the role of control and planning on safety and performance of automated driving systems. This survey identified gaps in the interaction and integration between sub-systems due to lack of experimental validation. This necessitates testing on real vehicles in real road conditions under selected testing scenarios. Puri and Varaiya (1995) questioned the safety of platooning systems and discussed a set of constraints that the vehicle's controllers need to satisfy to guarantee safety. In this study, merging and lane changing manoeuvres were examined. Safety from a vehicle dynamics perspective was also discussed in (Lygeros et. al., 1998), where the continuous motion as well as collision of platooning vehicles was modelled. More recently, Lee et. al. (2013) suggested that safety could be improved by improving the precision of controls, given the short distance between platooning vehicles.

FPInnovations initiated a cooperative project with Auburn University in 2017 to investigate implementing truck platooning in forestry applications as a means of improving log transportation efficiencies and addressing the shortage of experienced drivers. Auburn University's platooning system has been undergoing development and testing under a range of operating environments to further enhance and develop their system. In 2019, FPInnovations initiated testing with Auburn University's and Transport Canada's cooperation to investigate the potential dynamic issues identified in the de Pont paper.

2. Methodology

2.1 Dynamic Tests

A platoon comprised of two 5-axle tractor/semi-trailers (Figure 1) was instrumented with Inertial Measurement Units (IMU) at the tractor and trailer Centre of Gravity (CG) as well as high precision GPS at the each tractor CG. Steering wheel angle and vehicle speed were also obtained from the electronic engine interface. The tractor/semi-trailer was loaded to typical load levels for freight hauling in the USA for this evaluation (27 200 kg), which is well below the Canadian maximum allowance for a 5-axle of 39 500 kg.

Figure 1. Platooning test configurations

The tests were conducted at a target speed of 50 km/h at a SAE level 2 automation level (Driver present on following truck with “hands off” steering wheel, no accelerator or braking input). The lead tractor executed several variable[1] steering manoeuvres and the following parameters were measured on both units:

- Yaw rate @ tractor CG
- Yaw rate @ trailer CG

The rearward amplification (ratio of output over input) of yaw rate was determined as follows:

- Trailer1: Tractor1 (RA1)
- Trailer2: Tractor2 (RA2)
- Tractor2: Tractor1 (RA3) (Input Amplification)
- Trailer2: Tractor1 (RA4) (Overall RA)

2.2 Correlation of test data with simulation model

The test results were correlated with a simulation model using the following procedure for each test run:

- The lead unit was simulated using the test speed and steering inputs.
- The following unit was then simulated using two approaches:
    - Open loop – using test speed and steering inputs.
    - Closed loop– following steering axle path left by lead tractor’s steering axle (from simulation).

[1] These tests were exploratory and hence did not follow a prescribed path; the input levels of the tests were approximately 0.10 to 0.15 g over a variable period. The objective was to obtain baseline data to guide in developing a test methodology for future testing.

- Rearward amplification was calculated and compared with test results for input amplification (Tractor2:Tractor1) and overall amplification (Trailer2:Tractor1).

2.3 Investigation of alternative path following strategies

The correlated simulation model was employed to investigate alternative path following strategies. Using the as tested configuration specifications for the 5-axle tractor/semi-trailer, the lead unit executed a standard lane change manoeuvre at 88 km/h, where the input lateral acceleration at the steering axle was 0.15 g with a period of 2.5 seconds. Subsequently, the following unit was simulated with the steering axle following the trajectories recorded by the lead unit at these locations:

- steering axle
- rear drive axle
- rear trailer axle

Two methods of path following were used:

- close path adherence (path preview interval = 0.2 seconds).
- path smoothing (path preview interval = 1.5 seconds).

For each scenario investigated the following measures were calculated:

- Input amplification (yaw-rate)
- Overall amplification (yaw-rate)

For comparison, an alternative configuration, an 8-axle B-train loaded to a maximum Canadian allowance of 63 500 kg was also investigated to assess sensitivity of alternative configurations to different path following strategies.

