

IMPLEMENTATION OF ACTIVE REAR STEERING OF A TRACTOR – SEMI-TRAILER



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Abstract

A new active steering controller was developed for articulated heavy goods vehicles. It was designed to achieve ‘perfect’ path-following under all conditions. An experimental triaxle trailer, with three actively-steered axles was built and used to compare the performance of the new controller with a passive ‘command steer’ steering strategy, and a conventional trailer with fixed axles. A novel system of digital cameras was used to measure the line following performance of the vehicle. The path-following control strategy showed reductions of cut-in (79%), tail swing (100%), exit settling distance (97%) and lateral tyre force (83%) relative to the unsteered case, and 48%, 100%, 93%, and 64% respectively relative to the command steer case.

Keywords: Active, Rear, Steer, Heavy vehicle, Tractor, Semi-trailer, Command.

Résumé

Un nouveau système de contrôle actif de direction a été développé pour les poids lourds articulés. Il vise un suivi « parfait » de trajectoire en toutes conditions. Une remorque expérimentale à trois essieux directeurs actifs a été réalisée et utilisée pour comparer les performances du nouveau système de contrôle avec un système de commande de direction passif et une remorque traditionnelle à essieux fixes. Des caméras numériques ont été utilisées pour mesurer les performances du véhicule. Le système de contrôle de trajectoire a permis de réduire de 79% les coupures de virage, de 100% les oscillations de lacet, de 97% la distance de remise en ligne (du tracteur et la semi-remorque en sortie de rond-point), et de 83% les efforts latéraux sur les pneumatiques par rapport au cas sans essieu directeur, et de 48%, 100%, 93% et 64% pour les même grandeurs par rapport au cas avec commande de direction.

Mots-clés: Actif, arrière, direction, poids lourds, tracteur, semi-remorque, commande.

1. Introduction

In 2004, 69% of all freight in the United Kingdom was moved by articulated heavy goods vehicles; but such vehicles accounted for only 12% of the goods vehicles on minor roads (Anon, 2004). Heavy articulated vehicles lack the manoeuvrability to be driven on narrow winding roads with tight roundabouts – in these locations smaller vehicles have to be used for deliveries. This causes double handling of freight and reduces the operational efficiency of the transport system.

Modern articulated vehicles are normally fitted with multi-axle groups that don't steer. This causes the tyres to scrub against the road during tight cornering, damaging both the tyres and the road surface.

In order to address the problems of manoeuvrability and tyre scrub, a number of 'passive' steering systems have been developed, where semi-trailer wheels are steered according to a simple geometrical relationship with articulation angle or a tyre force balance.

Common systems include self steering axles, 'command steer' systems and pivotal bogie systems (Jujnovich and Cebon, 2002; Prem, 2002; Billing 1979). These systems improve steady state low speed performance, but exhibit tail-swing during transients such as roundabout entries and suffer from poor path following and low yaw stability at high speeds (Jujnovich, 2005; Prem, 2002; Sweatman, Atley and O'Reagan, 2004).

In 1989 Hata, Hasegawa and Takahashi from Nissan Diesel published a paper on a control method to reduce tail swing on a rigid truck. The method used steering of the rear wheels based on the geometry of the vehicle. The feed-forward control system made the rear of the body follow the path of the front, which reduced swept path width without introducing tail swing. The strategy was tested on a rigid vehicle and found to perform well at low speeds. No mention was made of high-speed performance. Similar work on rigid trucks was performed by Gohring et al (1994); and by Phlug et al (1996).

In 1991 Notsu, Takahashi and Watanabe published a paper on the turning behaviour of a steerable semi-trailer. The control system they presented aimed to improve the path following ability of the trailer. The disadvantage of the proposed strategy is that information has to be passed between the two vehicle units, which would be a hindrance to practical implementation of the system.

Notsu et al (1991) also proposed a controller strategy which they called 'coupling point path follow control'. In this strategy, the rear of the semi-trailer was intended to follow the 5th wheel. However, Notsu et al did not pursue this idea.

