

PBS FOR CONNECTED AND AUTOMATED VEHICLES



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Abstract

Performance Based Standards (PBS) are used as a tool in a number of jurisdictions to assess whether or not a vehicle can perform its required transport tasks safely. One of the main uses of PBS has been to facilitate the introduction of larger more productive vehicle combinations.

The development of Intelligent Transport System (ITS) technologies such as vehicle-to-vehicle communications and automated driving capabilities have created the possibility of operating heavy vehicles as platoons. A platoon is effectively a long combination vehicle with electronic rather than physical couplings connecting the individual vehicle units.

In this paper we investigate the performance characteristics of platoons assuming that the trailing vehicles are steered to follow the rear of the vehicle in front. The results of this analysis highlight some of the challenges for the designers of automated and connected vehicles and for regulators in creating a regulatory framework for managing this technology.

Keywords: Driver support and platooning, standards and regulations, performance-based standards, connected vehicles.

1. Introduction

Performance Based Standards (PBS) are used as a tool in a number of jurisdictions to assess whether or not a vehicle can perform its required transport tasks safely. The most widely used application of PBS has been to facilitate the use of larger and heavier vehicles by demonstrating that their safety performance is acceptable. The benefits of larger and heavier vehicles can be categorized as follows:

- **Driver productivity.** Fewer vehicle trips and hence fewer drivers are needed to move the same volume of freight
- **Vehicle productivity.** Larger vehicles also have a higher ratio of payload to total weight which further reduces the number of trips required for a given freight task.
- **Fuel efficiency and emissions reduction.** At highway speeds, less than half of the energy required is weight-dependent. Thus the amount of fuel used per tonne-km of freight moved reduces.
- **Reduced congestion.** This is a direct outcome of the reduction in the number of truck trips required. Most of the road space occupied by a vehicle is the required headway to the vehicle in front. At 90km/h, a two-second headway is 50m. Thus the increase in road space required by a longer vehicle is proportionately much less than the benefit from a reduced number of trips.
- **Greater safety.** There is an obvious safety gain through reduced exposure. However, it has also been shown that PBS vehicles in Australia are individually significantly safer than standard legal vehicles (Hassall, 2014).

The development of Intelligent Transport System (ITS) technologies such as vehicle-to-vehicle communications and automated driving capabilities has created the possibility of operating heavy vehicles as platoons. Potentially this provides an alternative approach to longer and heavier vehicles for increased productivity. A platoon is effectively a long combination vehicle with electronic rather than physical couplings connecting the individual vehicle units.

A number of the fundamental technologies required for platooning already exist and have been demonstrated in Europe (Aarts and Feddes, 2016) and North America (McAuliffe et al, 2017). For these demonstrations, the in-vehicle systems managed speed and headway control for the trailing vehicles but each vehicle still had a driver who steered the vehicle and could take over full control if necessary. With this level of technology, the benefits of platooning are modest and larger and heavier PBS vehicles would provide greater benefits.

On-going technology developments could see this situation change. Automated steering systems have already been demonstrated and these could potentially lead to eliminating the need for drivers in the trailing vehicles. In the long term the entire driving task could be automated which would possibly eliminate the need for a cab and transform the vehicles. The movie, Logan, which is set in 2029, postulates this vehicle concept as illustrated in **Figure 1**. This vehicle consists of a pilot module and a slave module connected by a load module which in this case is a 40' ISO container.



Figure 1: Future truck concept from the movie “Logan”.

The current demonstration platoons have used standard tractor semi-trailer combinations which are a proven configuration with good safety performance characteristics. However, as a platoon they are effectively a long combination vehicle and thus we should consider the performance of the whole platoon as an entity rather than just the considering the performance of the individual vehicles.

Future platoons are likely to include automated steering and eventually may be able to operate without a driver in each vehicle. Again the performance characteristics of the platoon as an entity needs to be considered.

In this paper we investigate the performance characteristics of platoons assuming that each of the trailing vehicles is steered to follow the rear of the vehicle in front of it. The results of this analysis highlight some of the challenges for the designers of automated and connected vehicles and for regulators in creating a regulatory framework for managing this technology.