3. Results and Discussion

3.1 Dynamic Tests

A total of 10 lane change tests were conducted at speeds between 50 and 57 km/h (Table 1). The input accelerations varied between 0.067 to 0.137 g, with the input period duration ranging between 9 and 19.3 seconds. The long input duration was necessary to obtain a response for the following unit at the moderate test speeds. The average rearward amplification of both the lead and following units remained relatively consistent at 0.820 and 0.887 respectively. These RA levels are very low and show a reduction (attenuation) of yaw-rate for each trailer relative to the tractor showing that this configuration performs safely at speeds of up to 57 km/h. As well, the variability of RA for each unit is relatively low despite the variable inputs with RA ranging between 0.721 to 0.951, showing that the yaw-rate of the trailer is reduced relative to the tractor in all cases. However, the input amplification (RA3) between units and overall RA (RA4) from lead tractor to following trailer was more variable. Input amplification ranged between 0.68 to 1.126, while overall RA ranged between 0.565 to 0.980. Despite the increased variability, the overall rearward amplification remains low and essentially unchanged relative to the lead unit’s RA illustrating that platooning of this configuration at a typical American load can be conducted safely at moderate speeds.

Table 1. Rearward amplification test results

Test	Speed (km/h)	Peak acceln (g)	Period (sec)	RA1 (Tlr1:Tr1)	RA2 (Tlr2:Tr2)	RA3 (Tr2:Tr1)	RA4 (Tlr2:Tr1)
40	50.2	0.106	10	0.841	0.902	0.998	0.901
50	50.2	0.069	14.1	0.759	0.842	0.912	0.768
51	50.0	0.099	14	0.898	0.950	1.020	0.970
52	50.3	0.099	14.9	0.721	0.833	0.760	0.633
53	50.1	0.105	15.4	0.795	0.866	0.920	0.797
54	50.4	0.123	11	0.814	0.951	0.835	0.794
55	56.7	0.067	17.9	0.837	0.924	0.997	0.922
56	56.6	0.103	17	0.851	0.902	0.992	0.895
57	57.2	0.092	19.3	0.921	0.870	1.126	0.980
58	57.0	0.137	9	0.764	0.831	0.680	0.565
Avg	52.9	0.100	14.3	0.820	0.887	0.924	0.822

Safety concerns prevented testing at typical highway speeds (100 km/h) since the platooning controller had not been operated beyond 60 km/h prior to testing. Further development and testing will be required to validate the platooning system at typical highway speeds. However, the test data allows the correlation of simulation models which can be used to investigate performance at higher speeds, different configurations and loads, and alternative path following strategies.

3.2 Correlation of test data with simulation model

The simulation model correlated very closely with the test data in predicting both the input amplification (Figure 2) and overall amplification (Figure 3) for the platoon. The open loop (OL) simulation correlated particularly well, where the measured speed and steering inputs were applied for both tractors, the 90% confidence limits between the simulation estimates and test measurements were very similar for both measures. In the closed loop (CL) simulation, where the following tractor followed the path of the lead tractor's steering axle, the average levels of input amplification was increased by 5% and overall amplification was decreased by 4% compared to the test results. As well, the variability of both measures was reduced using the closed loop simulation. Sample output for test #58 is shown in Figure 4, illustrates how closely the open loop simulation correlates with the test measurements, whereas the peak yaw-rates predicted by the closed loop simulation deviate to a greater extent. The increased deviations noted in the peaks of the closed loop simulation is likely due to the simplified path following strategy employed in this study, whereby the path of the lead tractor's steering axle is also followed by the following tractor's steering axle. The path-following method used by the platooning controller relies primarily on GPS points established by the lead tractor. It is possible that GPS position error in combination with unaccounted features of the platooning controller contributed to the noted deviations. Therefore, further collaboration with the platooning system developers will be required to refine the closed loop simulation model. However, the closed loop simulation model still provides good approximations of input and overall amplification and could be used to guide the development of improved path-following strategies and to evaluate platooning performance in other configurations.

