ASSESSMENT OF A CONTROL STRATEGY FOR COMBINED EMERGENCY BRAKING AND TURNING OF ARTICULATED HEAVY VEHICLES



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Abstract

"Slip control" (SC) braking has been demonstrated to reduce the straight line emergency stopping distances of heavy goods vehicles by up to 19%. However, this may be to the detriment of the vehicle's lateral dynamics. In a previous paper the authors proposed an "attenuated slip demand" (ASD) controller to overcome this, restoring the vehicle's directional performance while retaining a stopping distance advantage relative to a conventional electronic braking system (EBS). This paper describes recent full-scale vehicle tests on a tractor-semitrailer, comparing back-to-back, the combined emergency braking and cornering performance with conventional EBS, SC and ASD systems. Whereas SC is shown to have a negative impact on the vehicle's lateral performance, ASD successfully improves on the conventional EBS with respect to both stopping distance and directional dynamics in the combined braking and steering manoeuvre. A substantial reduction in steering effort, greatly improved lane-keeping ability and a reduced risk of jack-knife are all observed with the ASD controller.

Keywords: Anti-lock braking system, EBS, ABS, slip control braking, attenuated slip demand, ASD, articulated vehicle stability, combined braking and steering

1. Introduction

Heavy goods vehicles (HGVs) suffer from emergency stopping distances up to 40% longer than those of passenger cars [1]. Conventional electronic/anti-lock braking systems (EBS) for HGVs have limited bandwidth due to the compressibility of air, the large volumes required to fill the brake chambers and sluggish actuation of the ABS modulator valves. Large amplitude cycling of wheel slip therefore occurs between almost free-rolling and almost fully-locked, causing inefficient emergency stopping performance.

Several "slip control" (SC) braking strategies have been proposed for road vehicles [1-11]. SC aims to minimise stopping distance by accurately regulating wheel slip to the point of maximum braking force. For HGVs, since conventional EBS is so inefficient, the reduction in stopping distance can be substantial. A prototype pneumatic SC system for HGVs has been developed and tested by the Cambridge Vehicle Dynamics Consortium (CVDC). The system uses bespoke high-bandwidth bi-stable valves, placed close to the brake chamber to minimise pneumatic delays, and sliding mode control. Vehicle tests with a tractor-semitrailer have demonstrated up to 19% reductions in stopping distance compared to conventional EBS [11, 12].

However, given that the primary function of ABS is to maintain directional stability and controllability during heavy braking [13], there has been surprisingly little research regarding the effects of SC braking on the vehicle's lateral dynamics.

A modified SC control strategy, "attenuated slip demand" (ASD) control, was developed in order to rectify this. ASD was able to improve the directional performance with SC to a level comparable with EBS, but with minimal loss of stopping performance.

This paper summarizes the results of full-scale vehicle tests of the ASD controller, using a tractor-semitrailer vehicle equipped with both a conventional EBS and the CVDC's prototype pneumatic SC braking system. For a more thorough discussion and simulation of the controller, refer to [14, 15].

2. Attenuated slip demand (ASD) control

ASD concept

Figure 1 shows typical lateral and longitudinal force characteristics of a HGV tyre, plotted against longitudinal wheel slip. The plots were generated using the Fancher truck tyre model [16] with 30 kN vertical load, 3 degrees sideslip angle, 20 m/s longitudinal speed and $\mu = 0.4$.

SC braking aims to operate at the peak of the longitudinal force curve, where braking force is maximal but the capacity to generate lateral force is substantially reduced. Conventional EBS, on the other hand, cycles between the two extremes of the wheel slip range. Therefore maximal longitudinal force is generated only periodically. However, this also allows large lateral forces to be generated periodically when the wheel is close to free-rolling. During emergency braking these large lateral forces, which do not occur with SC, help to directionally stabilise and control the vehicle.

The ASD controller exploits the relative gradients of the lateral and longitudinal tyre force characteristics around the nominal SC operating point. Here a small reduction in wheel slip causes only a small drop in longitudinal force, but a much larger increase in lateral force. Therefore slightly attenuating the wheel slip demand to the SC system can provide a substantial improvement in lateral force, and hence improved directional performance, with

minimal loss of deceleration.

