BRAKE SYSTEM DESIGN FOR FUTURE HEAVY GOODS VEHICLES

Dr Leon Henderson
Postdoctoral Researcher,
Chalmers University of
Technology, Sweden
leon.henderson@chalmers.se

Prof. David Cebon
University of
Cambridge, UK
dc@eng.cam.ac.uk

Adj. Prof. Leo Laine
Senior Technology
Specialist L2 –CVC,
Volvo Global Trucks
Technology
leo.laine@volvo.com

Abstract

A fast-acting pneumatic braking system developed by Cambridge University and Haldex AB has been shown to reduce the stopping distance of a tractor-semitrailer combination by 17% on a low friction surface, compared to existing heavy vehicle brake systems. The high control bandwidth of the new braking system allows brake torque to be accurately controlled, independently, at each wheel station. This functionality complements a new control allocation based motion management system, which aims to optimally control individual wheel brake torques in combination with other actuator demands on the vehicle (e.g. steering, engine, diff-locks, etc.). In order to fully integrate the braking system with an optimal motion management system, brake torque capability information (including available friction) will need to be communicated from each wheel station to the motion management controller. This information is also essential for highly automated vehicles, which (as stated in SAE standard J3106) must be able to identify changes in operating environment.

Keywords: Anti-lock braking system, EBS, ABS, slip control braking, pneumatic braking systems, pneumatic actuators, brake system design, automated braking

1. Introduction

The Cambridge Vehicle Dynamics Consortium (CVDC) and Haldex Brake Products Ltd recently designed, built and demonstrated a prototype high-performance pneumatic braking system for HGVs which achieved a 17% reduction in stopping distance when compared to a modern trailer based electronic braking system (EBS), on a low friction surface (Henderson & Cebon, 2016). This straight-line-braking performance is near to the theoretical limit achievable for a truck tyre. Results from these tests were also presented at HVTT13 (Henderson & Cebon, 2014).

The CVDC slip-control system uses fast-acting bi-stable pneumatic modulator valves to accurately track a target longitudinal slip (λ_{dem}) during a braking event. The longitudinal slip λ is defined as follows:

$$\lambda = \frac{v - R\omega}{v} \qquad (1)$$

where v is the longitudinal vehicle speed, R is the rolling radius of the tyre, ω is the rotational speed of the wheel and λ_{dem} is near the peak of the braking force-slip curve. During braking λ varies between two extremes: $\lambda = 0$, corresponding to pure-rolling of the wheel; and $\lambda = 1$ where the wheel is completely locked.

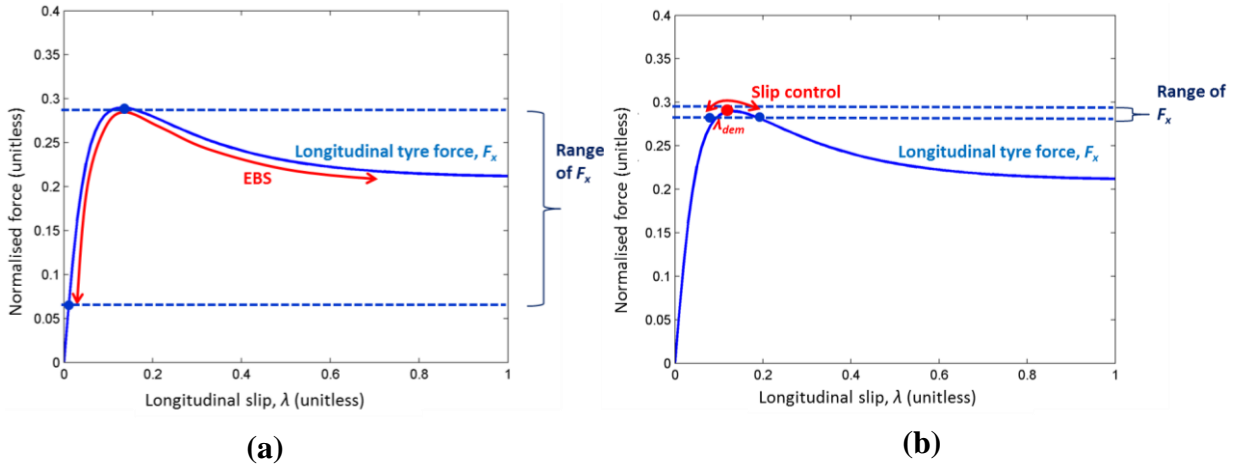**(a)**   **(b)**

Figure 1: Longitudinal tyre curves for a wet road, showing: a.) range of operation for modern EBS system, b.) fast-acting slip control range of operation

Figure 1 highlights the main motivation for improving the longitudinal slip tracking of a conventional EBS.

