IMPROVED EMERGENCY BRAKING PERFORMANCE FOR HGVS

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Abstract

Previous studies by the Cambridge Vehicle Dynamics Consortium (CVDC) have suggested that, by improving the control bandwidth of conventional pneumatic Heavy Goods Vehicle (HGV) brake actuators and using a ‘slip control’ braking strategy, HGV stopping distances could be reduced by up to 30% over existing systems.

This paper presents results from Hardware-in-the-Loop (HiL) simulations and full-scale straight-line braking tests comparing a prototype slip control braking system to a commercially available HGV trailer Anti-lock Braking System (ABS).

The novel braking system is shown to achieve a 14% improvement in stopping distance in preliminary braking tests from 40km/h on low adhesion surfaces with an unladen semi-trailer. Air consumption is also reduced, on average, by 22% using the new system. HiL tests suggest that, with further tuning, the system could achieve reductions in stopping distance of up to 26%.

Keywords: Anti-lock braking systems (ABS), slip control braking, pneumatic braking systems, pneumatic actuators.

1. Motivation

HGVs make up around 3% of the vehicle fleet (UK Department for Transport, 2008, 2011). In the UK, Heavy Goods Vehicles (HGV) were involved in 272 fatal traffic accidents in 2011. This equates to 8.4% of all fatal vehicle accidents, which is considerably higher than statistically expected. In the US, one in nine traffic fatalities were found to involve a HGV in 2008 (National Centre of Statistics and Analysis, 2009). Of these accidents, rear-end collisions were the most common type (21%), followed by rollover (16%) (Jarossi et al, 2008). Even with the recent transition from drum brakes to disk brakes, Dunn and Hoover (2004) showed that stopping distances of HGVs are typically 40% longer than those of passenger cars.

Conventional Anti-Lock-Braking System (ABS) systems use a heuristic control algorithm designed to prevent wheel lock up. Although this system is robust and improves lateral stability significantly, it does not optimally utilize the maximum available braking force or minimise stopping distance.

2. Slip Control Braking

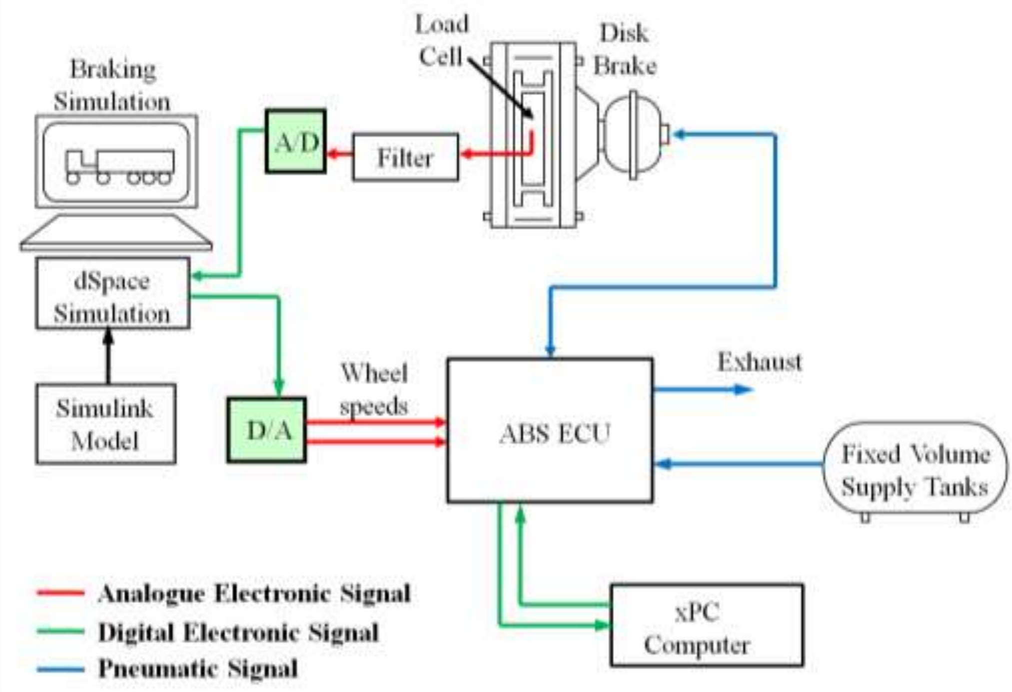
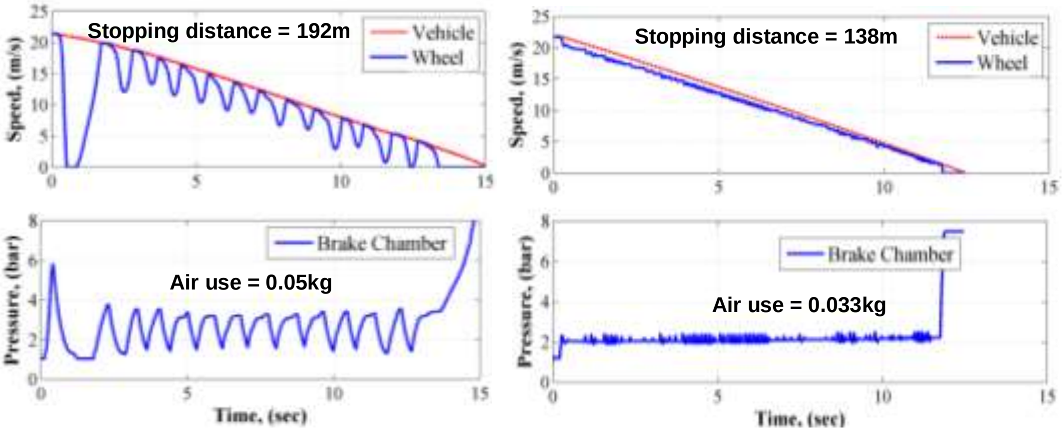