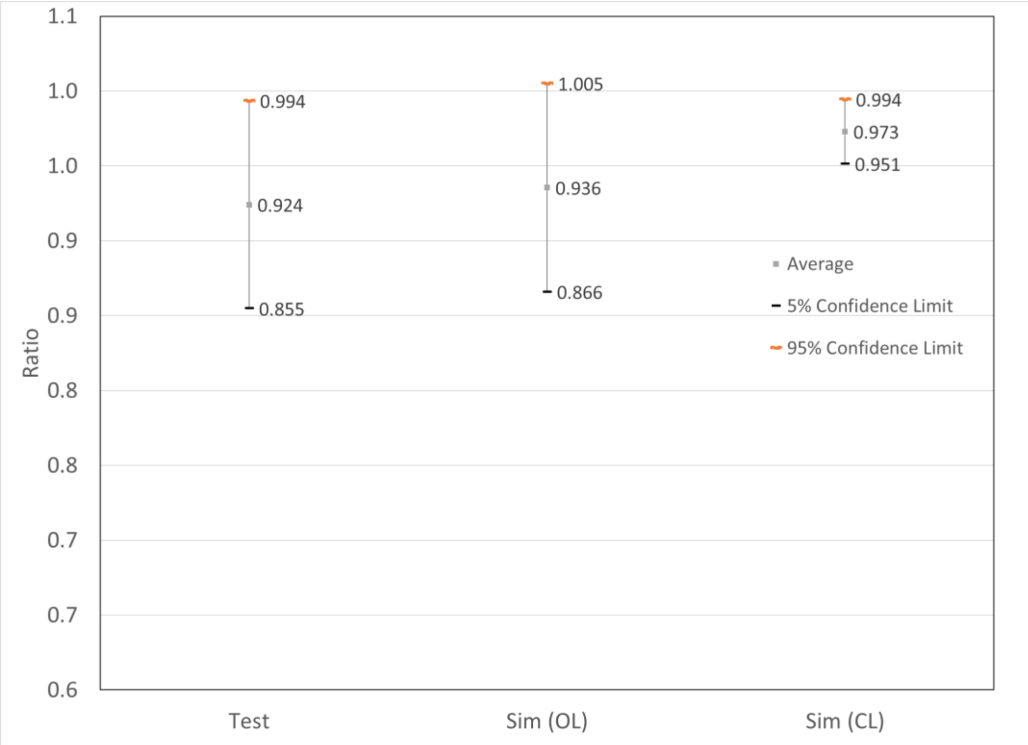

Figure 2. Comparison of simulation and test results- 90% confidence limits – Input amplification

