Intelligent, high-performance service brake module for heavy vehicles

Public report

Project within **FFI Road Safety and Automated Vehicles**

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Content

1. Summary

Historically, heavy vehicles exhibit longer stopping distances than passenger cars; this characteristic, along with lateral stability problems due to their size and multiple articulation points, contribute to heavy vehicles' overrepresentation in accident data. Improving the braking efficiency of these vehicles and improving their lateral controllability through better actuator coordination could reduce the likelihood of accident scenarios.

Since the early 2000's, Haldex has been working in collaboration with The University of Cambridge, UK, researching prototypes of pneumatic Fast-Acting Brake Valve (FABV) which, combined with a slip-control braking strategy, has been shown to reduce the stopping distance of modern heavy vehicles significantly. Especially on low friction surfaces. The modular, wheel-end based arrangement of the Haldex system also enables beyond industry standards accurate brake torque control of each wheel. This property is well suited for full-vehicle actuator coordination strategies being developed by Volvo in their vehicle motion management controller.

The project investigated improvements that can be achieved by fully integrating the Haldex system with Volvo's vehicle motion management controller. Expected improvements over conventional electronically controlled pneumatic braking systems (EBS) include: improved emergency braking performance in straight-line and brake-in-turn scenarios; improved electronic stability control (ESC) performance; improved real-time knowledge of road conditions and brake system capability; improved manoeuvrability through the use of actuator coordination.

The execution of this project has created great insights in the industrialisation of the FABV concept. Multiple generations have been designed and tested on rigs and vehicles. Every design step has revealed and confirmed properties required to support safe- and high performing wheel end modules. Issues being addressed; flow rates, speed of operation, system redundancy, separation of characteristics, and so on.

Vehicle integration tests have strengthened the signal interfaces between the central vehicle motion management controller and the wheel-end modules. The signal content has been further detailed to support the higher level of vehicle automation foreseen. The automation itself requires the use of multiple estimators and observers to replace not only the driver's inputs, but also his/her perception of error- and preview states.

The slip control concept, enabling maximum brake performance, has been further exploited and developed. A theoretical analysis has been published that clearly shows the characteristic differences between the sliding mode alternatives. Other alternatives have been tested, confirming the sliding mode control alternatives are outperforming.

Novel, proprietary, observers have been developed that allow great performance with the given low sampling rates. It supports better tunability of the sliding mode concept for slip control, because control performance and –stability is separated.

2. Sammanfattning på Svenska

Historiskt sett har tunga fordon längre stoppavstånd än personbilar. Denna egenskap, tillsammans med stabilitetsproblem i sidled på grund av deras höjd och ledpunkter, bidrar till tunga fordons överrepresentation i olycksdata. Att förbättra bromseffektiviteten för dessa fordon och förbättra deras laterala manövrerbarhet genom bättre samordning av aktuatorer kan minska sannolikheten för olycksscenarier.
Sedan början av 2000-talet har Haldex arbetat med University of Cambridge, Storbritannien, och undersökt prototyper av snabbverkande pneumatisk bromsventil, ”Fast Acting Brake Valve” (FABV). I kombination med längs-slipreglering av hjulen har dessa visat sig minska bromssträckan för moderna tunga fordon betydligt. Speciellt på ytor med låg friktion. Haldex-systemets modulära hjulbaserade arrangemang möjliggör industristandarder för noggrann styrning av bromsmomentet för varje hjul. Den här egenskapen är väl lämpad för koordinering av fordonets alla ställdon. Sådan koordinering utvecklas av Volvo i deras ”Vehicle Motion Managment” (VMM).
Projektet undersökte förbättringar som kan uppnås genom att helt integrera Haldex-systemet med Volvos VMM. Förväntade förbättringar jämfört med konventionella elektroniskt styrda pneumatiska bromssystem (EBS) inkluderar: förbättrad nödbromsprestanda vid såväl kröning rakt fram som i kurva; förbättrad prestanda för elektronisk stabilitetskontroll (ESC); förbättrad realtidskunskap om vägförhållanden och bromssystemets kapacitet; förbättrad manövrerbarhet genom koordinering av aktuator.
Genomförandet av detta projekt har skapat stora insikter i industrialiseringen av FABV-konceptet. Flera generationer har designats och testats på riggar och fordon. Varje designsteg har avslöjat och bekräftat egenskaper som krävs för säkra och högpresterande hjulmoduler. Frågor som tas upp; flödeshastigheter, driftshastighet, systemredundans, separering av egenskaper och så vidare.
Fordonsintegrationstester har stärkt signalgränssnitten mellan VMM och hjulmodulerna. Signalinnehållet har detaljerats ytterligare för att stödja den högre nivån av fordonsautomation som förutses i framtiden. Själva automatiseringen kräver användning av flera estimatörer/observatörer för att ersätta inte bara förarens ingångar, utan också hans / hennes uppfattning om feltillstånd och prediktioner.
Slip-regleringen, vilken möjliggör maximal bromsprestanda, har vidareutvecklats. En teoretisk analys har publicerats som tydligt visar de karakteristiska skillnaderna mellan alternativen ”sliding mode” reglering. Andra alternativ har testats och bekräftats överlägsna.
Nya observatörer har utvecklats som möjliggör bra prestanda med de givna låga samplingshastigheterna. Det stöder bättre justering för ”sliding mode”-regleringen, tack vare att regler-prestanda och –stabilitet hålls åtskilda.

