Engineering Assessment of Current and Future Vehicle Technologies

FMVSS No. 105 Hydraulic and electric brake systems
FMVSS No. 135 Passenger car brake systems
Final Report

Contract No. DTNH22-02-D-02104
Task Order No. 3

for

National Highway Traffic Safety Administration
U.S. Department of Transportation
Washington DC 20590

March, 2005

by

Christopher Winkler
Timothy Gordon
Zevi Bareket

The University of Michigan
Transportation Research Institute (UMTRI)
2901 Baxter Road
Ann Arbor, Michigan 48109-2150

with prime contractor

Battelle
505 King Avenue
Columbus, Ohio 43201-2693

Technical Report Documentation Page

<table>
<tr><td>1. Report No.
UMTRI-2005-11</td><td>2. Government Accession No.</td><td colspan="2">3. Recipient's Catalog No.</td></tr>
<tr><td colspan="2">4. Title and Subtitle
Engineering Assessment of Current and Future Vehicle Technologies
FMVSS No. 105 Hydraulic and electric brake systems
FMVSS No. 135 Passenger car brake systems
Final Report</td><td colspan="2">5. Report Date
March 2005
6. Performing Organization Code
xxxxxx</td></tr>
<tr><td colspan="2">7. Author(s)
Winkler, C.; Gordon, T.; Bareket, Z.</td><td colspan="2">8. Performing Organization Report No.
UMTRI-2005-11</td></tr>
<tr><td colspan="2">9. Performing Organization Name and Address
The University of Michigan
Transportation Research Institute
2901 Baxter Road
Ann Arbor, Michigan 48109-2150 U.S.A.</td><td colspan="2">10. Work Unit no. (TRAIS)
11. Contract or Grant No.</td></tr>
<tr><td colspan="2">12. Sponsoring Agency Name and Address
National Highway Traffic Safety Administration
U.S. Department of Transportation
400 7th Street S.W.
Washington, D.C. 20590</td><td colspan="2">13. Type of Report and Period Covered
Final Technical Report
14. Sponsoring Agency Code
NHTSA</td></tr>
<tr><td colspan="4">15. Supplementary Notes</td></tr>
<tr><td colspan="4">16. Abstract
This report provides a technical assessment of Federal Motor Vehicle Safety Standards (FMVSS) 105, *Hydraulic and electric brake systems*, and FMVSS 135, *Passenger car brake systems*. The review of these standards is part of a NHTSA's Regulatory Review Plan to systematically examine all of the FMVSS.

The primary thrust of the document is to address two questions: Do the current standards impede emerging technologies in passenger car and light/medium truck braking systems? Do the current standards require modification to adequately regulate emerging technologies? Emerging technologies are reviewed. Estimates of the extent and timing of their influence are made. It is concluded that the standards will not impede emerging technologies in the foreseeable future but could do so in the long term. The view is expressed that the approach of the current standards to ensuring adequate performance under partial-failure conditions may become ineffective as more, and more complex, automatic functions are added to automotive brake systems. A new approach may be required. Seventy-eight references are included in an annotated bibliography.</td></tr>
<tr><td colspan="2">17. Key Words
brakes, electro-hydraulic, electro-mechanical, regenerative, fault-tolerant, brake assist, crash mitigation, collision avoidance</td><td colspan="2">18. Distribution Statement
Unlimited</td></tr>
<tr><td>19. Security Classification (of this report)
None</td><td>20. Security Classification (of this page)
None</td><td>21. No. of Pages
39</td><td>22. Price</td></tr>
</table>

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

Executive Summary

Federal Motor Vehicle Safety Standard (FMVSS)105, *Hydraulic and electric brake systems*, specifies requirements for hydraulic and electric service brake systems for vehicles with a gross vehicle weight rating (GVWR) greater than 3500 kg (7716 lb). FMVSS 135, *Passenger car brake systems*, does the same for passenger cars with a GVWR less than 3500 kg (7716 lb). Both of these standards have the stated goal "to insure safe braking performance under normal and emergency conditions." To do so, both specify a number of requirements and test procedures to ensure (1) a reasonable level of braking performance under an appropriate range of representative operating conditions, (2) adequate reliability over time, (3) adequate performance under conditions of partial failure through redundancy, and (4) reasonable consistency in driver/vehicle interface properties across the vehicle population.