2. Research Approach

The analysis considers a platoon consisting of two semi-trailer combinations and evaluates three key performance characteristics:

- Low speed turning performance
- High speed offtracking
- High speed dynamics

These three aspects of performance were part of the analysis undertaken in the Canadian RTAC study (RTAC, 1986) and are a core part of the Australian and New Zealand PBS schemes (National Transport Commission, 2007, de Pont et al, 2016). For this analysis we have used the performance measures specified in the draft New Zealand PBS scheme (de Pont

et al 2016) but the findings will apply to all PBS systems that include these aspects of performance.

The performance measures were evaluated by computer simulation using the Yaw-Roll package developed at the University of Michigan (Gillespie and MacAdam, 1982). It was assumed that the second vehicle in the platoon was steered to follow the path of the rear of the lead vehicle throughout the manoeuvre.

This reflects the situation where the trailing vehicle is steered by the driver. If the inter-vehicle spacing is small the trailing driver has no practical cues for his steering path other than the path of the rear of the vehicle in front.

If the trailing vehicle has automated steering, it should be possible to set up the automated steering system so that it has a wider field of vision than the human driver and thus it will also have some lane position information that it can use. However, if the inter-vehicle spacing is small, the vehicle will be unable to react quickly enough to steering input changes for this additional information to have much effect. On the other hand, the vehicle-to-vehicle communication system could provide useful additional information to an automated steering system but this would require the vehicle control system to “understand” the dynamic characteristics of the other vehicle. The information required for steering control is much more complex than the information required for headway control. The trailing vehicle needs to “know” not only what the steering inputs of the leading vehicle are but also how it is responding to them.

The vehicle used for this analysis was an 18m 6-axle tractor semi-trailer combination approximately similar to the one illustrated in Figure 2. The dimensional limits shown are those that apply in New Zealand and these are different from those applying in other jurisdictions. These dimensional differences will influence the absolute values of the results of the performance assessments that follow but underlying principles still apply. For the analysis we used a tractor with a wheelbase of 4.955m and a front overhang of 1.455m. The trailer rear overhang was 3.465m.

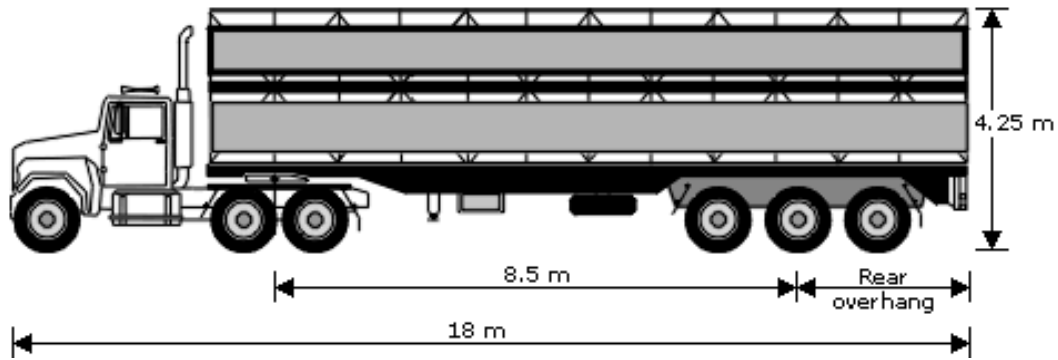


Figure 2. Standard New Zealand 6-axle semi-trailer combination.

3. Results

3.1 Low Speed Turning Performance

The draft New Zealand low speed turning performance standard uses a 90° 12.5m outside radius turn and evaluates the vehicle's swept width as shown in Figure 3. The draft standard proposes that this swept width should not exceed 6.75m. The Australian PBS system uses the same manoeuvre and for level 1 access specifies a maximum swept width of 7.4m. Using the test vehicle dimensions described above, the swept width of a single vehicle is 6.61m which meets the draft New Zealand PBS requirements. It also easily meets the Australian PBS requirements for level 1 access which is the closest level to general access.