Controller design

Figure 2 is a high-level block diagram of the ASD controller. In keeping with the architecture of the CVDC's prototype SC system [11, 12], it assumes there is a global controller for the vehicle and a local slip controller at each wheel station. The local controllers receive a slip demand signal from the global controller and regulate wheel slip to this level. The ASD controller operates within the global controller, as a "bolt-on" to the existing SC system.

The controller incorporates a linear, single-track, yaw plane reference model of a tractorsemitrailer. For a given steering input and vehicle speed, the steady-state solutions for tractor yaw rate $\dot{\psi}_{1,ss}$ and articulation angle $\psi_{12,ss}$ are calculated. These are combined with a zero reference for tractor sideslip angle β_1 to form the reference state vector:

$$\boldsymbol{x_{ref}} = \begin{bmatrix} \beta_{1,ref} & \dot{\psi}_{1,ref} & \psi_{12,ref} \end{bmatrix}^T = \begin{bmatrix} 0 & \dot{\psi}_{1,ss} & \psi_{12,ss} \end{bmatrix}^T$$
(1)

Control actions are then based on a comparison of the reference and observed vehicle states. A set of "slip attenuation factors" ξ_{1f} , ξ_{1r} and ξ_2 , for the tractor front, tractor rear and trailer axles respectively, are calculated. The nominal slip demands, i.e. those normally used by SC to maximise braking force, are scaled by the relevant slip attenuation factors (which are always between 0 and 1). The resulting attenuated slip demands are the final ASD controller outputs, which are sent to the local wheel slip controllers.

The slip attenuation factors are given by the following equations:

$$\xi_{1f} = max \left(1 - K_r |\dot{\psi}_1 - \dot{\psi}_{1,ref}| H(|\dot{\psi}_{1,ref}| - |\dot{\psi}_1|) - K_\beta |\beta_1 - \beta_{1,ref}|, 0 \right)$$
(2)

$$\xi_{1r} = max \left(1 - K_r |\dot{\psi}_1 - \dot{\psi}_{1,ref}| H(|\dot{\psi}_1| - |\dot{\psi}_{1,ref}|) - K_\beta |\beta_1 - \beta_{1,ref}|, 0 \right)$$
(3)

$$\xi_2 = max \big(1 - K_{\gamma} \big| \psi_{12} + \beta_1 - \psi_{12,ref} \big|, 0 \big) \tag{4}$$

where H(x) is the Heaviside step function:

$$H(x) = \begin{cases} 0, \ x \le 0\\ 1, \ x > 0 \end{cases}$$
(5)

and K_{β} , K_r and K_{γ} are positive gains relating to the tractor sideslip, tractor yaw rate and articulation angle respectively. These must be tuned. The control actions resulting from Eq. (2)-(4) can be described as follows. If the tractor unit understeers, the Heaviside step function in Eq. 2 attenuates the slip demand for the tractor front axle to restore its lateral tyre forces. If the tractor unit oversteers, the Heaviside step function in Eq. (3) attenuates the slip demand for the tractor rear axle to restore its lateral tyre forces. If the tractor unit sideslips excessively, Eq. (2) and (3) together attenuate the slip demands for both tractor axles to restore their lateral tyre forces. Finally if the trailer begins to swing out, Eq. (4) attenuates the slip demands for all trailer axles to restore their lateral tyre forces.

It is important to distinguish between two different possible causes of large articulation angle error: trailer swing-out and jack-knife. Trailer swing-out is caused by reduced lateral tyre forces on the trailer, therefore braking on the trailer should be attenuated. By contrast the jack-knife scenario, where the trailer "pushes" the tractor unit around to a large yaw angle, is caused by reduced lateral tyre forces on the tractor rear axle. Attenuating the braking on the trailer wheels would exacerbate the problem in the jack-knife scenario, causing the trailer to further push the tractor unit around.