Figure 1 - Hardware-in-the-Loop (HiL) brake test rig

A Hardware-in-the-Loop (HiL) braking rig (shown in Figure 1) was used to measure the braking performance of a conventional ABS Electronic Control Unit (ECU). The test setup shown in Figure 1, as well as the HGV quarter car vehicle model which was implemented in the dSpace computer, were previously presented by Kienhofer (2011). The xPC computer shown in Figure 1 was used to log Controller Area Network (CAN) messages from the ABS ECU.

Sample HiL wheel speed, vehicle speed and brake chamber pressure traces for conventional ABS on smooth icy road are shown in Figure 2a. The system's pressure 'build' and 'dump' phases are obvious.



(a) **(b)**

Figure 2 – HGV quarter car braking simulation results – braking from 80km/h on a smooth, icy road (μ=0.2); (a) Conventional ABS (Hardware-in-the-Loop), (b) Slip control with 3ms ABS modulator valves (pure simulation)

An alternative braking strategy known as 'slip control' is simulated in Figure 2b.

Slip control braking aims to manipulate the brake chamber pressure at each wheel to track a target wheel slip level, where wheel slip (λ) is defined as:

$$\lambda = \frac{v - R\omega}{v}. \tag{1}$$

Here v is the vehicle's longitudinal speed, R is the wheel radius and ω is the wheel's rotational velocity. In Figure 2b brake chamber pressure demand is calculated using a sliding mode slip controller designed by Miller and Cebon (2009). In this controller, a first-order sliding surface (s_s) is defined as:

$$s_s = \lambda - \lambda_{dem}\ , \tag{2}$$

where λ_{dem} is the demand wheel slip selected to correspond to the peak of the tyre-road's adhesion-slip curve, as shown in Figure 3.

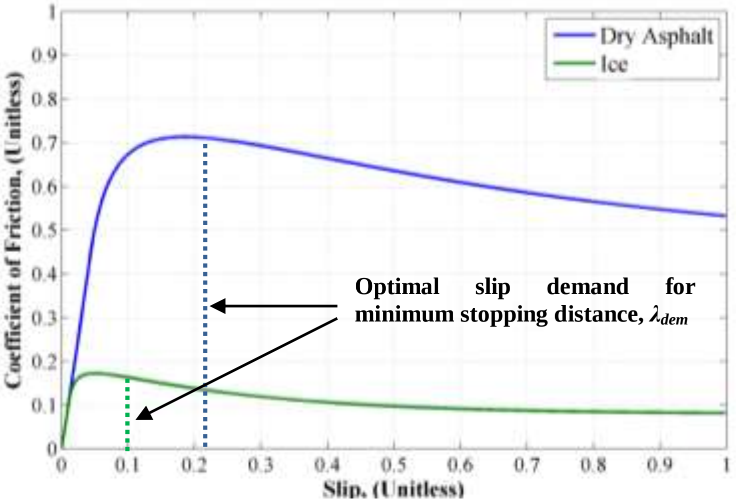


Figure 3 - Adhesion-slip models used in simulation study, 80km/h vehicle speed, as presented by Fancher and Winkler (2007)