In the left figure, the typical range of operation of a conventional EBS is shown. The right figure shows the same plot, this time for a fast-acting slip control system; the average longitudinal braking force at the contact patch (F_x) is clearly improved, therefore, improving the achievable braking rate of the vehicle. Previous research has shown that the level of slip-tracking performance shown in Figure 1.b an only be achieved when: the brake system delay (from brake demand signal to a change in brake torque at the wheel) is reduced to around 5ms; the heuristic anti-lock braking (ABS) control cycle (still employed by most EBSs) is

replaced by a nonlinear slip-control algorithm (Miller & Cebon, 2013). The 5ms switching time is achievable by the CVDC's bi-stable valve prototypes, which can change state in between 3 and 4ms, and have recently been shown to exhibit a delay (from initial brake demand to pressure change at the brake chamber) of 6-7ms; this is comparable to delays achieved by a fully electromechanical brake actuator (Ho, Roberts, Hartmann, & Gombert, 2006). Modern HGV EBS control valves exhibit delays of between 20 and 40ms.

In addition to straight-line braking performance, accurate longitudinal slip control can allow the resultant tyre force (longitudinal and lateral combined) at each wheel to be accurately controlled, even in low friction conditions – this improved controllability has applications in a range of driving scenarios. Combined brake-in-turn applications will be discussed in more detail in the related HVTT14 research paper 'Control of combined emergency braking and turning for articulated vehicles', presented by Prof Cebon.

Following on from the work presented by Henderson and Cebon at HVTT13 (which focussed on a prototype trailer braking system) the CVDC and Haldex Brake Products Ltd have now implemented the new braking system on a 4x2 Volvo FH12 tractor unit.

This paper briefly presents how the CVDC system has been developed to meet the redundancy requirements specified in European braking legislation. Straight-line braking performance results are also presented for a tractor-semitrailer combination which includes the newly CVDC-equipped Volvo FH12 and the tri-axle semitrailer which featured in (Henderson & Cebon, 2016). This braking performance is compared to the existing EBS fitted to Volvo tractor units. The final part of the paper discusses some of the challenges to be overcome by heavy vehicles in the not-so-distant future; in particular, the integration of the braking system with a vehicle-wide motion management system is discussed. The brake system requirements relating to fully autonomous vehicles are also considered.

2. Brake system design incorporating CVDC bi-stable valves

The first generation CVDC braking system, which was installed on a semitrailer in (Henderson & Cebon, 2016), required a conventional braking system to be fitted in parallel to the prototype system in order to achieve redundancy in the event of an electrical failure. This is because, unlike conventional solenoid valves, the CVDC bi-stable valves do not include a defined 'powered-down' state.

The CVDC modulator valve contains two individual CVDC bi-stable valves, an inlet and an outlet, as shown in Figure 2a. In this configuration the CVDC modulator has 4 possible failure modes, as presented in Figure 2b.
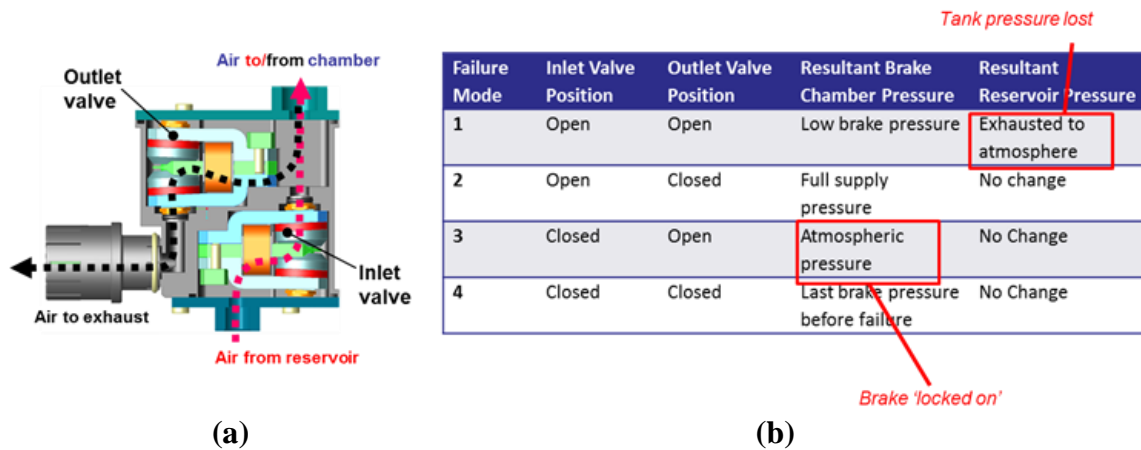
Figure 2: Schematic of a CVDC modulator valve used in a slip-control braking system (a), and its possible failure modes (b).