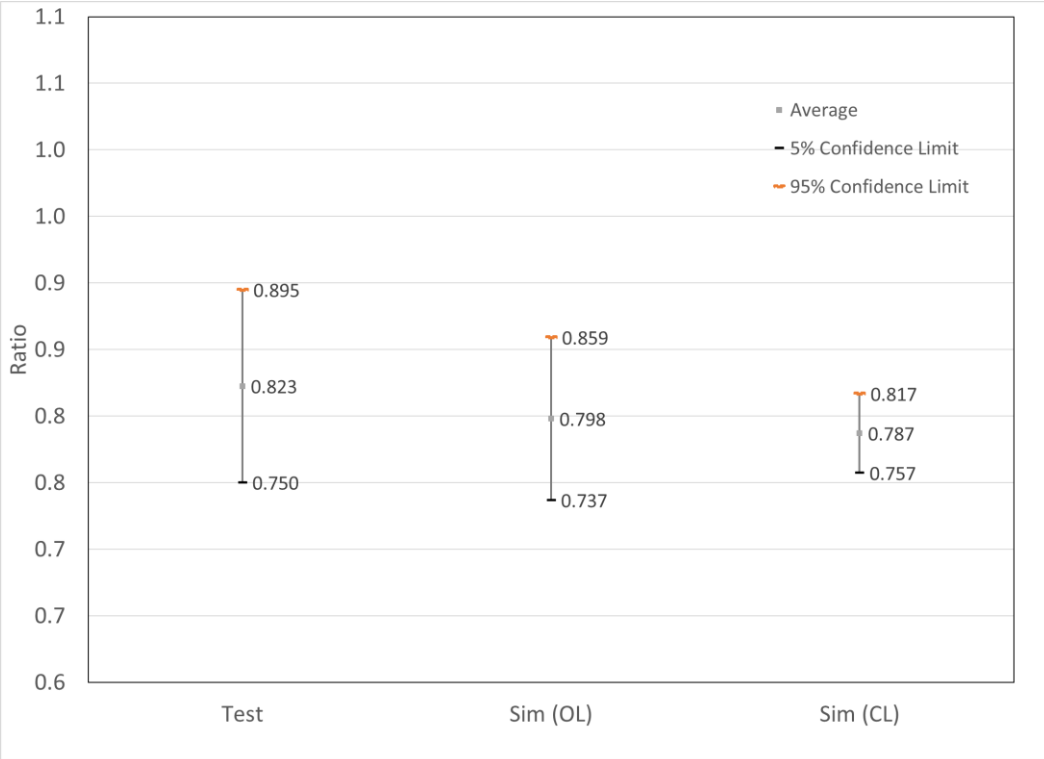

Figure 3. Comparison of simulation and test results -90% confidence limits – Overall amplification