3. Background

Heavy goods vehicles (HGVs) exhibit longer braking distances than passenger cars (Henderson & Cebon, 2015 (available online)). In addition to this, HGVs experience lateral stability problems (such as roll-over, jack-knifing and trailer-swing) which arise from their large dimensions and multiple articulation points. These factors result in HGVs being over-represented in crash data world-wide.

Recent work by Haldex AB and the Cambridge Vehicle Dynamics Consortium (CVDC), based at the University of Cambridge, has resulted in the development of a novel, fast-acting electro-pneumatic brake control valve (FABV) for HGVs which allows precise control of longitudinal wheel slip (Miller, Henderson, & Cebon, 2013).

Full-scale vehicle tests carried out in collaboration with Volvo GTT between 2013 and 2015 have shown that the new valve hardware (capable of switching state in less than 5 ms), coupled with a wheel-slip control strategy, can reduce HGV stopping distances on wet road surfaces by 16% compared to a modern HGV electro-pneumatic braking system (Henderson & Cebon, 2015 (available online)). Some of these straight-line-braking results also received media attention (the BBC) (Wescott, 2015). In addition to straight-line braking, the Haldex system (coupled with slip control strategies developed at Cambridge) has been shown to improve the lateral stability of articulated HGVs during brake-in-turn manoeuvres compared to conventional ABS (Morrison, 2015). The improved control bandwidth which has been achieved by the Haldex FABV system has strong potential to improve the performance of a range of other existing braking functions on modern HGVs (e.g. RSC and ESC). Such improvements are envisaged to significantly improve the safety of HGVs in a range of driving scenarios, therefore, reducing the chance of HGV accidents – a benefit to all road users.

The improved controllability of individual wheel torque and slip demonstrated by the Haldex system can be seen as an enabling technology for advanced ‘full vehicle control’ systems, where optimized co-ordination of motion control systems (such as brakes, steering, engine, etc.) can be achieved. The fast system response also allows advanced state estimation routines (e.g. estimation of available friction) to be run at each wheel. This ‘capability’ information is not published by existing braking systems. According to the SAE’s recently published standard on autonomous driving levels (J1306) (Society of Automotive Engineers (SAE), 2014), in order to achieve full autonomy 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” (Society of Automotive Engineers (SAE), 2014). Clearly this cannot be achieved without up-to-date, accurate knowledge of the tyre-road characteristics, in all driving modes.

4. Purpose, research questions and method

The purpose of this project was to investigate the safety improvements that can be achieved by fully integrating the Haldex FABV system with Volvo’s vehicle motion management controller. Specific areas of focus where improvements were foreseen over conventional electronically-controlled pneumatic braking systems (EBS) were: improved emergency braking performance in straight-line and brake-in-turn scenarios; improved electronic stability control (ESC) performance; improved real-time knowledge of road conditions and brake system capability; improved manoeuvrability (through the use of actuator coordination).