As highlighted in Figure 2b some of these failure modes are particularly undesirable, e.g. failure to full brakes and exhausting of the air supply to atmosphere. In order to make the failure modes of the CVDC modulator valve more predictable a 'fail-safe' electrical circuit has been developed; this stores a small amount of energy in a capacitor which can be discharged back through the valve coil, in a pre-defined direction, in the event of sudden electrical power loss. Figure 3 shows how the fail-safe circuit can be incorporated into the slip-control loop, which includes local slip controllers (which are based at the wheel stations) and a global braking control electronic control unit (ECU). Figure 3a shows how the main power to each individual CVDC valve is arranged via the fail-safe circuit and two relays. In this arrangement, both the local and global controllers can force the valve into its fail-safe state, even if the main drive circuit has failed. This fail-safe state is also achieved if the main 24V power is cut.

Figure 3b shows how the CVDC braking system can be arranged pneumatically for a single wheel station; here dashed and solid lines correspond to electrical and pneumatic signals respectively. When signals e2 and e4 are powered down, the pneumatic signal p3 from the driver's foot pedal is passed directly to the wheel, therefore providing a full pneumatic back-up (as is still common on most HGVs). This schematic assumes the incorporation of the fail-safe circuit shown in Figure 3a, with the 'fail-safe' circuit wired such that, when powered down, the inlet valve is opened and the outlet valve is closed.

In order to meet the secondary braking requirements set out in United Nations Economic Commission for Europe (UNECE) Regulation 13 (UNECE, 2008), two independent pneumatic circuits (each with its own air reservoir and pneumatic connection to the foot valve) would need to be used when extending the single wheel station layout shown in Figure 3b to the full vehicle system. The individual wheel stations would be divided such that half of the wheel stations are fed by one circuit and half from the other. Once again, this is already common in commercially available EBSs today.

The system layout presented in Figure 3b, and discussed above, is well suited to HGVs on the road today, as it does not require any significant changes from the EBS system layouts already available. If, however, future HGVs are going to include fully autonomous driving

functionalities and still meet redundancy requirements, more drastic changes from the conventional layout will need to be made – this will be discussed later in the paper.
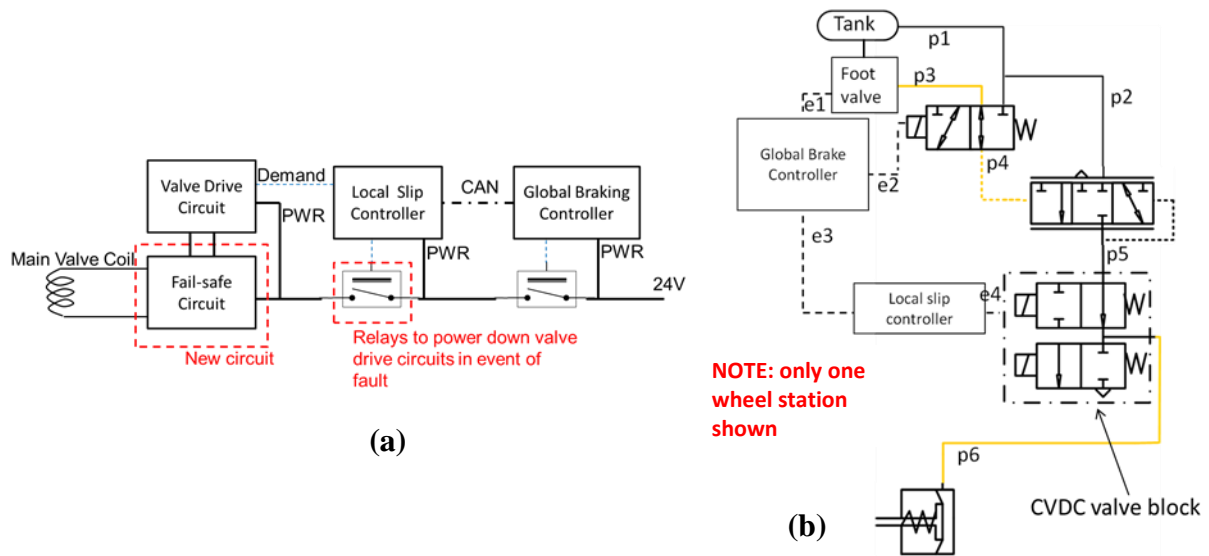

(a)

(b)

Figure 3: Proposed truck brake system configuration, using CVDC bi-stable modulator valves, that meets redundancy requirements in European braking legislation: electrical power supply configuration (a), and pneumatic and communications layout (b).