This report was prepared by the University of Michigan Transportation Research Institute (UMTRI) under a subcontract from Battelle Memorial Institute of Columbus, Ohio, which is the prime contractor to the National Highway Traffic Safety Administration (NHTSA) for a project supporting NHTSA's Regulatory Review Plan. This plan systematically reviews all federal FMVSS on a scheduled basis. The purpose of this report is to document the results of a review and engineering assessment of developments in technology that may be relevant to FMVSS 105 and FMVSS 135. Other aspects of the Regulatory Review Plan, including the target safety problem assessment and a listing of other societal factors, are being performed separately by NHTSA.

Over most of the history of the automotive industry, the foundation brake system of passenger cars and light and medium trucks has been composed of mechanical friction brakes at the road wheels actuated via an hydraulic system that transmits (and often amplifies) the energizing forces applied by the driver to a brake pedal. Decisions on when and how strongly to apply brakes were always the driver's, and the conversion of kinetic (or potential) energy was virtually always into heat expelled to the surroundings.

Today, brake systems are undergoing radical change. Decisions to apply (or release) brakes are being made automatically by computer-controlled systems (e.g., ABS and ACC). The type, complexity and shear number of such automatic systems is growing. To enabled automatic control, electro-hydraulic valves acting under computer control have been introduced to the traditional hydraulic systems. Electro-hydraulic brake-by-wire has been introduced, and in the foreseeable future, the brake application system is likely to become predominately electro-mechanical, largely doing away with hydraulic components.

The brake itself is also changing. Electric regenerative braking has been introduced as augmentation to the friction brake to improve the energy efficiency of electric and hybrid vehicles. Hydraulic regenerative braking may be introduced soon. In the long term, regenerative braking could become the primary braking mechanism.

FMVSS 105 and 135 as currently written do not appear to present serious impediments to emerging brake technologies in the near term (i.e., within the foreseeable plans of vehicle

manufacturers). In the longer term, these regulations could inhibit the use of regenerative brakes as the primary vehicle brake.

Modification of FMVSS 105 and 135 may become appropriate due to emerging brake technologies. Primary among the issues involved is the increasing dominance and complexity of the electronic computer/software elements of the brake system and their integration with other computer/software systems on the vehicle. As a result, issues of fail-safe and partial failure performance, once concerned with rather simple, purely mechanical and hydraulic systems, are becoming highly complex. In the short term, additions to the standards for individual new systems may suffice. In the longer term, a new philosophical approach to insuring fault-tolerant braking systems may be required.

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Introduction

The National Highway Traffic Safety Administration (NHTSA) has implemented a Regulatory Review Plan to systematically examine each of the Federal Motor Vehicle Safety Standards (FMVSS), 49 CFR 571. This review examines all factors that are relevant to the standards, including demographics, societal values, crash statistics, and vehicle mix in the national fleet. An important element of the review is an engineering assessment of new developments in technology that may influence the standard. The purpose of the technology assessment is to determine if there have been changes that have significantly altered the vehicle systems affected by the standard, thereby necessitating enhancements of the standard. It will also yield information on the capabilities of the newly available technologies, or technologies in development, to meet a higher level of safety performance.

NHTSA has contracted with a team comprising Battelle, the University of Michigan Transportation Research Institute, TRC Inc., and Smithers Scientific Services to support the technology component of the regulatory review. This team examines the standards individually on a schedule established by NHTSA. This report is the result of assessment of two related standards: FMVSS No. 105: Hydraulic and Electric Brake Systems and FMVSS No. 135: Passenger Car Brake Systems.

The team follows a common work plan for each assessment, adapting the plan for the nature of the standard and the scope of the review. At the outset of each review, members of the contractor team meet with the NHTSA Contracting Officers Technical Representative (COTR) and other engineers responsible for the standard to establish the scope for the assessment of the particular standard. The scope for this search is reviewed in the Section I of this report. The team gathers information from published literature and private contacts within the industry. The information is summarized and categorized. Subject matter experts are consulted to assess the relevance and expected significance of each technology. The results are presented in the tables and the discussion sections of Section II. The Section III presents a summary of the major conclusions of the assessment and the possible implications of the developing technologies on the safety standards.

A bibliographic list of references is presented at the end of this report. Copies of many of the listed references have been forwarded to the COTR.

I. Scope of the Search

A phone conference was held on 13 October 2004 to establish the scope of the project. Participants in the conference were: from NHTSA, Hyun Peck, Jim Britell, Larry Hershman, Duane Perrin, Stu Seigel, and George Soodoo; from Battelle: Doug Pape; from UMTRI: Tim Gordon, Chris Winkler, and John Sullivan.