Brake pressure demand (P_{dem}) is then calculated as:

$$P_{dem} = \frac{RR_b F_x - (1-\lambda)\dot{v}J}{K_B R} - k_s \left\{ \frac{s_s}{|s_s| + \delta_s} \right\} - \Phi_s s_s . \qquad (3)$$

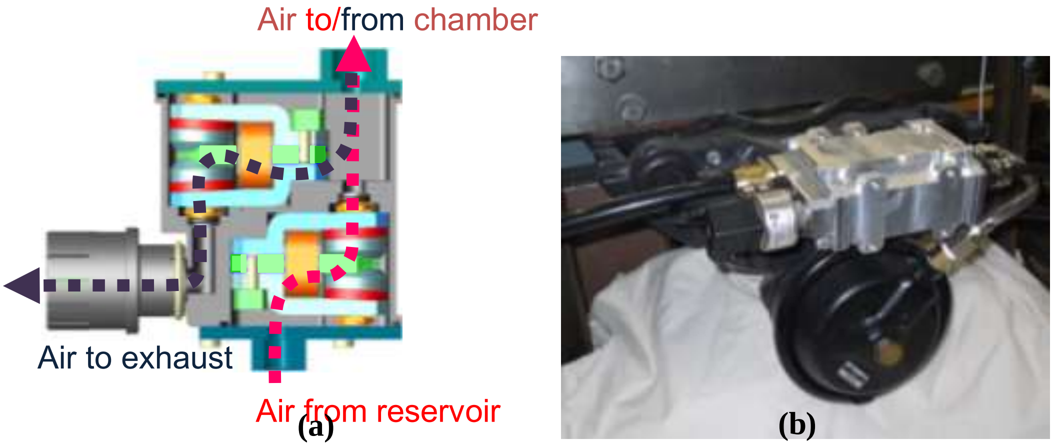
Here R_b is the radius through the brake force (F_x) acts, J is the wheels rotational inertia, K_B is the brake gain (from brake chamber pressure to brake torque), k_s, δ_s and s_s are tunable gains.

As can be seen in Figure 2b, Miller and Cebon's slip control algorithm was predicted to reduce stopping distance and air use by 28% and 34% respectively compared with the conventional ABS, for the low friction case shown.

3. Hardware Development

Commercially available ABS modulator valves consist of a large-orifice pneumatic relay valve, controlled indirectly via a pneumatic signal from a smaller 'pilot' solenoid valve. Kienhofer (2011) showed that the total mechanical and pneumatic delay through these valves (which are located centrally on the vehicle) to the brake chamber can be as large as 40ms. Work by Miller (2010) showed that such valves are too slow to successfully implement slip control on an HGV.

The slip control results shown in Figure 2b assume a pneumatic valve with a pneumatic-mechanical delay of 3ms. Commercially available pneumatic hardware with this switching time does not provide the required flow-rate for a HGV braking system. A design specification was therefore set for a new pneumatic modulator valve which would be able to achieve the performance shown in Figure 2b and could be fitted to a standard HGV. These specifications were: 3ms or less mechanical-pneumatic switching delay, 24V operation and 12.5bar maximum supply pressure. A novel bi-stable valve was developed by CVDC researchers and Haldex Brake Products Ltd to meet these specifications. A CAD model of the current CVDC bi-stable valve manifold is shown in Figure 4a, with a working prototype shown in Figure 4b.



(a) (b)