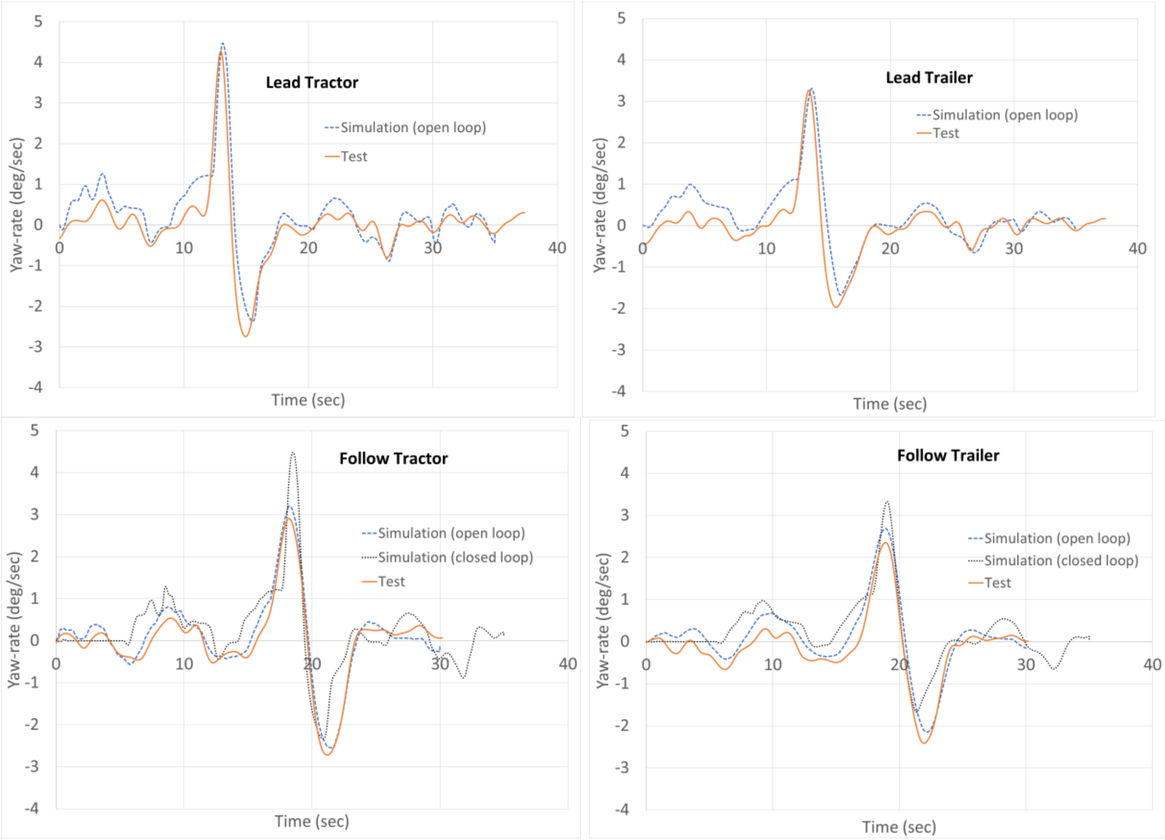

Figure 4. Sample run – yaw-rate comparison of test and simulation output

3.3 Investigation of alternative path following strategies

The 5-axle tractor/semi-trailer's platooning dynamic performance was not particularly affected by the path reference used when executing a standard lane change manoeuvre at 88 km/h using close path adherence (Figure 5). The overall amplification ranged between 0.636 (steering axle reference) to 0.704 (rear drive axle reference). The input amplification remained very consistent at between 0.914 to 1.006. These results suggest that for this configuration and load condition that the path reference is not critical. It is likely that the reduced load, low CG height and long trailer wheelbase result in reduced levels of trailer lateral movement yielding good overall dynamic performance. However dynamic performance for the 5-axle configuration can be significantly improved when a path smoothing strategy is employed with input amplification between 0.363 and 0.366 (i.e. attenuation), and an overall amplification of between 0.291 and 0.298 (Figure 6). The path smoothing essentially dampens out the steering inputs for the following unit. An appropriate level of path smoothing will be necessary to ensure that the following unit does not adjust its path so drastically that it runs off the road or hits an obstacle.

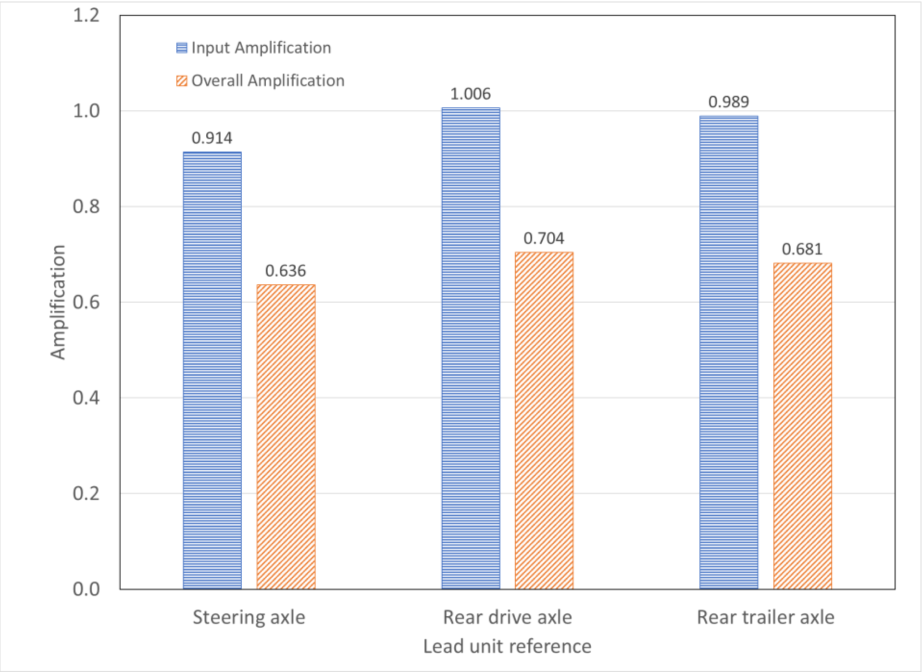

Figure 5. Effect of alternative path references on 5-axle tractor/semi-trailer (as tested) platooning dynamic performance- close path adherence