A. Systems for Assessment

Table I. Systems affected by FMVSS 105 and 135.

Goals of the standard	As stated in the standards, the goal of both of these standard is "to insure safe braking performance under normal and emergency conditions." More specifically, the goals are to ensure (1) a reasonable level of braking performance under an appropriate range of representative operating conditions, (2) adequate reliability over time, (3) adequate performance under partial failure through redundancy, (4) reasonable consistency in driver/vehicle interface properties across the vehicle population.
Systems affected	Service, emergency/parking and regenerative braking systems, ABS
Indirectly affected subsystems	traction control, stability- and control-enhancement systems
Other relevant standards	As called out in the standards: SAE J227a *Electric Vehicle Test Procedure* SAE J972 *Moving Barrier Collision Tests* ASTM E1136 standard reference test tire; ASTM Method E 1337–90 and ASTM Method E–274–70 pavement friction measurement In addition there are numerous SAE, ISO, EU, EuroNCAP and other national standards in existence and currently under development relating to the vehicle's braking performance, the braking system and braking system components.

Table II. Scope of the search.

1. Actuation	Review existing and proposed brake actuation systems such as Electro-hydraulic braking systems (EHBS), mechanical, electro-mechanical and electronically actuated brakes. Highlight areas where the existing standards may be insufficient or problematic in terms of system requirement (S5), test conditions (S6) and test procedures (S7)
2. Sensing	Review existing and proposed sensing systems for brake application, where brake application is directly affected by the output from such sensors. Although the overall functionality of integrated systems such as ESP is not within the scope of the standards under review, the search will include review of the sensors being used or under consideration.
3. Driver Interface	Review existing and intended interfaces for brake system action, haptic and visual feedback, as well as monitoring. The point here is that standardization should not overly inhibit the development of new methods
4. Vehicle Types	The above will be further categorized across vehicle classes, to help inform NHTSA on whether the current gross vehicle weight classifications between standards 105 and 135 are the most appropriate.

B. Methodology

Table III. Key questions to answer during the search

Key questions to ask the sources are:
The two key conceptual questions are: (1) Do the current standards inhibit advances and appropriate introduction of emerging braking-related technologies? (2) Should the standards be modified from current, or introduce new requirements to adequately cover these emerging technologies? These questions need to be addressed regarding: • Electro-hydraulic and full electric service brake application • Electric parking-brake systems • Hybrid and fully electric power systems vis a vis regenerative braking • Electric vehicles vis a vis in-wheel propulsion • Active control systems involving brakes: ECBS, traction control, brake assist, stability enhancement, automatic directional control (e.g., lane departure avoidance) These questions also need to be addressed from the point of few of: • Vehicle performance requirements • Component performance requirements • Component configuration and property requirements (pedal configuration, application forces • System and component reliability (mechanical, electrical, software) • The mechanics of testing procedures

The Task leader at UMTRI was Chris Winkler . He was assisted at the senior engineering level by Tim Gordon of UMTRI and by staff engineer Zevi Bareket.

C. Sources

Resources of the UMTRI and University of Michigan library systems were be employed in the literature source. In addition to the UMTRI library collection, the University provides web-based connectivity to a variety of technical literature databases. UMTRI also contacted several industry sources with requests to arrange interviews with key personnel from the vehicle and component manufacturing community. These included General Motors, Ford, Chrysler, Honda, and Arvin Meritor. Interviews could only be arranged with General Motors and Arvin Meritor. The experience of UMTRI personnel in braking-related research was, of course, also a source of information.

II. Search Results and Engineering Assessment

A. Search Strategy

A literature search was conducted searching for the broad key words of “hydraulic” and “brake,” “electric” and “brake,” and “regenerative” and “brake.” Additional more specific searches were made on key words such as “brake assist,” “brake-by-wire,” “crash avoidance,” etc. Databases available to UMTRI staff through the UM library system were used. The databases used are listed below, the most effective of which were certainly the Engineering Index and the SAE Technical Papers. Searches were generally limited to the publications within the last five to seven years.