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In order to reduce the attenuation of trailer braking in the jack-knife scenario, tractor sideslip angle β_1 was included in Eq. (4). When approaching jack-knife both articulation angle and tractor sideslip angle should become large, but with opposite sign. Therefore the effective articulation angle error $|\psi_{12} + \beta_1 - \psi_{12,ref}|$, used in Eq. (4), becomes large during trailer swing-out but remains small during jack-knife.

3. Experimental setup

Test vehicle

The test vehicle consisted of a 4x2 Volvo FH12 tractor unit and the CVDC's actively steered tri-axle semitrailer. The tractor unit's rear axle had dual tyres, while all other axles had single tyres. The active steering system on the semitrailer was mechanically locked in the unsteered position. All electronic stability control and traction control systems were disabled.

Eighteen sealed IBC water tanks, each 1000 litres in capacity, were rigidly mounted to the floor of the semitrailer in nine rows of two. Ten tanks (in five alternating rows) were filled and the rest left empty, bringing the total combination mass to 31.24 tonnes. This was lower than the rated 40 tonne gross vehicle mass for the combination, due to concerns over the structural integrity of the CVDC semitrailer in high speed manoeuvring.

Braking systems

As illustrated in Fig. 3, the CVDC's prototype SC system was installed in parallel to the existing conventional EBS: a Knorr-Bremse EBS 5 on the tractor unit and a Haldex EB+ Gen 1 on the semitrailer.

The conventional EBS was operated by the driver's foot pedal as standard, whereas the SC system was activated electronically by the test engineer from the passenger seat. By fitting 3-way check valves between the SC valves, conventional ABS modulator valves and brake chamber at each wheel station, the higher pressure from either braking system was passed through to the brake chamber. This enabled back-to-back testing of the conventional EBS and SC without any re-plumbing. It also meant that the conventional braking system could be operated by the driver as backup in the event of a CVDC system fault.

The CVDC system's valves at each wheel station were operated by their own local slip control loop, implemented on a Siemens C167 microcontroller. Each local controller received measured inputs of wheel speed and brake chamber pressure from sensors located at the corresponding wheel station (not shown in Fig. 4). A computer installed in the tractor cab, running Matlab xPC Target, acted as the global controller for the CVDC system and communicated with the local controllers via CANbus. From the global controller, the local controllers receive either a vehicle speed and demand wheel slip signal (if operating in "slip control" mode) or a demand brake chamber pressure signal (if operating in "pressure control" mode).

Other instrumentation

Figure 4 shows schematically the rest of the instrumentation installed on the vehicle. In order to obtain repeatable results, the tractor unit was fitted with an Anthony Best Dynamics SR30 steering robot. The robot is capable of performing closed-loop path-following control along a pre-programmed or recorded path. Data from the steering robot were logged using a laptop in the tractor cab.

To perform path-following control, the steering robot received inputs from an Oxford Technical Solutions RT3022 inertial navigation system. The RT3022 consists of a six axis

inertial sensor block (three accelerometers and three gyros) and a Global Navigation Satellite System (GNSS) receiver. When linked to a local GNSS base station for differential operation, the RT3022 can provide real-time position information accurate to 0.02 m. The inertial sensor block of the RT3022 was mounted as close as possible to the CoG of the tractor unit. Its software was then set to displace the output to the exact vehicle centre-line and longitudinal CoG location. The CoG location was determined from static axle weights measured prior to the experiments.

It is necessary for the inertial sensor block and GNSS receiver to be mounted to the same rigid body and for the GNSS receiver to have clear view of the sky. This is difficult to achieve on the tractor-semitrailer, since the receiver must be positioned higher than the tops of both vehicle units. The inertial sensor block cannot be attached to the cab, since this will roll significantly relative to the tractor frame and cause inaccurate or oscillatory path following. It must therefore be attached to the tractor frame, as must the receiver so as not to violate the rigid body requirement. To enable the receiver to still have clear view of to the sky, a rigid aluminium pylon was constructed and mounted to the tractor frame just behind the cab and the GNSS antenna was mounted on top.