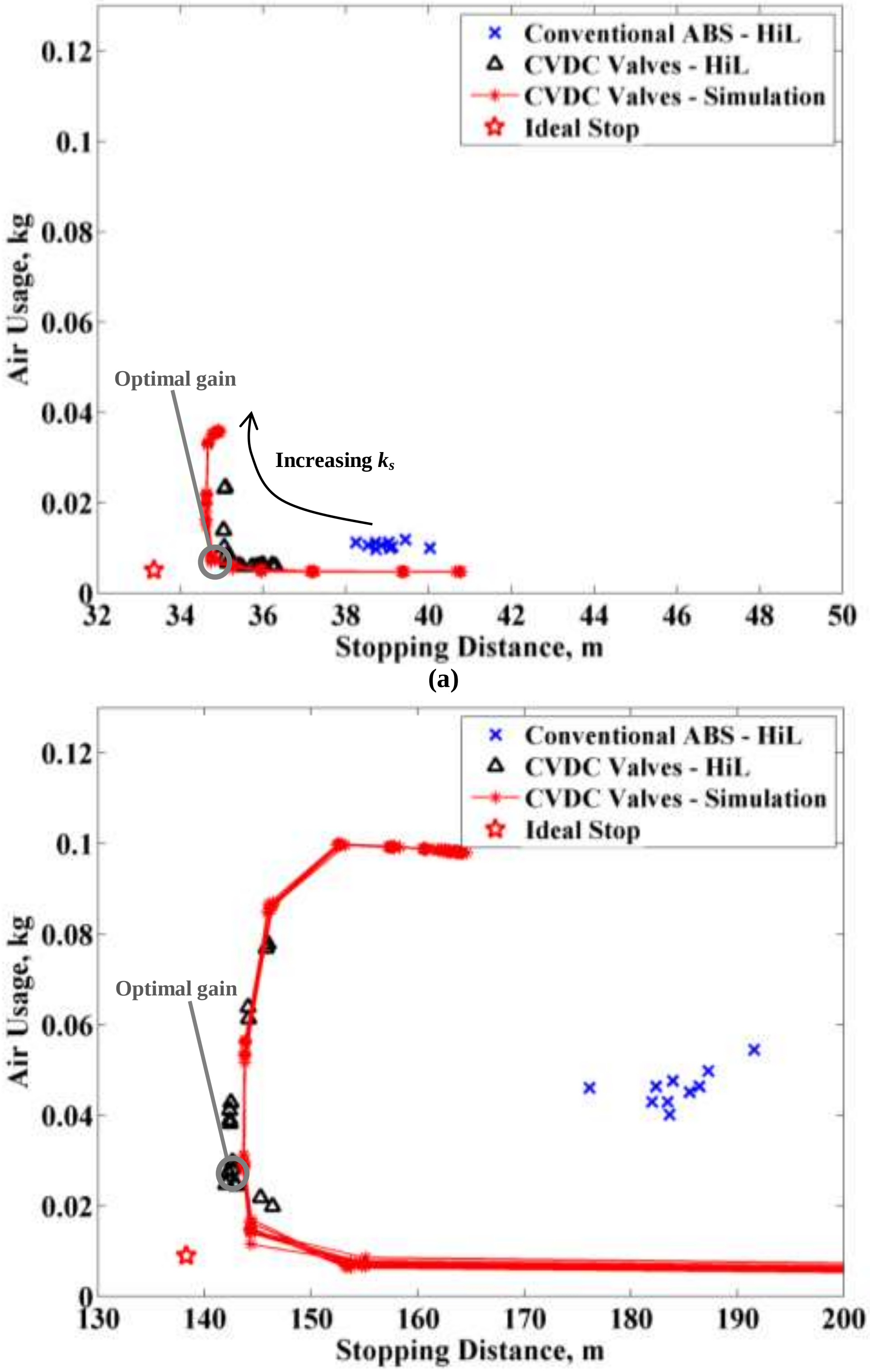
Figure 4 - CVDC valve manifold for individual wheel braking control. CAD model (left), prototype valve block positioned next to brake chamber (right)

Hardware-in-the-Loop (HiL) braking tests were carried out using the prototype valve hardware shown in Figure 4. The layout of the HiL braking test rig was similar to that shown in Figure 1, with the conventional ABS ECU replaced by a ICON control computer (running the main slip control algorithm), prototype valve hardware and analogue drive circuitry.

Comparative tests were carried out with a commercially available trailer ABS ECU using the same test rig. Results obtained for two simulated test surfaces (dry asphalt and ice, previously presented in Figure 3) are summarised in Figure 5. Tests were carried out with a range of slip controller gains (k_s) to tune the controller. Pure simulation results (obtained using the pneumatic valve and chamber model developed by Miller (2010) and HiL results are shown in the figure. As can be seen, the HiL results match those predicted by the simulation well.