3. Tractor-semitrailer braking comparison: CVDC slip-control vs EBS

CVDC modulator valves were installed on a disk-braked Volvo FH12 tractor unit, as shown in Figure 4.
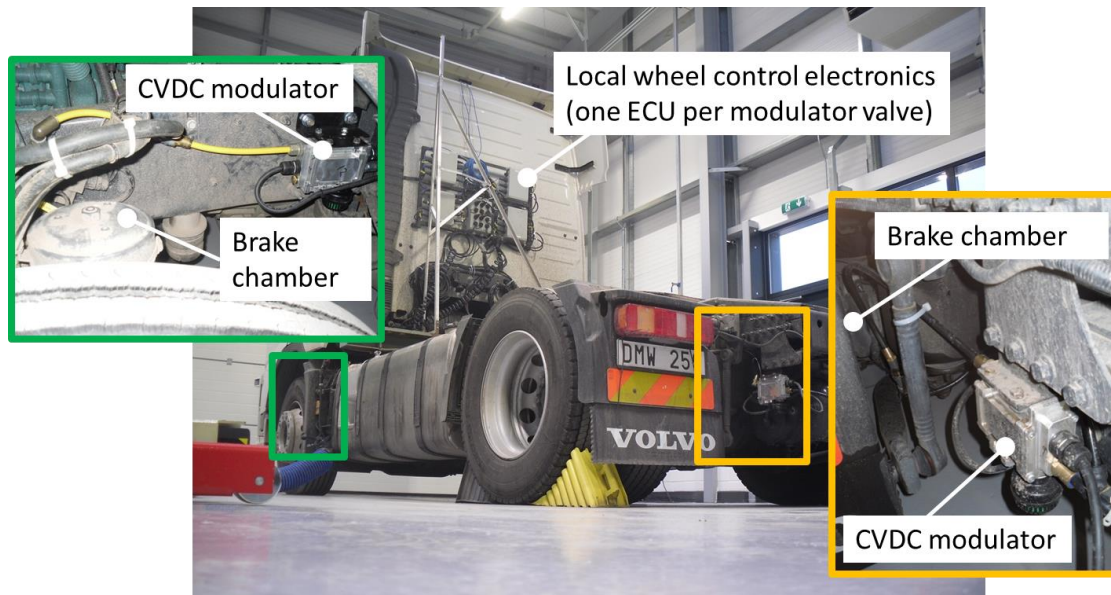

Figure 4: CVDC modulator valves installed on Volvo FH12 tractor unit

One modulator was installed per wheel station, and was placed as close as possible to the brake chamber, minimising pneumatic delays associated with long pipe lengths. As can be seen in Figure 4, the electronics associated with each wheel station was separated from the valve block (mounted on the back of the vehicle's cab). It is envisaged that, in a future version of the CVDC system, the modulator valve and slip control electronics will be incorporated into a single unit.

A control flow diagram, showing the main tasks carried by each of the local wheel controllers, is presented in Figure 5.
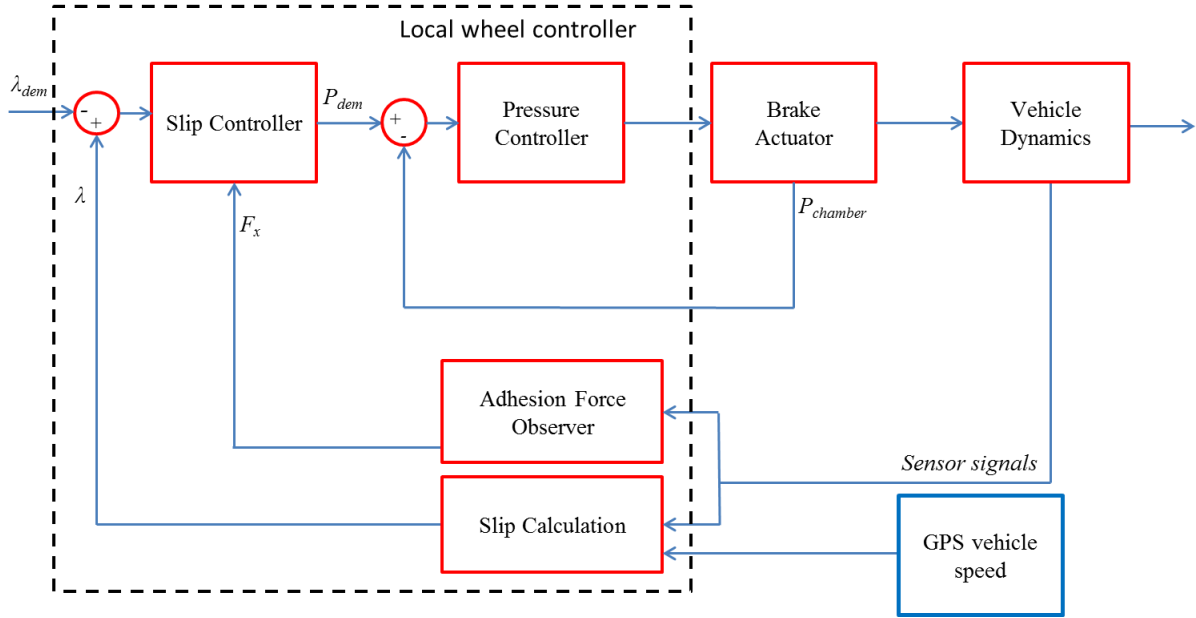