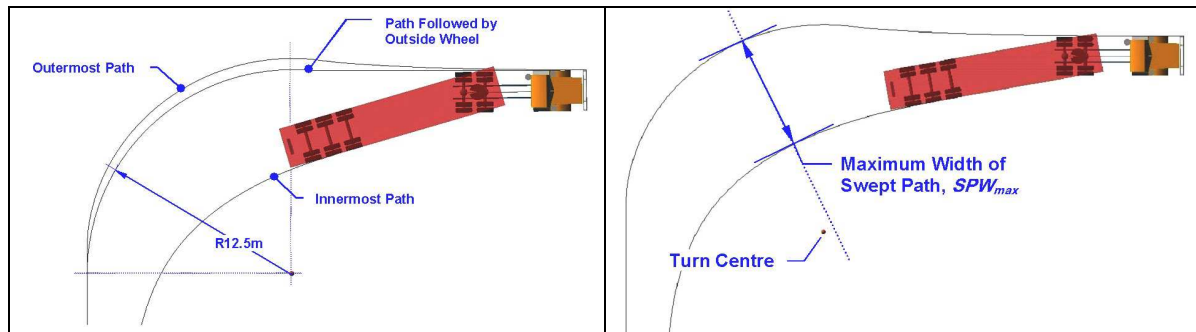


Figure 3. Illustration of swept width performance measure reproduced from (National Transport Commission 2007)

To model the low speed turning performance of a two-vehicle platoon, the centre of the steer axle of the trailing vehicle was attached to a simple trailer coupling located at the centre of the rear of the first vehicle trailer. Thus the steer axle of the second vehicle was constrained to follow the path of the rear of the first vehicle.

At low speed with no vehicle dynamics effects, coupling a trailing vehicle was not expected to have a significant impact on the path of the lead vehicle. This assumption was verified by comparing the output data for the first vehicle with and without the trailing vehicle connected.

The maximum difference between paths of the rear axis of trailer for the two cases was approximately 0.05m so the effect is relatively small.

With a two-vehicle platoon the total swept width of the combination is 9.72m which is clearly excessive. In terms of the proposed New Zealand PBS requirements, this is nearly 3m over the allowable level. The allowable level is based in the performance of representative vehicles in the current fleet and thus reflects what the existing infrastructure can accommodate.

The Australian baseline semi-trailer vehicle is 19m long and has a maximum trailer wheelbase of 9.5m. Thus its swept width is greater than that of the reference vehicle used here and this is why the Australian PBS limit is higher. It is clear that a two-vehicle platoon of Australian semi-trailers would similarly substantially exceed the Australian PBS limit for low speed swept path.

With additional vehicles in a platoon the swept width will increase further. Thus it is not practical to operate platoons where the vehicles are steered by following the path of the rear of the preceding vehicle through low speed turns.

3.2 High Speed Offtracking

High speed off-tracking is measured as the offset between the path of the centre of the steer axle and the path of the centre of the rearmost axle during a steady speed constant radius turn. The draft New Zealand PBS system proposes a 319m radius turn at 90km/h which results in a lateral acceleration of 0.2g. The Australian PBS system does not include high speed off-tracking as a performance standard but its “tracking ability in a straight path” standard is related to it although this is based on lower levels of lateral acceleration due to cross-slope coupled with dynamic effects due to road roughness.

The draft New Zealand PBS system proposes a maximum value of 0.46m for this measure. The single 18m semi-trailer has a high speed off-tracking value of 0.31m and so it meets the proposed requirement comfortably.

For evaluating this performance measure on the platoon we did not couple the trailing vehicle to the lead vehicle because we would expect the lateral acceleration of the trailing vehicle to influence the response of the leading vehicle if they were coupled. However, it is reasonable to expect this effect to be cumulative through the platoon. The trailing vehicle simply follows the path of the rear of the vehicle in front. The curve radius for the trailing vehicle would be 0.31m greater than the curve radius for lead vehicle but as this curve radius is 319m the increase is only 0.1%. Thus the effect of the increased radius on lateral acceleration is negligible. The off-tracking of two vehicles in a platoon will simply be double the off-tracking of a single vehicle.