There are a number of limitations of controllers proposed by previous authors which need to be addressed for active trailer steering to become a practical proposition:

- (i) Previous controllers do not account for the limits on wheel steering angles that can be reached during low-speed manoeuvres. This can lead to off-tracking of the trailer long after the manoeuvre is completed.
- (ii) Previous controllers do not account for multiple trailer axles.
- (iii) Previous controllers are generally designed to improve path-following at low-speeds and do not account for manoeuvres performed at high-speeds

The aim of the controller development in this project was to improve all of these aspects of performance.

2. Theory

The ‘path-following’ steering controller derived in this project (Jujnovich, 2005) aims to make the rear of the trailer (‘follow point’) follow the path defined by the fifth wheel (‘lead point’) in a similar way to Notsu et al’s ‘coupling point path following’ controller (Jujnovich, 2005 also considered a vehicle with steering on all axles, including the tractor drive axle. He denoted this strategy: Active Tractor Active Trailer, AT-AT. The AT-AT strategy is not discussed in this paper) (see Figure 1), but it achieves this at all speeds. This strategy is termed ‘Conventional Tractor – Active Trailer’ (CT-AT).

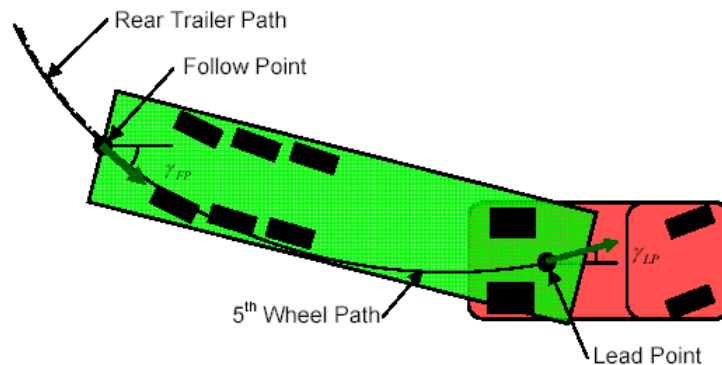


Figure 1 - CT-AT path following strategy.

Unlike Notsu’s controller, the CT-AT strategy also includes a model following controller, which allows the vehicle to return to the path defined by the lead point if it develops an off-tracking error. This situation can arise in tight corners if the demanded trailer steer angles exceed the available wheel angle clearance.

The CT-AT controller also sets the steer angles of the individual axles of the semi-trailer axle group to minimise lateral tyre forces. In developing the CT-AT algorithm, it was assumed for low speeds the lateral accelerations are negligible. See Jujnovich (2005) for details of the implementation.

3. Implementation

3.1 Test Trailer Design

An electrically driven hydraulic powerpack is used to operate hydraulic actuators on each axle. The control system consists of a ‘local controller’ (LC) which performs closed loop control of steer angles, and a global controller (GC) which generates the demand steer angles based on sensor information. The GC and the LC are linked by CANbus.

The test vehicle is equipped with many sensors including those measuring: hitch pin articulation angle, wheel steer angles, yaw rates of tractor and trailer, wheel speeds, and sprung mass angular velocities and accelerations. Only a limited number of these are required for the CT-AT low speed controller.

3.2 Line Following Cameras

A video camera based line tracking system was fitted to the vehicle. Cameras were mounted so as to monitor the front of the tractor, directly beneath the 5th wheel and the rear of the trailer. During vehicle tests the cameras recorded the position of each vehicle unit relative to lines painted on the road surface.

4. Testing and Results

The aim of the testing was to determine vehicle performance with three different steering strategies: 'locked', 'command steer' and CT-AT. The command steer strategy involves steering the trailer wheels in proportion to the articulation angle between tractor and trailer.

In the validation tests lateral tyre forces were estimated from measured side-slip using a tyre model rather than directly measured.