Figure 5: Slip control flow diagram, as implemented on tractor-semitrailer test vehicle combination ($P_{chamber}$ = brake chamber pressure, P_{dem} = brake pressure demand)

In this configuration each wheel receives a slip demand (λ_{dem}) as well as a measurement of the longitudinal vehicle speed of the vehicle (required for calculating slip values) from a global braking controller (a PC running MATLAB's real-time environment, xPC Target). The local wheel controller includes a real-time adhesion force observer; this was not included in the system presented at HVTT13 and represents a significant development. The observer is similar in design to that presented by Miller and Cebon in HVTT11 (Miller & Cebon, 2010); which had previously been successfully implemented in simulation, and offline on vehicle test data. The revised observer used in the vehicle tests presented in this paper monitors the acceleration of the wheel, along with the pneumatic brake pressure, and uses this information to estimate the instantaneous longitudinal braking force developed between the tyre and the road (F_x); therefore allowing the slip control system to adapt to different tyre-road conditions. Unlike Miller and Cebon's previous version, longitudinal acceleration is not used in the adhesion force calculations.

The tractor unit shown in Figure 6 was coupled to the tri-axle semitrailer which was fitted with the CVDC brake system in previous work (Henderson & Cebon, 2016). Straight-line braking tests were then carried out from 60km/h on a wet-basalt tile surface (μ_{max}=0.12). The

test results presented below were for a semi-laden case, with the following static axle loads: tractor front = 6.1 tonne; tractor drive 9.8 tonne; trailer axles (individual average) = 5.1 tonne; total combination = 31 tonne.

Sample wheel speed, longitudinal slip and brake pressure measurements for one wheel on the tractor front (steer) axle are shown in Figure 6. Results are included for both conventional EBS and the CVDC system (tests were carried out on the same test vehicle). The longitudinal slip values corresponding to the approximate peak of the Fx-slip tyre curve are super-imposed on the central figures. As can be seen in the results, the CVDC system closely tracks this slip value, using only small changes in brake pressure (as opposed to the large 'build' and 'exhaust' cycles obvious in the conventional EBS results).
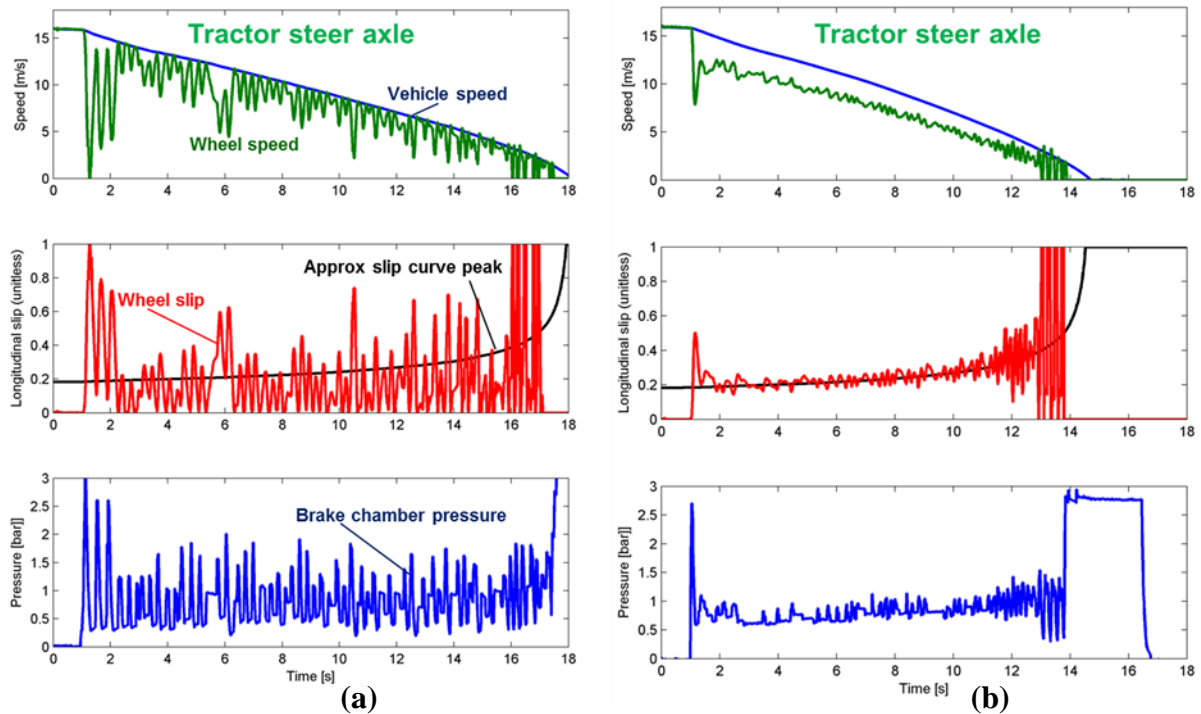