The high-level research questions set out at the beginning of this project were:

1. What safety improvements can be achieved with the Haldex FABV system?
2. How can such a system be integrated with a full-vehicle motion management system, where actuator co-ordination is used?

In order to address these high-level questions, the following investigations were performed:

1. How should a generic signal/parameter interface between a central motion control node and a modular intelligent wheel-end brake module in order to deliver the fore-seen safety improvements?
   See publication [1] for results and discussion.
2. What are the biggest challenges to implement such a modular brake system and control interface?
   Significant challenges were seen in the areas of wheel-end based methods for longitudinal tyre force estimation, brake factor estimation and tyre-road friction estimation, see [5], [10] and [11] for developments in these areas.
3. Can tyre-road characteristics be estimated at the wheel end?
   See publications [4], [9] and [11] for contributions made in this area.
4. Can extreme-seeking algorithms be used to improve the performance and robustness of the existing slip control methods used in the FABVs?
   Publication [12], as well as [15] (which is currently being finalised), summarise work completed on this topic.

5. Objective

The project objectives were defined in the project proposal are listed below. Some objectives were not addressed due to time constraints, these are shown as 'for future work'.

1. Develop a prototype modular wheel station based service brake system that:
   a. Can achieve maximum braking performance in all tyre-road conditions
   b. Identifies and communicates braking capability of each wheel module to global motion management controller (taking into account tyre-road conditions, brake temperature, lining wear, etc.)
   c. Allows fast, accurate control of brake torque at individual wheels
   d. Has commercial potential
2. Identify and quantify the full benefits that may be achieved through the use of the new braking system, using high-fidelity simulations of a range of possible heavy vehicle configurations. Potential improvements could include (but are not limited to):
   - Improved straight-line-braking performance
   - Improved brake-in-turn performance
   - Improved traction-control *(for future work)*

- Improved (autonomous) collision avoidance *(for future work)*
- Improved vehicle motion management and actuator allocation, due to improved knowledge of brake system capability
- Reduced air consumption of braking system
- Potential for use of low rolling resistance tyres (and associated fuel consumption improvements) due to improved 'adhesion utilization' *(for future work)*
- Improved safety of long-combination vehicles *(for future work)*

3. Install prototype modular braking systems (developed during objective 1) on Volvo test vehicles and use actuator co-ordination strategies to combine individual brake torques with other vehicle motion control devices (e.g. steering) to achieve optimal longitudinal and lateral performance.
4. Carry out vehicle tests using the test vehicles developed as part of Objective 3, in challenging driving manoeuvres in a range of road conditions.

6. Results and deliverables

D1: 3rd generation prototypes of FABV system, including hardware and software (TRL 5)

Two previous generations of Haldex FABV prototype systems have brought the system to TRL 3. During the course of this project additional design stages have passed to improve flow rates, manufacturability, functional safety and so on, leading to the fourth generation of the FABV, now with a single flexure control the three control states, build, dump and hold.

- We have tested the FABV's in real environment with success a few winters at real trucks.
- We have created much better understanding of the design concept. E.g. understand the design change's impact on the characteristics.
- We have design solutions to separate force generation (high magnetic flux) and spring stiffness.
- We have run an endurance on the original flexure to establish life
- We have completed noise evaluation
- We have undertaken an initial assessment of the ECE Reg 13 tests
- We have undertaken an evaluation of the flow characteristics

The activities conducted have led to TRL5 allowing Haldex to market its Scalable Brake System with FABV.

D2: Demonstration vehicle 1

Demonstrator vehicle 1 (a Volvo FMX 8x4 truck, shown below) was fitted with the Haldex FABV system in 2016 and was used throughout the project. The vehicle was used to carry out straight line emergency braking tests (in summer and winter conditions) as well 'normal driving' scenarios to assess the driver's perception of the system's braking feeling. It was also used to test some of the new software functions from D1 early on in the project. Basic autonomous driving functionality was also demonstrated on this vehicle. Test data gathered from this vehicle was used in many of the publications listed in this report.