The low speed test manoeuvre was a 360° roundabout as defined in the United Kingdom's Road Vehicles (Construction and Use) Regulations (Anon, 1986). The regulation stipulates that the tractor and trailer combination must negotiate the roundabout staying between the 5.3m and 12.5m radius circles.

All tests in this part of the study were conducted with the vehicle fully laden to a gross weight of 40t in accordance with UK mass limits, and at a speed of 10km/h.

The performance measures used to assess vehicle performance in this test are presented in the following sections. The performance of the three control strategies is summarised in Table 1.

Table 1 – Performance measures

PERFORMANCE MEASURE	LOCKED	COMMAND STEER	CT-AT
Roundabout Swept Path Width	7.23m	5.45m	5.20m
Steady State Off-tracking	4.25m	1.60m	1.20m
Tail Swing (Entrance)	0.17m	0.61m	0.00m
Peak Tyre Force	36.6kN	5.3kN	6.1kN
Exit Settling Distance	23.5m	8.8m	0.6m

The greyed cells indicate those values that are worse than the locked case.

4.1 Roundabout Swept Path Width (SPW360)

Swept path width is defined as the difference in radius between the smallest radius and largest radius points on the articulated vehicle when it has reached steady state cornering. This was measured by bringing the vehicle to a halt during the manoeuvre and then measuring from the closest and furthest points to the centre of the circle. The results are shown in Table 1.

The results show a swept path width of 7.23m for the locked vehicle. The command steer and CT-AT vehicles both give reductions in swept path width of around 2m (5.45m, and 5.20m respectively). This represents an entire lane width. The difference is due to the command steer and CT-AT vehicles having different 'effective lengths'. (See Jujnovich, 2002, for a

discussion of effective length.) .The command steer vehicle had an effective length of 6m, which gave the best balance between swept path width and tail swing for the vehicle used. The CT-AT vehicle had an effective length of 5.75m, half the distance between the 5th wheel to the rear of the trailer.