Figure 6: Straight-line braking results on wet basalt-tile surface (HORIBA MIRA, Nuneaton, UK), tractor-semitrailer equipped with EBS vs CVDC slip-control braking system: sample wheel speed, longitudinal wheel slip and brake pressure of tractor steer axle shown for (a) conventional EBS (which uses an ABS control algorithm) and (b) the CVDC slip control system.

Figure 7 shows sample wheel traces from each of the axle groups on the test vehicle. The CVDC system can be seen to significantly reduce the oscillations in wheel speed on all axles compared to conventional EBS.

(a)   **(b)**
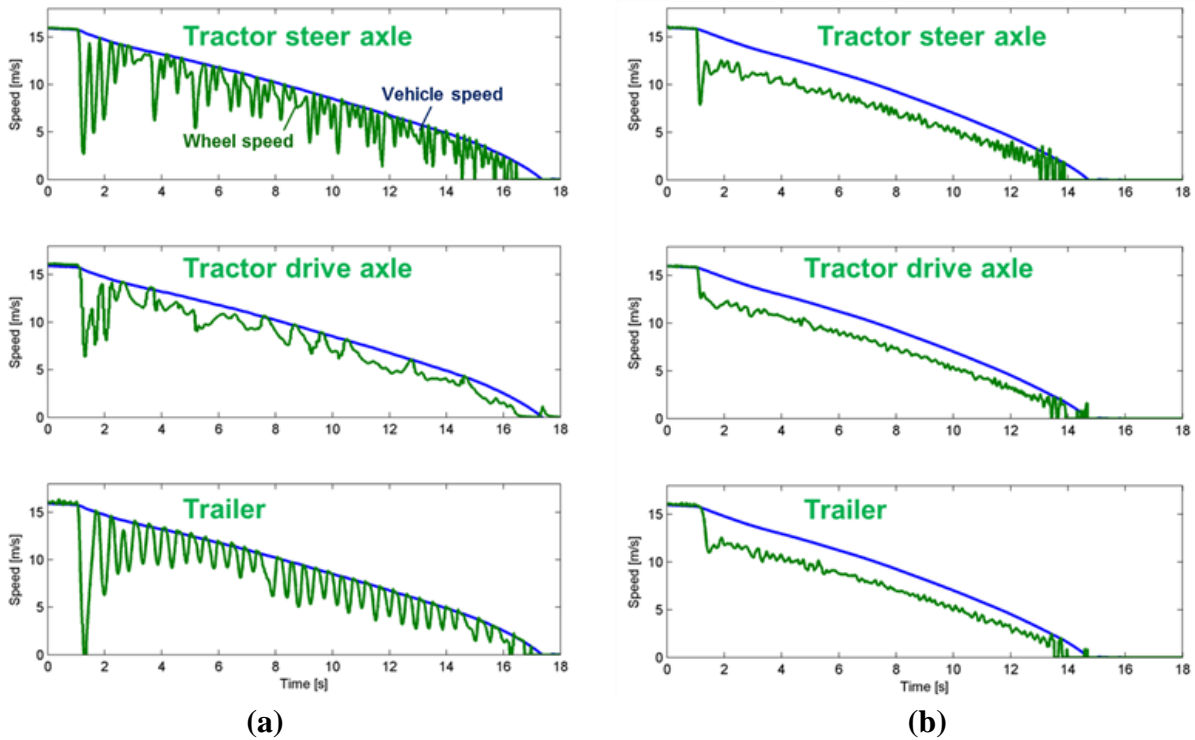
Figure 7: Straight-line braking results on wet basalt-tile surface (HORIBA MIRA, Nuneaton, UK), tractor-semitrailer equipped with EBS vs CVDC slip-control braking system: wheel speeds of different vehicle units shown for (a) conventional EBS (which uses an ABS control algorithm) and (b) the CVDC slip control system.