D3: Demonstration vehicle 2

Demonstrator vehicle 2 (a Volvo FM 4x2 tractor unit, shown below) was fitted with updated FABV hardware and software in early 2018. This vehicle enabled testing of the Haldex FABV system in a tractor semitrailer combination. An updated brake pedal was also included to improve the driver brake feeling compared to demonstrator 1, as well as an updated signal interface between the Volvo motion controller and the individual FABV wheel control modules. This vehicle was used for both wheel end software function development (D1) as well as control allocation experiments using Volvo's Vehicle Motion Management controller, in both summer and winter conditions.

D4: Mass production concept proposal, including full cost estimate, for FABV system

Haldex has fully assessed the industrialisation potential of the FABV system. This assessment includes: manufacturability, costing, market analysis and vehicle system testing. Investigative ECE R13 tests have been performed.

Manufacturability and costs have been analysed and Haldex has produced a sound business case on the introduction of the researched technology within this project.

D5: Docent lecture

The main academic format was a post-doc researcher, i.e. a person with grade PhD which do academic research to reach the next grade, which is Docent. In this case, the docent would be particularly well trained to take on industrialization of the brake technology studied in the project. Since the intended person, Leon Henderson, was transferred to industry (Volvo GTT) already after approximately one year, Chalmers recruited a new Post-Doc, Shenjin Zhu. Unfortunately, Shenjin had to end his participation in the project after a year. Then, the funding was not enough to employ a 3rd Post-Doc. Instead, Alireza Marzbanrad was employed by Haldex and placed at Chalmers as Guest Researcher. So, in total, a single Docent grade was not reached in the project. However, Leon Henderson has, as Adjunct Researcher from Volvo GTT, continued his academic research but with a lower pace. It is now planned that Leon will reach the Docent grade in autumn of 2020.

D6: Master theses

A Master thesis was planned to develop the simulation phase of this project. More specifically, it should focus modelling of vehicle, brake system and manoeuvre for requirement setting of complete vehicle functions where brake system is key system. system can be utilised on different long-combination heavy vehicles. Examples are: yaw and roll stability control performance, combined braking and steering (low and high-speed), brake blending and added traction.
Two Master theses was formulated and carried out. However, the project did not find a suitable student to do the intended simulation Master thesis.

D7: Journal and conference articles

See section "Publications".

7. Dissemination and publications

7.1 Dissemination

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	
Be passed on to other advanced technological development projects	X	Yes, but confidential
Be passed on to product development projects	X	Yes, Haldex EMB
Introduced on the market	no	
Used in investigations / regulatory / licensing / political decisions	no	

7.2 Publications

Scientific Publications

[1] L. Henderson, D. Cebon and L. Laine, *Brake System Design for Future Heavy Goods Vehicles*, Presented at the 14th International Heavy Vehicle Transport Technology Symposium, Rotorua, New Zealand, 2016.

[2] Jim Crawley and Carl Mellings, *High Performance Pneumatic Actuator for Commercial Vehicles and Controllability Impact of Autonomous Systems*, Eurobrake 2017, http://2017.eurobrake.net/programme/technical-programme/EB2017-BSY-009, 2017

[3] Jim Crawley, *Fast and precise brake actuation for motion control and redundant brake and steer of heavy vehicles*, SVEA seminar 2017, Södertälje, Sweden, https://www.sveafordon.com/media/50549/6__Haldex_SVEA_Presentation_2017_by_-Jim_Crawley_Rel.pdf, 2017

[4] B. Westerhof, D. Kalakos, L. Henderson, B. Jacobson, *Heavy vehicle braking using friction estimation for controller optimization*, Presented at the 15th International Heavy Vehicle Transport Technology Symposium, Rotterdam, The Netherlands, 2018.

[5] Shenjin S. Zhu, L. Henderson, E. Drenth, F. Bruzelius, B. Jacobson, *An Investigation of Longitudinal Tyre Force Observation for Slip Control System Development,* Presented at the IAVSD Symposium on Dynamics of Vehicles on Roads and Tracks, Gothenburg, Sweden, 2019.