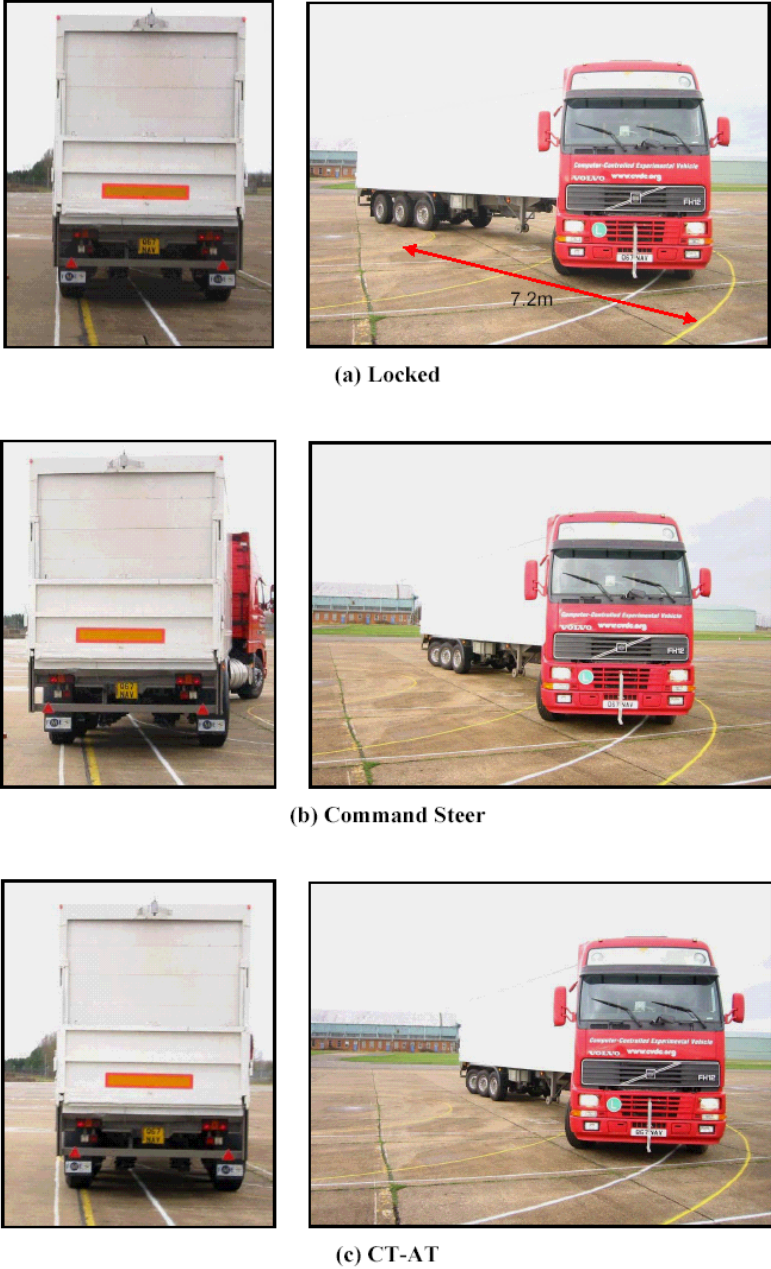


Figure 2 – Positions of the test vehicle with the three control strategies.

Left picture: tail swing at entry to the circle;
 Right picture: steady-state position on the circle.

The photographs on the right of Figure 2 show the vehicle during the roundabout manoeuvre in steady-state for each of the three control strategies. The photographs confirm that the locked case gave significantly more swept path width than both the command steer and CT-AT steering strategies.

4.2 Steady-State Off-tracking

Steady-state off-tracking is the difference in radius between the centre of the front of the tractor and the centre of the rear of the trailer. This was measured using the camera system.

Figure 3 shows variation of the off-tracking through the entire roundabout manoeuvre for the three vehicles. When steady-state was reached it can be seen that with the steering locked, the trailer rear cut-in by more than 4m from the path of the tractor front. The command steer system reduced the cut-in to approximately 1.5m while the CT-AT system reduced the cut-in to 1.15m. The last value is the same as the cut-in of the 5th wheel. This confirms that the CT-AT controller was working as designed and the rear of the trailer was following the 5th wheel accurately at low speeds.

4.3 Tail Swing (TS)

Tail swing is the deviation of the rear of the trailer *outside* the path of the lead point when entering the roundabout. The tail swing performance of each steering strategy was compared as they entered the roundabout manoeuvre.

Table 1 and Figure 3 show that when locked, the vehicle exhibited an entry tail swing of 0.17m.

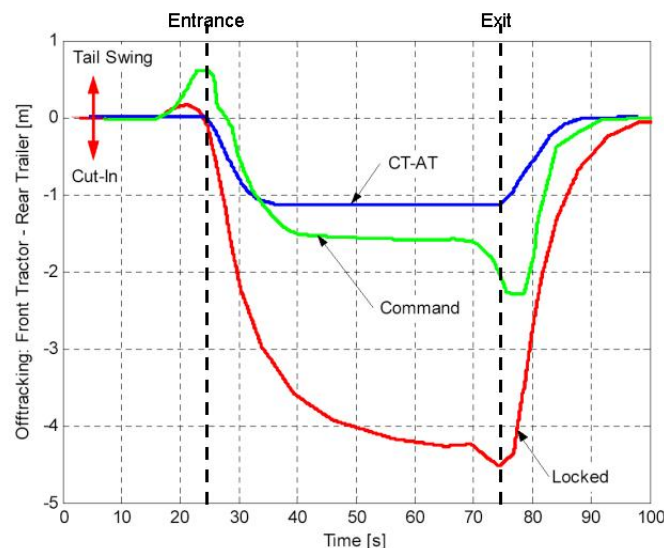


Figure 3 – Rear trailer off-tracking - roundabout.