The 'optimal' gain for the dry asphalt test case is highlighted in Figure 5a. For this case, the slip control system was shown to reduce stopping distance and air use by 12% and 27% respectively compared to conventional ABS. For the icy road case (shown in Figure 5b), improvements of 25% and 67% were observed.

'Ideal' braking events are also shown in Figure 5. These points represent the braking performance that would be achieved if the theoretically instantaneous maximum available braking force was maintained throughout the stop. As can be seen, the slip control system's performance is close to the ideal values.



(a)

(b)

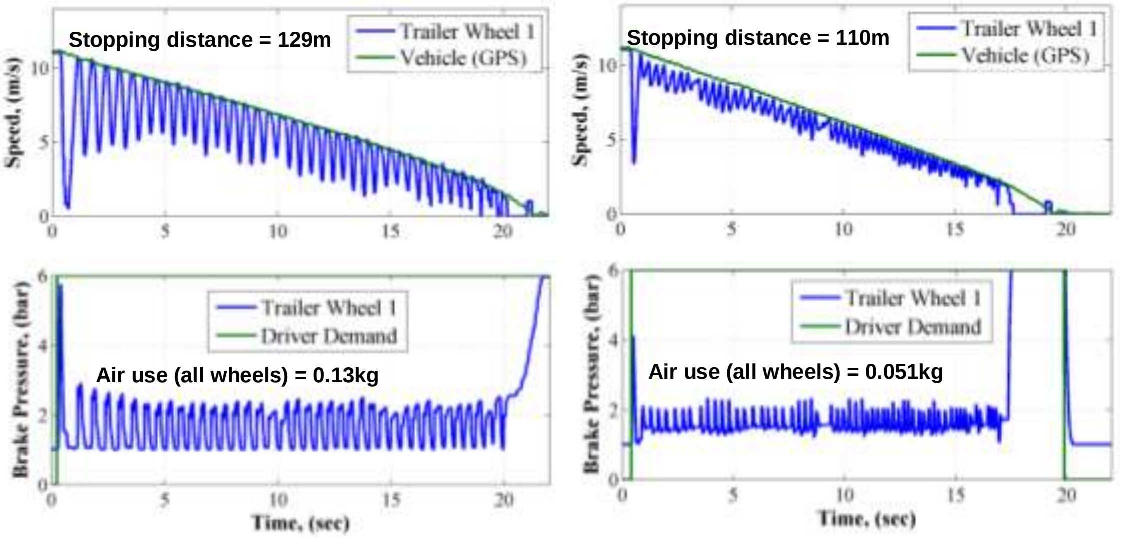
Figure 5 – Hardware-in-the-Loop straight-line braking results for a partially-laden trailer from 80km/h: (a) smooth dry asphalt, (b) smooth ice

4. Vehicle Tests: Straight-line Braking on Low Adhesion Surfaces

Following the success of the HiL study, a tri-axle semitrailer (shown in Figure 6) was fitted with both the CVDC bi-stable modulator valves and a commercially available trailer ABS system, allowing back-to-back braking comparisons to be carried out between the two systems.

Figure 6 - CVDC semi-trailer and tractor combination used for brake system installation (tractor unit supplied by Haldex Brake Products Ltd.)

Straight-line-braking tests were conducted at the MIRA straight-line, wet grip testing facility in Nuneaton, UK. Sample wheel speed and brake pressure traces of the conventional ABS system and the CVDC valve system (with slip control) are shown in Figures 7a and 7b respectively for a braking event on a wet basalt tile surface (similar to ice), with the vehicle in an unladen state. As can be seen, for this test case, stopping distance was reduced from 129m to 110m and air use was reduced from 0.13kg to 0.05kg. These correspond to reductions of 15% and 61% respectively.



(a) (b)

Figure 7 - Straight-line braking test results, wet basalt tile (μ=0.12), braking from 40km/h; (a) Conventional trailer ABS (6M-6S), (b) CVDC bi-stable valves with slip control

The probability density function of wheel slip (λ), averaged over all six trailer wheels during the braking event on basalt tiles (i.e. the braking event shown in Figure 7) is presented in Figure 8. The area under a portion of this graph indicates the probability of wheel slip occurring in that range, where λ = 0 corresponds to pure rolling and λ = 1 corresponds to complete wheel lock. The region of wheel slip providing maximum braking force for this test surface is highlighted in Figure 8. As can be seen, the CVDC slip control system spends significantly more time in this region than conventional ABS. ABS also spends a lot of time near λ = 0 where no braking force is produced.