On this basis the two-vehicle platoon has a high speed off-tracking value of 0.62m and each additional vehicle increases the off-tracking by 0.31m. Thus two or more vehicles in a platoon will produce an unacceptable level of high speed off-tracking.

3.3 High Speed Dynamic Performance

High speed dynamic performance is usually characterized using a high speed lane change manoeuvre. The standard manoeuvre used has been defined in an ISO standard (International Standards Organisation, 2000).

Three performance measures are typically calculated from the vehicle's response:

- Rearward Amplification
- Load Transfer ratio
- High Speed Transient Off-tracking

RTAC and the draft New Zealand PBS system use all three of these measures. The Australian PBS system does not include load transfer ratio and uses a modified version of rearward amplification which incorporates the effect of roll coupling.

For this test manoeuvre, the simulation model uses closed loop control where a driver model applies steering inputs to get the vehicle to follow the specified target path. At each simulation step, the driver model compares the vehicle's actual position and heading with the target position and heading and adjusts the steering accordingly. For the first vehicle in the platoon, the target path is that defined in the ISO standard. For the second vehicle in the platoon, the target path was specified by extracting the actual path followed by the rear of the first vehicle.

Figure 4 shows the rearward amplification of the first and second vehicles in a platoon. The rearward amplification is the ratio of the peak lateral acceleration of the trailer to the peak lateral acceleration of the tractor. For the first vehicle this is 1.15. Although, strictly the rearward amplification of the second vehicle in the platoon is no greater than the rearward amplification of the lead vehicle, the lateral accelerations of the first vehicle are substantially amplified in the second vehicle. If the platoon is considered as a single vehicle, then the rear amplification would be the ratio of the peak lateral acceleration of the trailer of the second vehicle to the peak lateral acceleration of the tractor of the first vehicle. Taking this approach the rearward amplification of the platoon would be 1.57. The acceptability limit for rearward amplification is that it should be less than or equal to 2.0. Thus a two-vehicle platoon of semi-trailers is still within the allowable level for this performance measure but it is likely that a third vehicle would exceed 2.0. Typically the rearward amplification of a truck and full trailer combination is 1.7 – 2.0. Thus, if a platoon consisted of truck and full trailer combinations it is almost certain that a two-vehicle platoon would not have acceptable performance.

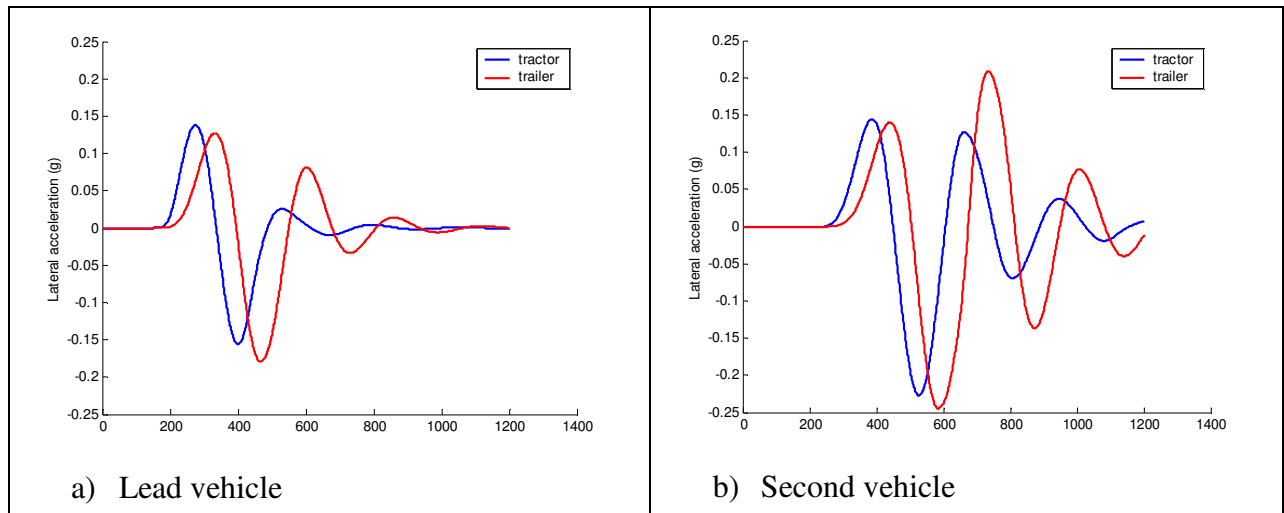


Figure 4. Rearward amplification of two semi-trailer vehicles in a platoon.