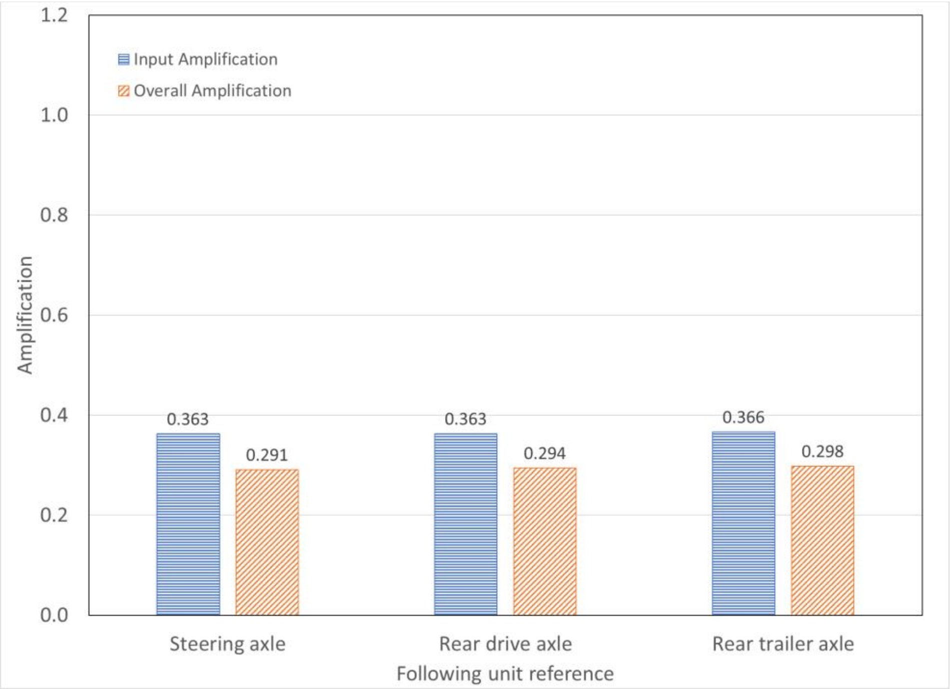

Figure 6. Effect of alternative path references on 5-axle tractor/semi-trailer (as tested) platooning dynamic performance- path smoothing

The analysis for the 8-axle B-train showed that contrary to the tractor/ semi-trailer, path following references are very critical for the B-train's dynamic performance while platooning using close path adherence (Figure 7). The best overall performance was achieved when the following unit used the lead unit's tractor steering axle as reference where the input and overall amplification were 1.102 and 1.354, respectively. Performance was degraded slightly when using the rear drive axle as reference with input and overall amplification of 1.155 and 1.528, respectively but remain at acceptable levels. However, when the rear trailer axle was used as reference, amplification levels were very high with input and overall amplification of 1.714 and 2.568 respectively, which will result in poor dynamic performance. The implementation of a path smoothing strategy will allow the platooning dynamic performance of the B-train to be significantly improved even when using the rearmost axle as reference (Figure 8), where the input and overall amplifications were reduced to 0.534 and 0.756 respectively. However the best overall performance was achieved with path smoothing for the B-train when using the lead unit's steering axle as reference for the following unit's path where the input and overall amplification was 0.330 and 0.411 respectively.