A string potentiometer was fitted between a rigid mounting on the tractor body and the steering drop arm. The signal was calibrated to measure road-wheel steering angle. A calibrated articulation angle sensor, manufactured by VSE, was fitted to the trailer.

Data from the steering and articulation angle sensors were digitised using a PEAK System "PCAN-Micromod Analog 2" and ICON industrial computer [17] respectively. These signals, plus data from the RT3022 and wheel speeds and chamber pressures from the braking systems, were sent via CANbus and logged at 100 Hz by the xPC Target computer used as the global controller for the CVDC braking system. These data were later synchronised with the steering robot data (logged separately on a laptop) using the shared GNSS time signal from the RT3022.

Test manoeuvres

The test manoeuvre discussed here involved emergency braking in a constant radius corner on a surface consisting of wet basalt tile ($\mu = 0.12$ to 0.15) at the HORIBA-MIRA test facility in Warwickshire, UK. The steering robot was programmed to ensure that the tractor unit followed a precise pre-recorded path into and around the corner.

A monitor in the cab displayed a countdown, using live position information from the RT3022, to inform the human driver or test engineer when to brake. This ensured a relatively consistent braking point. The human driver manually controlled the speed of the vehicle during the manoeuvre approach, before shifting the gearbox into neutral just before the brakes were applied. In the conventional EBS tests, the human driver applied maximum pressure to the brake pedal until the vehicle came to complete rest. In the CVDC slip control tests, both with and without ASD, the test engineer in the passenger seat sent an electronic brake pressure demand signal for an emergency stop from a laptop to the global xPC controller, and released the brakes only once the vehicle came to a complete stop.

4. Controller implementation

ASD control was included within the global controller of the slip control system, on the xPC Target computer, as an optional feature to be enabled or disabled as required. Figure 5 is a high-level block diagram illustrating the global controller when operating in "slip control" mode.

The global controller was responsible for setting the CVDC system's nominal wheel slip demands to the "optimal" slips with regard to maximising braking forces. These were determined using separate straight-line braking tests on the same surface to identify the tyre force characteristics [14, 15].

Controller inputs

The RT3022 provided measurements of forward vehicle speed (required by the global controller to set the nominal slip demands, by the local controllers to calculate wheel slip and as an input to the ASD reference model) and tractor unit sideslip angle and yaw rate (required as inputs to ASD control). Vehicle speed estimation using inexpensive or standard sensors was considered by Kienhöfer [18] and in [19-24], while sideslip estimation for articulated HGVs under low friction or high longitudinal wheel slip conditions was considered by Morrison and Cebon [25]. Yaw rate sensors can be considered standard on HGV tractors. The articulation angle input to the ASD controller was provided by the calibrated VSE sensor, while the string potentiometer provided the steering angle input to the reference model.

Tuning

Due to the tight schedule of the testing programme, only a single tuning point for the ASD controller was investigated. This was the same tuning point which found to work well across a wide range of simulated operating scenarios in the authors' previous paper [14]: $K_{\beta} = 23.5$, $K_r = 34.6$, $K_{\gamma} = 30.8$. A lower limit of 0.2 was placed on the trailer slip attenuation factor, to prevent excessive controller intervention on the extremely low friction test surface.

5. Main experiments

Figure 6 compares results for one run using each of the three braking strategies: conventional EBS (ABS), CVDC slip control without ASD (SC) and CVDC slip control with ASD (ASD). Table 1 compares key results averaged over these runs and a second repeat run with each system. All of the results in Fig. 6 and Table 1 were obtained during the same track session, with the steering robot following the same reference path.

Comparing the results for SC and ABS, the substantial improvement in deceleration (21.8%) and stopping distance (18.2%) with SC is evident, but this came at the cost of degraded lateral performance. A 36.9% increase in RMS road wheel steering angle and 19.6% increase in path-following error at the tractor front axle highlight a severe understeering tendency, which would dangerously inhibit lane-keeping ability. The only benefit in this case was a 13% reduction in maximum articulation angle, perhaps suggesting a lower risk of jack-knife, but this was merely a result of the tractor unit's inability to generate any significant yawing motion.