The load transfer ratio is the peak value of the proportion of the vehicle's weight that is transferred from one side of the vehicle to the other during this manoeuvre. A load transfer ratio of 1 indicates that all the wheels on one side of the vehicle have lifted off the ground and thus rollover is imminent. The acceptability criterion for this performance measure in New Zealand and Canada is that the peak load transfer ratio should be 0.6 or less. For the single vehicle modelled, the load transfer ratio was 0.43. For the second vehicle in the two-vehicle platoon it was 0.63. Thus the performance of a single vehicle is acceptable while the performance of the second vehicle in the platoon is not.

As the vehicle exits the lane change manoeuvre the path of the trailer axles tends to overshoot the path of the tractor steer axle. The magnitude of this overshoot is called the high speed transient off-tracking and the acceptability level in both the Australian PBS system (for level 1) and the proposed New Zealand PBS system is that it should not exceed 0.6m.

The high speed transient off-tracking results for the two-vehicle platoon are shown in Figure 5. For the lead vehicle the high speed transient off-tracking is 0.26m while for the second vehicle it is 0.49m. However, as with rearward amplification, this is misleading because the steer axle of the second vehicle is itself deviating substantially from the desired path. The appropriate measure for the second vehicle is the offset between the path of its rearmost axle from the path of the first vehicle's steer axle. Using this approach the high speed transient off-tracking is 0.78m which does not meet the acceptability level for this performance standard.

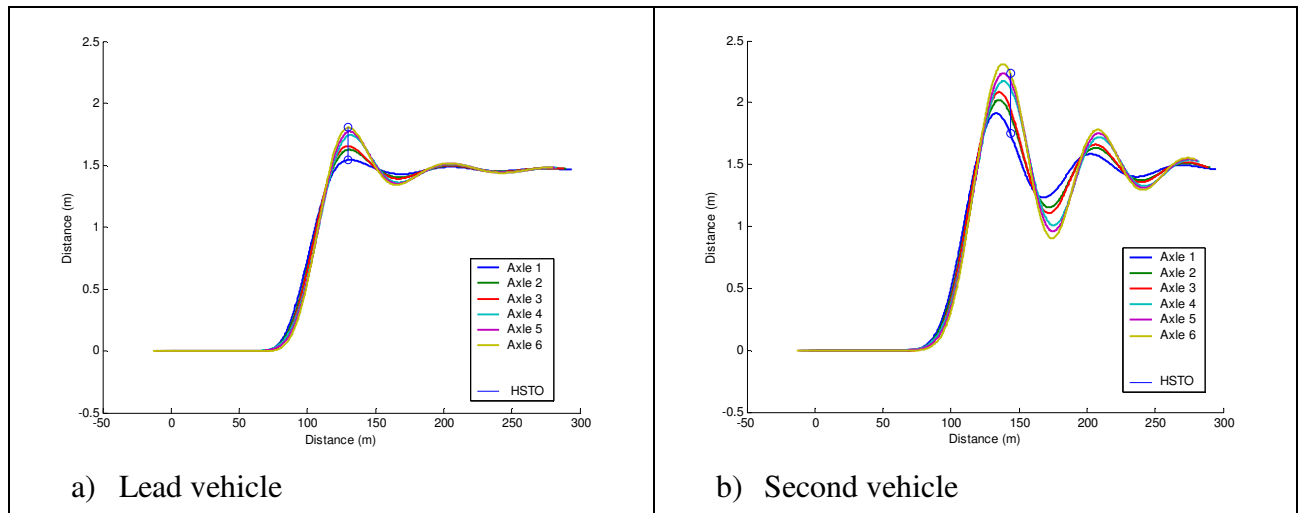


Figure 5. High speed transient off-tracking of two semi-trailer vehicles in a platoon.