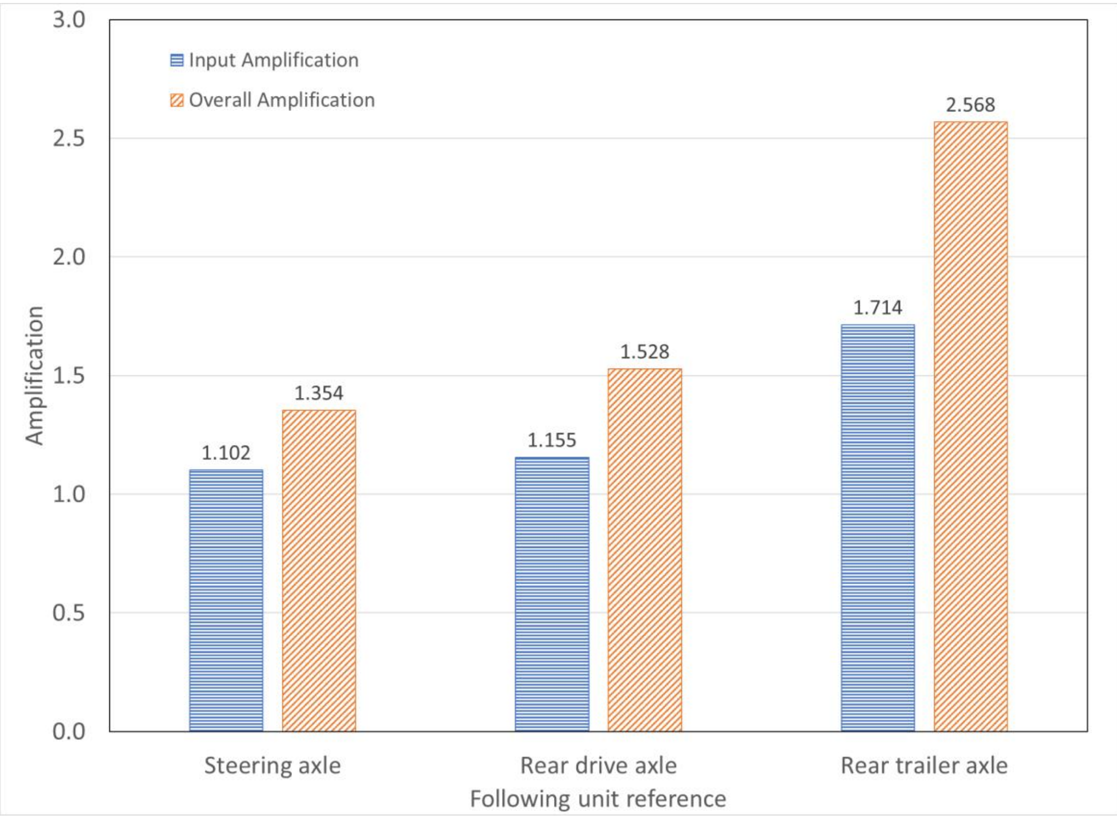

Figure 7. Effect of alternative path references on 8-axle B-train (63 500 kg) platooning dynamic performance- close path adherence