The command steer system increased the amount of entry tail swing to 0.61m while the CT-AT system eliminated tail swing altogether. On exit, the command steer controller displayed an additional transient movement inwards, increasing the cut-in to a peak of 2.3m (Figure 3). This motion can be seen to be “anti-symmetric” with the entrance tail swing. Both occur because the command steer strategy is designed to improve steady state steering performance without consideration for the different steering action needed during the transient motion at the entrance to and exit from the circle.

From Figure 2(a) it can be seen that when locked, the rear of the trailer travelled just outside of the leftmost white line (which marked the edge of the road). Figure 2(b) shows that in command steer mode, tail swing greatly increased. By contrast, Figure 2(c) shows that in CT-AT mode the vehicle exhibited no entry tail swing whatsoever.

The significant difference in tail swing performance between the command steer and CT-AT steering systems is best explained by the steer angle graphs in Figure 4.

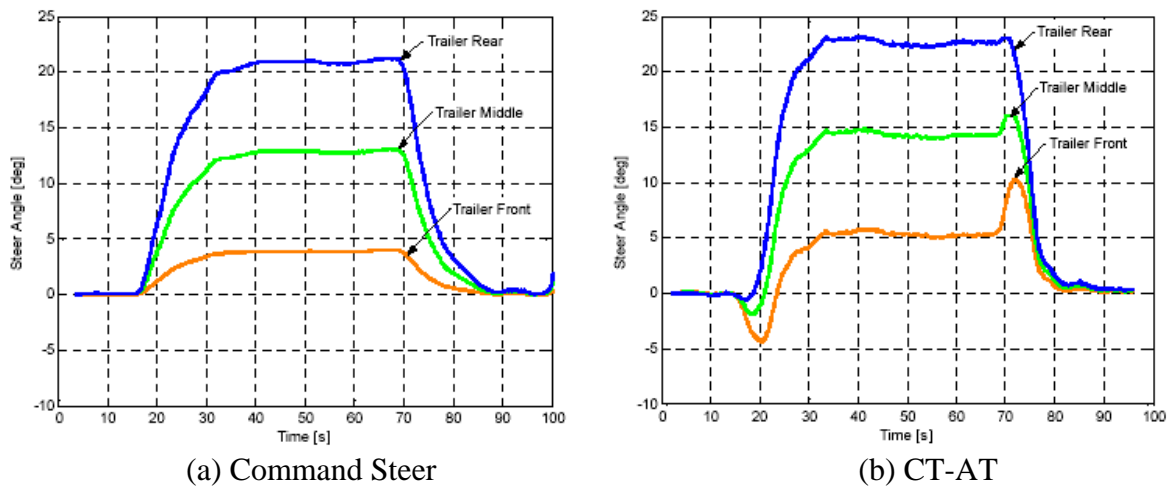


Figure 4 – Steer angles - roundabout.

Figure 4(a) shows that the command steer system always steered the trailer wheels in the positive direction (away from the turn centre) in response to an articulation angle being developed between the tractor and trailer units. This caused the rear of the trailer to swing outside the line of the tractor unit. By contrast, Figure 4(b) shows that the CT-AT controller initially steered the trailer wheels in the negative direction (towards the turn centre). This prevented rearward excursion.

4.4 Lateral Tyre Forces

Figure 5 shows the lateral tyre forces experienced by the trailer and tractor drive axles on all vehicles during the roundabout manoeuvre.

The forces on the left (outer) tyres are represented by solid lines while the forces on the right side (inner) tyres are represented by dash-dot lines. At the top and bottom of each graph a red dashed line is plotted to indicate the force generated by a fully sliding, statically loaded tyre. This nominally represents the maximum lateral force that the tyre can generate.