4. Discussion

The performance standards that have been evaluated in this analysis reflect aspects of vehicle performance that are considered important for the safe operation of the vehicle. However, how these performance measures relate to real world driving situations is not entirely straightforward.

The low speed turning performance manoeuvre is undertaken at very low speed so that the vehicle experiences very little lateral acceleration. The off-tracking that occurs is a result of the vehicle's geometry and is influenced by the number and location of couplings and the wheelbases of the individual vehicle units that make up the combination. Low speed off-tracking occurs on the inboard side of the curve.

High speed off-tracking, on the other hand, is measured at high speed (90 or 100 km/h) on a large radius curve such that the vehicle geometric effects are small. The vehicle experiences a significant lateral acceleration and this centrifugal force has to be balanced by an equal and opposite force generated by the tyres. To generate this lateral force, the tyres need to operate with a slip angle, i.e. the heading of the vehicle is not the same as the direction that the tyres are pointing, and as a result the vehicle off-tracks. High speed off-tracking occurs on the outboard side of the curve.

In real world driving situations on winding roads both low speed and high off-tracking effects are present when cornering. For low speed curves with small radii, low speed effects dominate while for high speed curves with large radii high speed effects take over. Generally road builders widen the lanes on curves to allow for this vehicle off-tracking effect.

It was shown that the second vehicle in a platoon of two semi-trailers had both excessive low speed and high speed off-tracking. Although, in theory, the low speed off-tracking problem could be avoided by requiring platoons to separate at intersections and roundabouts, this does not address how the vehicles will behave on lower speed highway curves. Because both forms of off-tracking are excessive, the lane width requirements of a platoon on winding roads

will be substantially greater than that of a single vehicle and it is likely that the platoon will not stay within its lane.

The high speed dynamic performance measures are based on an evasive manoeuvre and thus characterise the vehicle's performance when the driver reacts to an unexpected event. The dynamic response of the lead vehicle is amplified through the platoon to the extent that the safety of the trailing vehicles is likely to be compromised, particularly if there is more than one trailing vehicle. Because the event that triggers the manoeuvre is unexpected, it is difficult to see how the driver(s) of the trailing vehicle(s) would do anything other than try to follow the lead vehicle.

The analysis approach has assumed that the trailing vehicle(s) is being steered to follow the path of the rear of the vehicle in front of it. This situation is expected to apply with a human driver steering when the headway between vehicles in the platoon is small and the driver has little or no view of the roadway ahead. Even if the steering of the trailing vehicles is automated, the same situation is likely to apply unless the vehicle-to-vehicle communications provides detailed information on both the preceding vehicle's steering inputs and its dynamic response. An automated steering system may well have better peripheral vision than a human driver and thus have better information on the vehicle's lane position but if the headway is small it will not have sufficient information to respond appropriately.

5. Conclusions

Automated vehicle technologies and vehicle-to-vehicle communications create the potential to operate vehicles in platoons. Effectively these are combination vehicles with electronic couplings and they offer the potential for significant productivity and fuel efficiency gains. However, if the trailing vehicles in a platoon simply steer by following the rear of the vehicle in front of them then the performance of the platoon as a combination vehicle is compromised. Thus platoons where the trailing vehicles are steered by human drivers will need to have sufficiently large headways for the driver to be able to see where the road is going. This does limit the potential fuel efficiency gains.

When the trailing vehicles have automated steering small headways could be possible but vehicle-to-vehicle communications will need to transmit sufficient information from the leading vehicles to the trailing vehicles to enable them to execute appropriate steering actions. This data is likely to have to include information on the geometry and dynamic behaviour of the leading vehicle.

For the regulator, platoons pose some significant safety challenges.

- How should the performance characteristics of a platoon be quantified?
- What constitutes satisfactory performance?
- How can performance be tested?
- What standards should apply for vehicle-to-vehicle communications?
- On what infrastructure can platoons be permitted and under what circumstances should they be required to separate?

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