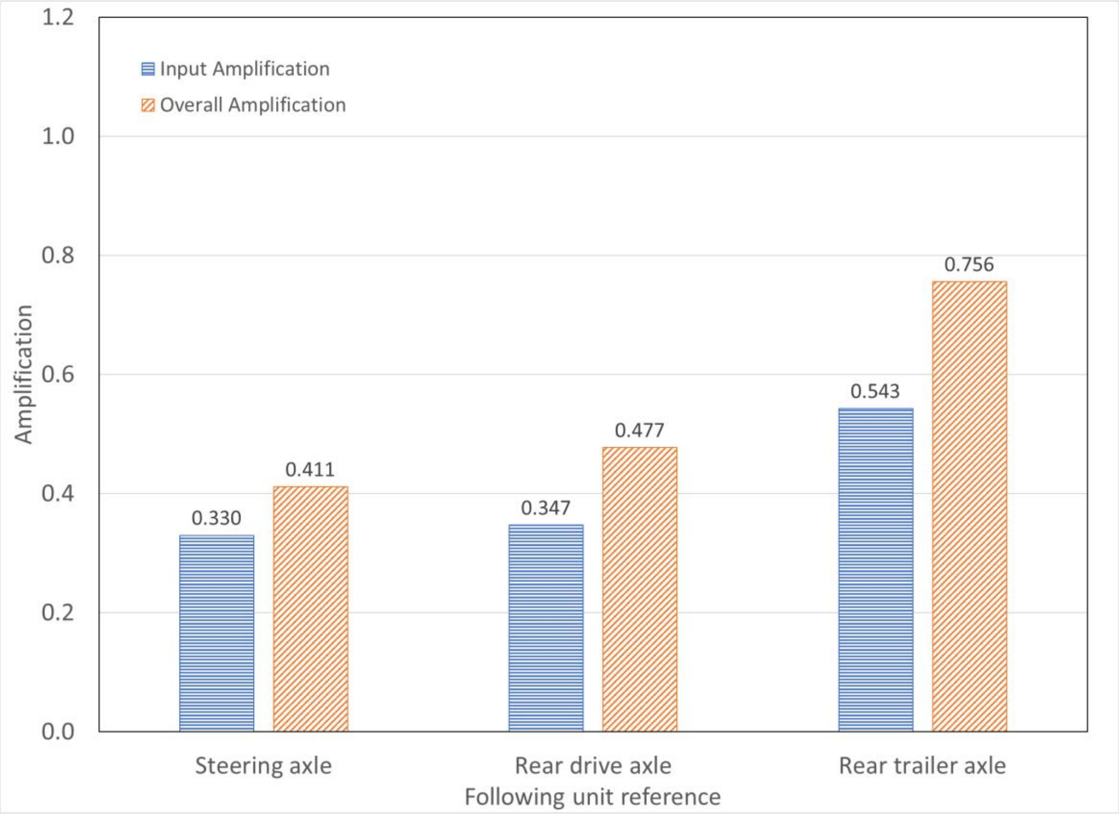

Figure 8. Effect of alternative path references on 8-axle B-train (63 500 kg) platooning dynamic performance- path smoothing

This analysis illustrates the importance of path following strategies and the sensitivity of different configurations to these strategies. The lightly loaded 5-axle tractor/semi-trailer can perform well even when using the rear trailer axle as reference without any path smoothing. However, a fully loaded B-train would need to employ an improved path following strategy (path smoothing) and if possible, use the lead unit's steering axle as reference for optimal results. Therefore, further testing and cooperation between platoon system developers and road transport stakeholders is required to ensure optimal deployment of truck platooning systems.

4. Conclusions

1. Dynamic testing of 5-axle tractor semi-trailers in a two-unit platoon showed good overall performance at speeds of up to 57 km/h. The overall rearward amplification of yaw-rate remains low between 0.565 and 0.980. Further testing will be required to validate the platooning system at highway speeds.
2. The simulation model correlated very closely with the test data in predicting both the input amplification and overall amplification for the platoon. The open loop simulation correlated particularly well, where the 90% confidence limits between the simulation estimates and test measurements were similar for both measures. The closed loop

simulation showed the average levels of input and overall amplification were within 5% of the test results, but with less variability.

3. Further collaboration with the platooning system developers will be required to refine the closed loop simulation model. However, the closed loop simulation model still provides good approximations of input and overall amplification and could be used to develop improved path following strategies and evaluate platooning performance for other configurations.
4. The 5-axle tractor/semi-trailer's platooning dynamic performance was not particularly affected by the path reference used when executing a standard lane change manoeuvre at 88 km/h using close path adherence. It is likely that the reduced load and long trailer wheelbase result in reduced levels of trailer lateral movement so that even when the following unit follows the path of the lead unit's rear trailer axle the input to the following unit's tractor remains similar or reduced relative to the lead unit.
5. A two-unit platoon of B-trains loaded to maximum allowable weights was found to be very sensitive to path reference location when using close path adherence. The best overall performance was achieved when the following unit used the lead unit's tractor steering axle as reference with performance degraded slightly when using the rear drive axle as reference. When the rear trailer axle was used as reference, amplification levels were very high resulting in poor dynamic performance.
6. Dynamic performance of the two-unit platoon can be improved significantly when a path smoothing strategy is employed. The B-train configuration can achieve reduced overall amplification of 0.756 even when using the rear trailer axle as reference with a path smoothing strategy.
7. Further testing and cooperation between platoon system developers and road transport stakeholders is required to ensure optimal deployment of these systems.

5. References

- de Pont, J. (2018), "PBS for connected and automated vehicles" in Proceedings of the 15th Heavy Vehicle Transport Technology Conference (HVTT15), Rotterdam.
- Guanetti, J., Kim, Y. and F. Borrelli (2018). "Control of connected and automated vehicles: State of the art and future challenges," Annual Reviews in Control, Volume 45, Pages 18-40.
- Lee, S., Nakano, K., Ohori, M. (2013) "Identification of Yaw Moment of Inertia of a Truck during Travelling", IFAC Proceedings, Volume 46, Issue 21, Pages 768-772.
- Lygeros, J., Godbole, D. and S. Sastry (1998). "Verified hybrid controllers for automated vehicles," IEEE Trans. Autom. Control 43(4) Pages 522–539.
- Puri A. and P. Varaiya (1995). "Driving safely in smart cars," Proceedings of 1995 American Control Conference - ACC'95, Seattle, WA, USA, Pages 3597-3599 vol.5.