Figure 5(a) shows the lateral tyre forces on the locked vehicle. From the graph it can be seen that large opposing ‘locked-in’ forces were generated by the front and rear trailer axles. The front left trailer tyre experienced the greatest force and had a fully sliding contact patch. Note that because the test trailer has slightly wider axle spacing than normal (1.43m c/w 1.31m) the locked-in forces were higher than those experienced by conventional locked vehicles (Jujnovich, 2005).

The difference between the left and right tyre forces on both the front and rear trailer axles was due to axle roll. The large lateral tyre forces produced a roll moment on the axle, which vertically loaded one tyre more than the other. This in turn affected the relative magnitude of the left and right lateral tyre forces. In addition to the roll moments, the lateral tyre forces caused a yaw moment on the trailer axle group. To overcome this yaw moment, the tractor drive axle also had to develop a large lateral force (Figure 5(a)).

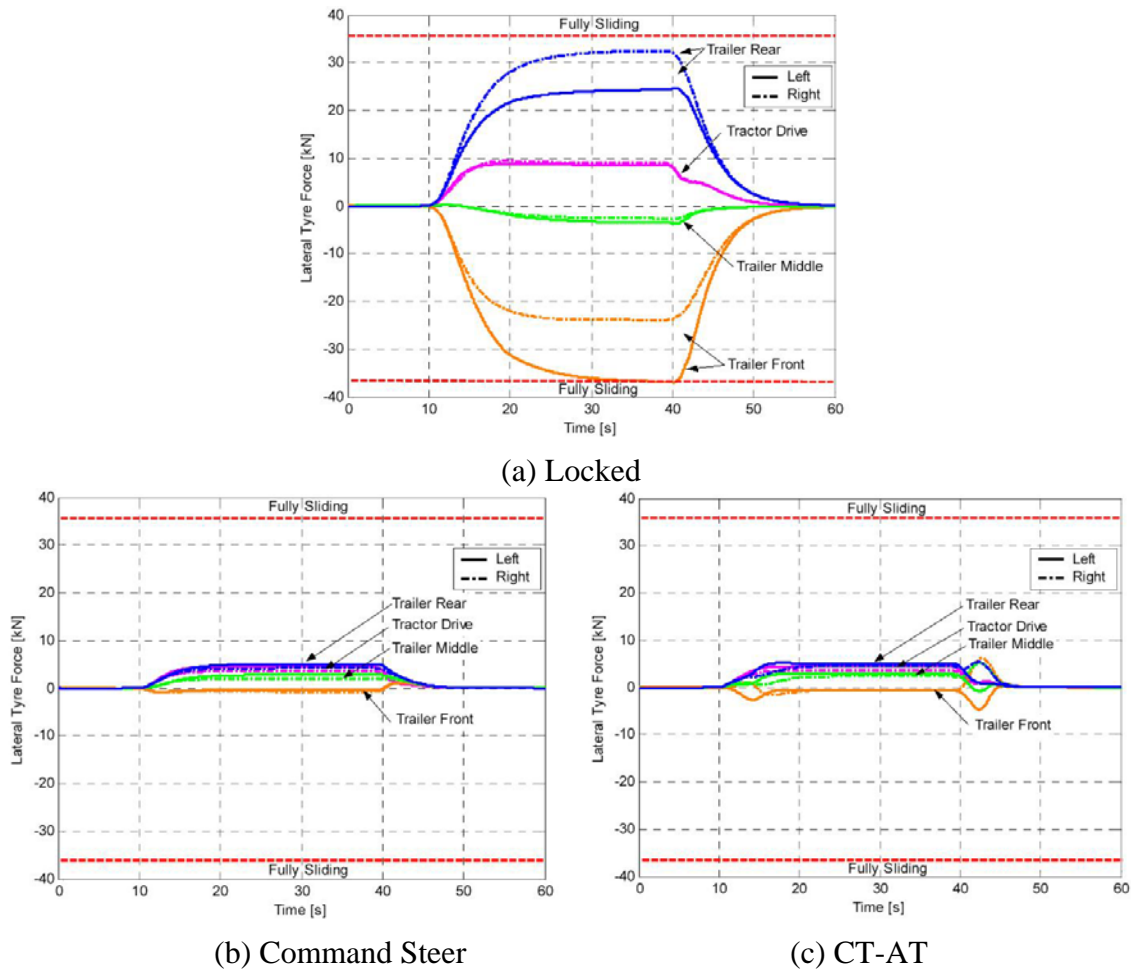


Figure 5 – Lateral tyre forces – roundabout.