On average the CVDC system was shown to reduce the stopping distance of the test vehicle by 17% in the test case presented above, compared to the conventional EBS system fitted to the vehicle. The mean-fully-developed-deceleration achieved during the braking event (an important braking metric used to calculate adhesion utilisation in UNECE Regulation 13) was, on average, improved by 25% when the CVDC system was used.

Similar straight-line-braking tests were also carried out with the tractor unit alone (trailer decoupled), in both unladen and laden conditions (laden conditions achieved using a load frame fixed to the fifth wheel of the tractor); stopping distance was reduced by 15% in both of these cases.

4. Future heavy vehicle braking technology

The improved controllability of individual wheel torques and longitudinal slip demonstrated by the CVDC system can be seen as an enabling technology for advanced 'full vehicle control' systems, where optimized co-ordination of all motion support devices on a vehicle is carried out by a single global vehicle motion management (VMM) controller, in response to a driver demand; the 'motion support devices' mentioned here could include: brakes (wheel end-brake service brakes, retarders, regenerative braking systems, parking brake), steering, engine, transmission, active-differentials, electric propulsion, etc.

Figure 8 shows how the service brake system could be integrated into a full-vehicle control solution similar to that presented by Laine (Laine, 2007). In this control architecture a central Vehicle Motion Management controller communicates directly with all available motion support devices on the vehicle. Each device (including each individual wheel brake) broadcasts its instantaneous capability to the VMM, which uses this information in optimised control allocation calculations. The VMM then transmits individual 'requests' to each actuator. In the arrangement shown, each local brake controller communicates directly with the VMM. This differs from conventional EBSs which typically include a central global braking controller. Removing this additional controller enables the VMM to directly control each wheel's brake torque and reduces communication delays between the brakes and the VMM.
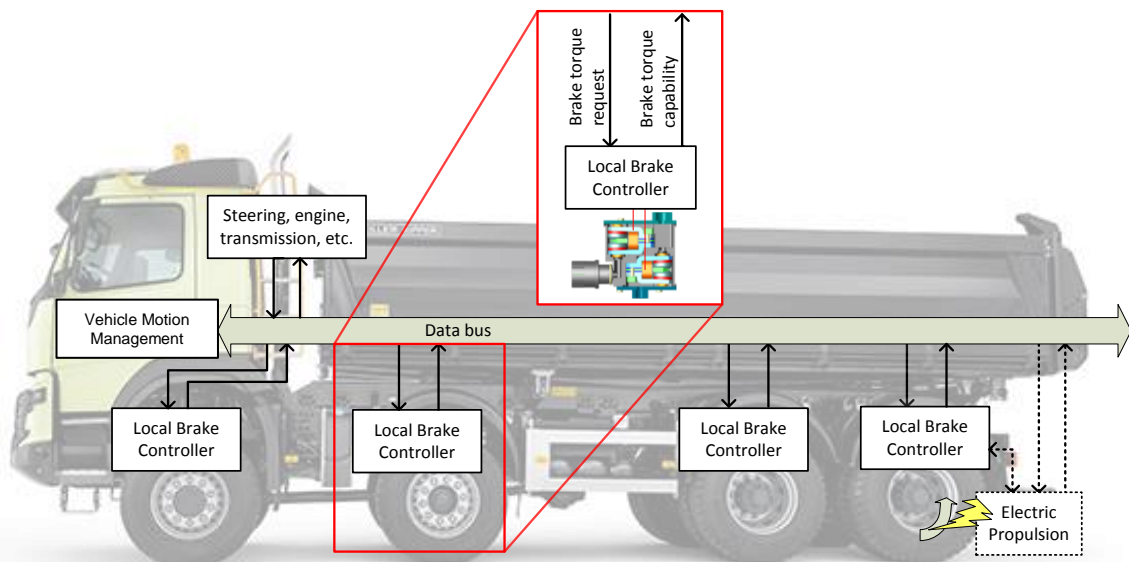

Figure 8: Full-vehicle control architecture for a future HGV, incorporating modular brake system

Accurate knowledge of each wheel's braking capability must be available to the VMM if the system architecture presented above is to perform well in all conditions. This capability should take into account: tyre-road conditions (friction level), physical brake hardware limits, and thermal effects (brake fade). Such information is not made available by existing braking systems and represents a significant hurdle to implementation of control allocation based motion management systems. The real-time Fx estimate calculated by each wheel in the CVDC brake system (discussed earlier in this paper) could potentially be used to calculate the capability information related to the tyre-road friction conditions. On-going work between Haldex, Cambridge University and Chalmers University of Technology will investigate whether this Fx estimate can be used to accurately calculate the road friction level and associated brake torque capability on a test vehicle.