When ASD control was added, the improvement in directional dynamics was substantial compared to both ABS and SC. The yaw rate response in Fig. 6(d) is noticeably faster and better tracks the reference value, while the maximum sideslip angle of the tractor unit is reduced in Fig. 6(c). Maximum articulation angle was reduced by an average 49.2% compared to ABS and in Fig. 6(e) it is seen to reach a steady value almost exactly equal to the "geometric reference" plotted, which represents the low speed steady-state cornering of the vehicle in a manoeuvre of the same radius. RMS steering angle was reduced by 71.8% on average compared to ABS and path-following error at the tractor front axle was almost completely eliminated with an average 80.4% reduction. This impressive improvement in lateral dynamics did come at the expense of stopping performance, at least relative to SC, however modest 6.7% and 2.8% improvements in mean deceleration and stopping distance

respectively were maintained on average compared to ABS.

Figure 7 shows the measured wheel slips on the tractor front, tractor rear and trailer middle axles and the three slip attenuation factors, for the ASD run plotted in Fig. 6. The nominal and attenuated slip demands are also shown. With the exception of oscillatory behaviour at very low speeds, where slip regulation is known to be difficult [11, 26, 27], the CVDC slip control system was able to accurately track the attenuated slip demands. This was despite high frequency content in the demand signals at times.

The slip attenuation factor on the trailer reached the lower limit of 0.2 for large parts of the manoeuvre. In [15], simulations predicted this would occur only on very low friction surfaces when the slow yaw response encourages a large steering angle to be used, thereby distorting the outputs of the reference model and causing a large transient articulation angle error. The lower limit of 0.2 prevented any further increase in stopping distance due to excessive attenuation of trailer braking. Both tractor front and rear axle slip attenuation factors dropped to zero during brief portions of the test. If limits were also applied to the tractor slip attenuation factors, this would serve to further improve stopping performance with ASD on such low friction surfaces, though this might come with a loss of directional performance. The time-pressured testing schedule did not allow for this to be investigated.

Note that the plotted wheel slips fall to zero near the end of the manoeuvre, because the CVDC system stops logging wheel speeds at vehicle speeds below 2 m/s. Since the system applies full brake pressure below 2 m/s, it can be assumed that the wheels would have been locked at this point.

Table 2 compares results from nominally identical experiments during a second track session, averaged over 3 repeat runs. The quantitative results obtained differed somewhat during this second track session. This is most likely due to a combination of variable friction conditions on the artificially wetted surface and slight differences in the reference path recorded for the steering robot during the second session.

In this second set of tests the stopping performance of ASD was much closer to that of SC. Mean deceleration was 14.4% higher with SC than with ABS and 80% of this advantage was maintained when moving to ASD. Stopping distance with ASD was on average 7.2% shorter than with ABS, compared to 12.7% with SC. The directional performance improvements with ASD were similar to in the previous results. ASD gave an average 57.6% reduction in RMS steering angle, 49.6% reduction in maximum articulation angle and 65.7% reduction in path-following error relative to ABS.

Figure 8 shows screen shots from videos of the constant radius corner experiments, for EBS and ASD. In the topmost images, at the point of braking, the vehicle is clearly on exactly the same trajectory in both cases, highlighting the level of repeatability which was achievable using the steering robot. In the middle images around 2 s later, the ABS vehicle has understeered to the very edge of the test surface, whereas the ASD vehicle still tracks the desired path close to the inside edge of the surface. Finally the bottom images show when the vehicle has come to rest. With ABS the vehicle finishes skewed across the track with a large articulation angle, the trailer having begun to push the tractor around towards jack-knife. With ASD the vehicle lies aligned with the manoeuvre path with a small articulation angle. The modest reduction in stopping distance can also be observed.

6. Conclusions

An instrumented tractor-semitrailer was used to conduct back-to-back tests of conventional

electronic/anti-lock braking (EBS), slip control (SC) braking and SC braking with additional "attenuated slip demand" (ASD) control. During simultaneous emergency braking and cornering manoeuvres, slip control braking was seen to degrade the directional dynamics of the vehicle, hindering the lane-keeping ability of the driver and potentially increasing the risk of jack-knife relative to conventional EBS.