Figure 5(b) shows the lateral tyre forces on the command steer vehicle. The command steer system steered the trailer wheels so that, at zero speed in the steady state, their normals passed through the turn centre. This greatly reduced the lateral tyre forces on both the tractor and trailer. Note that in the simulation the forces were not zero because the vehicle was travelling at a non-zero speed (10km/h) and hence the tyres experienced the side-slip necessary to generate the lateral acceleration.

Figure 5(c) shows the lateral tyre forces on the CT-AT vehicle. The graph shows that the steady-state forces were similar to the command steer vehicle but that slightly higher forces were generated during the transitions. These higher forces were due to using a fixed geometry linkage between left and right wheels on each axle. The fixed linkage was only able to achieve Ackerman steering under low-speed, steady-state conditions when the effective wheelbase of the trailer remained constant. During the transitions the effective wheelbase varied from the steady-state value, which resulted in the left and right wheels generating small opposing lateral tyre forces.

Table 1 shows that the active system reduced the drive axle lateral forces by approximately 55% and the trailer axle lateral forces by 82%. Such large reductions are likely to result in substantially less tyre wear. This would be a major benefit to the operator. It is possible that

substantially lower lateral tyre forces would also reduce road wear (surface cracking and loss of skid resistance) at corners and roundabouts. This would benefit the wider community.

4.5 Exit Settling Distance

The exit settling distance gives an indication of how long after the manoeuvre the trailer's directional response is affected. It is defined as the distance after the exit of the manoeuvre by which the rear of the trailer comes back into line with the path of the front tractor axle, ie zero off-tracking. Comparison of the performance of the CT-AT active steering system to the command steer and locked strategies can be seen in Table 1.

4.6 Discussion of performance of the CT-AT Control System

Overall the tests were successful in demonstrating the superior low-speed performance of the CT-AT active steering system over the locked and command steer strategies. The tests showed that the CT-AT active steering system greatly reduced swept path width without generating tail swing. Therefore, CT-AT vehicles could safely be used on narrower roads in regions currently only accessible by rigid trucks. Articulated vehicles are more efficient than rigid trucks (Anon, 2003), so the introduction of CT-AT steering systems could potentially improve the efficiency of the UK's transport network.

A similar reduction in swept path width could be obtained by fitting a passive command steer system. However, this cannot be achieved without increasing tail swing. Tail swing is of concern from a safety perspective because it is not visible to the driver, which can lead to collisions with other road users and roadside objects. The fact that the CT-AT steering system eliminates tail swing improves the safety of the vehicle.

Tyre force reduction benefits are available with both command steer and CT-AT vehicles. These have potential benefits to operators in reducing tyre wear and also to the road network in reducing road surface wear. Exit settling distance is reduced from the locked case by the command steer vehicle, and is eliminated entirely by the CT-AT vehicle.

Further benefits are available from the CT-AT strategy when it is used at high speeds to control the yaw stability of the vehicle and reject external disturbances (eg cross winds and split-friction conditions) see Jujnovich (2005) for details.

5. Conclusions

1. An active steering controller was developed for a tractor – semi-trailer. It was designed to achieve good path following along any path at any speed whilst also minimizing lateral tyre forces.
2. The path following strategy was implemented on a test vehicle, along with locked and command steer steering controllers for comparison. Track tests were conducted to compare the performance of the three steering controllers.
3. Relative to passive and command steer vehicles, the active controller was able to improve low speed performance by reducing: swept path width, tail swing, exit settling distance, and lateral tyre forces.

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