The brake capability described above also has direct relevance to semi-autonomous and fully-autonomous driving applications. Figure 9 shows the requirements set out by the Society of

Automotive Engineers (SAE) for different levels of automated vehicle control (SAE, 2014), where SAE automation level 5 corresponds to 'full automation'.

SAE level	Name	Narrative Definition	Execution of Steering and Acceleration/ Deceleration	Monitoring of Driving Environment	Fallback Performance of Dynamic Driving Task	System Capability (Driving Modes)
Human driver monitors the driving environment						
0	No Automation	the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
1	Driver Assistance	the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes
2	Partial Automation	the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/ deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	**System**	Human driver	Human driver	Some driving modes
Automated driving system ("system") monitors the driving environment						
3	Conditional Automation	the *driving mode*-specific performance by an *automated driving system* of all aspects of the dynamic driving task with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	**System**	Human driver	Some driving modes
4	High Automation	the *driving mode*-specific performance by an automated driving system of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene*	System	System	**System**	Some driving modes
5	Full Automation	the full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	System	**All driving modes**

Figure 9: Levels of automation for on-road vehicles, as specified by the SAE J3016 international standard (SAE, 2014)

As is shown in Figure 9, in order to reach level 5 the following must be achieved: "full-time performance by an automated driving system of all aspects of the dynamic driving task under all roadway and environmental conditions that can be managed by a human driver" (SAE, 2014). This cannot be realized without up-to-date, accurate knowledge of the tyre-road characteristics, in all driving modes.

Another aspect of brake system design that needs to be addressed in relation to automated driving is redundancy. For SAE levels 4 and 5 (listed in Figure 9), the vehicle control system can no longer rely on a human driver to intervene in the event of a system fault, even if the fault has been correctly detected and identified. This makes EBSs that include a pure pneumatic back-up, which can only be actuated by a human driver (e.g. the system presented in Figure 3b), unsuitable for fully autonomous vehicles. To the authors' knowledge, no commercial EBS available today could meet this requirement in its present form. Similar issues also need to be addressed in other safety-critical control systems on the vehicle (e.g.

active steering) where (in current implementations) a human is also required to take over control in certain failure-modes. It is difficult to envisage a vehicle control system capable of achieving automation levels 4 and 5 without dual, independent electrical power sources (batteries) and communication networks.

From the brake system design point of view, the distributed layout of the local brake controllers in the CVDC system (presented in Figures 5 and 8) can provide additional redundancy in the event of electrical power loss in the Vehicle Motion Management system and/or a communication fault, by retaining some localised intelligence in the brake system. In addition to this, the capability information which is communicated by each individual wheel brake controller (Figure 8) could be used to alert the VMM of faults at individual wheels (communicated as zero brake torque capability at the affected wheels); control could then be re-allocated to account for this reduced capability. Capability information could also be used to warn the VMM of possible future faults (e.g. overheating of brake hardware) by specifying a time limit on the current brake torque capability.

The points discussed above represent only a few of the many challenges faced by HGV manufacturers and brake system suppliers in relation to future vehicles. It is hoped that they will encourage further conversation and discussion in this area both during and after the HVTT14 conference.

5. Conclusions

(i) Straight-line braking tests on a semi-laden tractor-semitrailer combination have shown that a fast-acting slip control braking system developed by the Cambridge Vehicle Dynamics Consortium (CVDC) can reduce stopping distance by 17% on a low friction (μ=0.12) surface compared to an existing HGV EBS.

(ii) A brake system layout concept has been developed that would enable the CVDC braking system to meet the redundancy requirements set out in UNECE's brake system legislation (Regulation 13).

(iii) In order for a braking system to be fully integrated into an optimal full-vehicle motion management system (where a single global controller is used to coordinate all of the vehicle motion support devices on the vehicle), the following needs must be met:

   a. The brake system must allow individual brake torque requests to be sent to each wheel on the vehicle.

   b. Real-time brake torque capability for each wheel station must be calculated (taking into account tyre-road conditions) and made available to the vehicle-wide motion management controller.

(iv) An automotive standard recently published by the Society of Automotive Engineers presents requirements for 'fully autonomous' vehicle control systems. The following requirements listed in the standard are directly applicable to the brake system:

   a. The automated driving system must perform a dynamic driving task under all roadway and environmental conditions.

   b. The automated driving system must perform all-aspects of a dynamic driving task even if a human driver does not respond appropriately to a request to

intervene.

Point (a.) above implies that the vehicle must be able to sense the tyre-road adhesion characteristics; point (b.) implies that the system should not rely on a human driver to provide system redundancy - neither of these requirements are met by currently available HGV EBSs.

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