[6] Bengt J H Jacobson, Peter Nilsson, Mats Jonasson, *Needs for Physical Models and Related Methods for Development of Automated Road Vehicles*, Conference contribution, 2019

[7] Mats Jonasson, Bengt J H Jacobson, Leo Laine, *Safe estimation of tyre normal forces on multi-axle vehicles*, Patent application, 2019

[8] Edo Drenth, *Scalable Brake System*, 3rd Autonomous Truck conference, Munich, Germany, 2019

[9] Seyed Mojtaba Sharifzadeh, Fredrik Bruzelius, Bengt J H Jacobson et al, *Tyre Models for Online Identification in ADAS Applications*, IEEE/ASME Transactions on Mechatronics, Paper in proceedings, https://research.chalmers.se/publication/514564, 2019

Master of Science Theses

[10] Ramprasad Soundhararajan and Prajwal Devegowdana Koppal Chandrashekar, Online Monitoring Of Brake Capability for Heavy Vehicles, https://odr.chalmers.se/handle/20.500.12380/256683, 2019

[11] Westerhof, Bernhard and Kalakos, Dimitrios, *Heavy Vehicle Braking using Friction Estimation for Controller Optimization*, 2017, https://odr.chalmers.se/handle/20.500.12380/251220, 2017

Scientific publications in Preparation

[12] Alireza Marzbanrad, Fredrik Bruzelius, Bengt Jacobson, Edo Drenth, *Enhanced Sliding Mode Wheel Slip Controller for Heavy Goods Vehicles,* Eurobrake 2020, Submitted, 2020.

[13] Mojtaba Sharifzadeh, Fredrik Bruzelius, Bengt Jacobson, Leon Henderson, Adolfo Senatore and Francesco Timpone, *Online Tyre to Road Friction Estimation Applied to Heavy Vehicles*, In preparation for submission to International Journal of Vehicle System Dynamics, 2020.

[14] Fredrik Bruzelius, Mats Jonasson, Edo Drenth, Alireza Marzbanrad, Leon Henderson, *Longitudinal tyre force estimation, a comparison between methods*, Submitted to AVEC’20, Japan, 2020.

[15] Alireza Marzbanrad and Fredrik Bruzelius, *Extreme Seeking (approximate title)*, Manuscript for journal in preparation, 2020

8. Conclusions and future research

Conclusions

1. Haldex has developed the wheel brake actuator over the course of several generations and gained knowledge towards a market-ready product. Discussions with OEM’s on market introduction are ongoing.
2. Volvo GTT have gained experience with Haldex’ novel wheel-end based modular brake system and have been able to successfully integrate the

system into a new motion control concept. Vehicle tests with the new motion control system have shown promising results, and a potential for future products using such technology.
3. Chalmers have studied and developed longitudinal force estimators and slip estimators for pneumatic friction brake actuators. Increased knowledge of friction braking and tyre models and their interaction with wheel and axle dynamics. The interface needed between vehicle and brake actuator have been developed and confirmed. The knowledge is useful for other brake actuators, such as EMB.

Future research

The project has worked up the knowledge for general scalable brake systems, including e.g. Electro-Mechanical Brakes, EMB. Scalable coordination with other actuators, such as propulsion (especially wheel-/axle-individual electric such) and vertical suspension actuators, can also be considered as a next step.

9. Participating parties and contact persons

- Haldex:
  - Carl Mellings
  - Edo Drenth
  - Fredrik Seglö
  - A team of design, project and test engineers (too many to list)
- Volvo GTT:
  - Anders Vikström
- Chalmers:
  - Bengt Jacobson
  - Fredrik Bruzelius
  - Mats Jonasson
  - Mojtaba Sharifzadeh
  - Shenjin Zhu
- Multiple affiliations among project partners:
  - Leon Henderson (Volvo GTT and Chalmers)
  - Leo Laine (Volvo GTT and Chalmers)
  - Alireza Marzbanrad (Haldex and Chalmers)