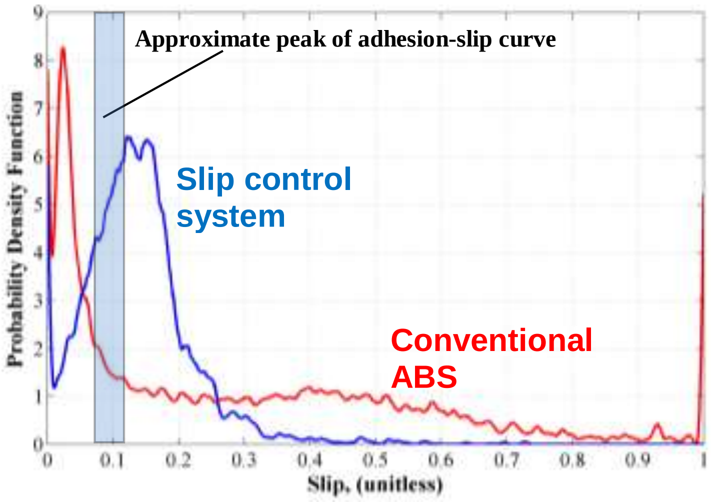


Figure 8 - Probability density functions of wheel slip during braking event (all trailer wheels) - straight-line braking on wet basalt tile (μ=0.12), from 40km/h

Repeated tests were carried out from 40km/h on three surfaces: wet basalt tile (μ=0.12), wet pebble (μ=0.39) and wet asphalt (μ=0.7). All tests were carried out with the trailer in an unladen state, and the tractor unit brakes disabled. Results for all three surfaces are summarised in Table 1.

On average the CVDC system reduced stopping distance and air use by 14% and 22% respectively compared to conventional ABS

Table 1 - Straight-line braking test performance summary, from 40km/h (11.11m/s)

Test Surface	**Metric**	**Conventional ABS**	**High-Speed Valves, Slip Control**	**Average percent change**
Wet Asphalt (μ_{peak}=0.58)	Number of tests	4	4	
	Stopping distance (m)	28.9±0.4*	25.7±0.3	-11%
	Air use (kg)	0.049±0.002	0.04±0.01	-18%
Wet Bridport Pebble (μ_{peak}=0.28)	Number of tests	8	6	
	Stopping distance (m)	54±2	46±1	-15%
	Air use (kg)	0.073±0.006	0.049±0.007	-33%
Wet Basalt Tile (μ_{peak}=0.12)	Number of tests	10	8	
	Stopping distance (m)	129±2	109±6	-16%
	Air use (kg)	0.133±0.004	0.046±0.007	-65%

*Results are in the format: mean±one standard deviation

As can be seen in Table 1, the most significant improvements were observed on the wet basalt tile surface. This surface is similar to the icy surface simulated during HiL testing. The reduction in air use seen for these tests (65%) is very close to that predicted in HiL tests (67%). The improvement in stopping distance was, however, slightly less than expected (16% in vehicle tests vs 25% in HiL tests). This difference can be attributed to several factors, these include: lower initial vehicle speed in vehicle tests, lighter wheel loads in vehicle tests and imperfect knowledge of the road adhesion properties. These issues will be addressed as part of a follow on project, discussed briefly in Future Work.

5. Conclusions

(i) A novel pneumatic ABS modulator valve has been designed and built, suitable for use on a HGV.

(ii) HiL braking tests have shown that a sliding mode slip controller, coupled with fast acting ABS modulator valves could reduce the stopping distance and air use of an

HGV by up to 26% and 67% respectively.

(iii) Vehicle tests using an unldaen tri-axle semitrailer fitted with fast acting modulator valves have been carried out, achieving average reductions in stopping distance and air use of 14% and 22% respectively compared to a commercially available trailer EBS ABS system.

6. Future Work

Work has now commenced to fit a 4x2 tractor unit with the CVDC slip control system. Further straight-line braking tests will be carried out in late 2014 using this tractor unit and the semitrailer already fitted with the braking system. Along with emergency braking tests, normal driving/braking performance will also assessed to see if any reductions in air consumption and storage capacity can be achieved in everyday driving. The test vehicle will later be used to implement a combined braking and steering stability control system currently being developed by Morrison (2013). Performance of this system will be assessed using emergency lane change manoeuvres.

7. References

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