When combined with the ASD controller however, there was an improvement relative to conventional EBS with respect to both longitudinal and lateral vehicle performance. Stopping distances remained around 3-7% shorter on average with ASD than with EBS during cornering, with mean deceleration improved by 7-11%. This was accompanied by substantial reductions in steering effort and jack-knife risk, with greatly improved lane-keeping ability: RMS steering angle was reduced by up to 72%, maximum articulation angle was reduced by up to 50% and path-following error was reduced by 56-80%.

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10.Tables and Figures

	ABS	SC (Relative to ABS [%])	ASD (Relative to ABS [%])
Stopping distance [m]	44.13	36.09 ±0.31	42.91 ±0.47
	±0.48	(-18.2)	(-2.76)
Mean deceleration [m/s ²]	1.19 ±0.00	1.45 ±0.01 (+21.8)	1.27 ±0.01 (+6.72)
Max steering angle [deg]	18.32	21.53 ±1.64	7.25 ±0.14
	±2.07	(+17.5)	(-60.4)
RMS steering angle [deg]	8.34 ±1.74	11.42 ±1.16 (+36.9)	2.35 ±0.25 (-71.8)
Max articulation angle	13.30	11.57 ±1.00	6.76 ±0.10
[deg]	±1.45	(-13.0)	(-49.2)
Max path-following error	0.51 ±0.11	0.61 ±0.09	0.10 ±0.01
[m]		(+19.6)	(-80.4)

Table 1 – Comparison of key results for EBS, SC and ASD in the constant radius corner manoeuvre. Averaged over 2 repeat runs during the same track session.

	ABS	SC (Relative to ABS [%])	ASD (Relative to ABS [%])
Stopping distance [m]	41.53	36.24 ±0.19	38.56 ±0.21
	±0.61	(-12.7)	(-7.15)
Mean deceleration [m/s ²]	1.25 ±0.01	1.43 ±0.01 (+14.4)	1.39 ±0.01 (+11.2)
Max steering angle [deg]	13.83	19.05 ±4.10	5.26 ±0.88
	±2.55	(+37.7)	(-62.0)
RMS steering angle [deg]	5.94 ±1.67	10.22 ±2.04 (+72.1)	2.52 ±0.38 (-57.6)
Max articulation angle	10.98	10.45 ±0.81	5.53 ±1.02
[deg]	±3.36	(-4.83)	(-49.6)
Max path-following error	0.35 ±0.11	0.47 ±0.00	0.12 ±0.06
[m]		(+34.3)	(-65.7)

Table 2 – Comparison of key results for EBS, SC and ASD in the constant radius corner manoeuvre. Averaged over 3 repeat runs during the same track session, on a different day to Table 1.



(b)

Figure 1 – Typical tyre force characteristics against longitudinal slip at constant sideslip angle:

- (a) at peak longitudinal force, lateral force is substantially reduced;
- (b) the "attenuated slip demand" concept, where a small reduction in target slip near the peak causes a significant increase in lateral force for only a small change in longitudinal force.



Figure 2 – ASD controller block diagram.



Figure 3 – Installation of braking systems on test vehicle.



Figure 4 – Schematic of instrumentation installed on test vehicle.



Figure 5 – High-level block diagram of CVDC braking system global controller with optional ASD control, as implemented on test vehicle.



Figure 6 – Comparison of constant radius corner test results with EBS, SC and ASD:

- a) forward vehicle speed;
- b) tractor front axle steer angle;
- c) tractor sideslip angle;
- d) tractor yaw rate;
- e) articulation angle;
- f) tractor front axle path-following error.



Figure 7 – Wheel slips on (a) tractor front, (b) tractor rear and (c) trailer middle axles during ASD test from Figure 6, and (d) corresponding slip attenuation factors.



Figure 8 – External video stills comparing EBS (left) and ASD (right) in constant radius corner test. Top: point of braking. Middle: approximately 2 s after braking. Bottom: at rest.