- Cambridge Scientific Abstracts (CSA): A broad index covering arts and humanities, natural sciences, social sciences, and technology.
- Engineering Index (Engineering Village 2): The combined Compendex®, Ei Backfile & Inspec® databases allow for searching on a broad range of topics within the scientific, applied science, technical and engineering disciplines.
- NTIS (National Technical Information Services): Indexes reports on government sponsored research and development from selected federal agencies, their contractors, and their grantees.
- ProQuest: Includes access to ProQuest Research Library, a general periodical index with full text; ProQuest Newspapers, and ABI/INFORM.
- SAE Technical Papers: via UM Library Citrix Service; SAE Proceedings, Special Publications, and Transactions since 1998.
- Transport via SilverPlatter WebSPIRS 5.0: Includes TRIS, OECD's International Road Research Documentation, and the ECMT TRANSDOC database.
- TRIS: Transportation Research Information Service, the abstracting and indexing database compiled by TRB.

B. Search Results and Engineering Assessment

Table IV summaries the search results by reviewing the findings on emerging brake technologies.

Table IV. Emerging brake technologies

Technology	***Objective Technical Description***	***Qualitative Engineering Assessment***	***Estimated Timetable for Deployment***	***Likelihood of Commercial Introduction***	***References***
1. Electronic brake-by-wire	A braking system in which the primary action of the driver's control device (to date, the brake pedal, but potentially other devices) is to modulate an electrical signal. The control may incorporate additional mechanical action for fault protection, and force feedback for driveability.	Provides a flexible control interface that is especially appropriate for braking systems with advanced functionalities. Also reduces reliance on hydraulic components, and offers greater flexibility in vehicle packaging and assembly. Some form of transducer redundancy at the brake pedal is necessary for overall fail-safe protection of the braking system. Includes electro-hydraulic and electro-mechanical braking systems.	Already in production, with an estimated 48,000 factory installed units in 2000, rising to over 1 million by 2010.	Currently in production, and likely to become a significant technology by 2010.	1,7, 10, 12, 22, 31, 36, 41, 46, 52, 55, 58, 64-67
2. Electro-hydraulic braking system (EHB)	Particular form of brake-by-wire system. Uses electronic sensing from the brake pedal to control hydraulic valves, connecting to conventional hydraulic actuators at the road wheels	Allows control of individual wheel cylinders to optimize braking performance and reduce stopping distances. Can be designed to incorporate fully hydraulic backup system in the event of electronic system failure (and requires a fault diagnosis and isolation function to trigger the backup system). Especially useful as a platform for higher level braking system functions such as ABS, ESB and crash mitigation.	Already in production with Mercedes-Benz (E-class and CLS-class)	Already in commercial production, but likely to be a short-lived 'hybrid' between conventional hydraulic and electro-mechanical brake-by-wire.	12, 31, 36, 39, 41, 46, 52, 58, 64, 65, 67
3. Electro-mechanical braking system (EMB)	Particular form of brake-by-wire system that uses electro-magnetic actuators to directly control the friction forces at the road wheels	Has all the performance and flexibility benefits of electro-hydraulic braking systems, and offers additional benefits for system integration (e.g. offers electric parking brake capability). offers no mechanical backup system, so electronic and electrical system redundancy and fault tolerance is a key factor for the safe introduction of this type of system.	Likely to see significant introduction around 2010. Timing will depend on the reliability and customer acceptance of recently introduced EHB. Timing likely to be linked to the economic availability of 42 volt systems (currently in production)	Almost certain. Major brake system suppliers such as TRW and Continental-Teves are demonstrating prototype products. The wide-ranging advantages of EMB appear overwhelming.	1, 22, 31, 55, 56, 59, 65, 68
4. Regenerative braking, electric	A system that under braking converts some of the vehicle's kinetic energy into electrical energy. Uses an electrical machine to generate eclectic current, and either battery or ultra capacitor to store charge.	This system has real benefits for improving fuel economy, but is limited by the need for powerful electrical machines and power storage. This means the technology is not a practical add-on to existing vehicle power trains, and is restricted to being used within a hybrid or mild hybrid electric power train, where a suitable high-voltage electrical system is already in place. 42 volt Integrated Starter Alternator Dampers (ISAD) devices represent a minimum level for such devices.	Already deployed in the Toyota Prius, Honda Insight and Chevrolet Silverado (mild) hybrid vehicles. Significant penetration likely 2010-2015 as the hybrid market expands.	Certain, based on the clear opportunity for improved fuel economy, and the growth of the mild hybrid market.	14, 34, 45, 57, 69, 70
5. Regenerative braking, hydraulic	Hydraulic regenerative braking recovers energy and stores it as high-pressure hydraulic fluid in an accumulator	With a similar function to electric regenerative braking, in this system a hydraulic motor is coupled to the vehicle drive train; under vehicle braking the hydraulic motor pressurizes an accumulator, storing some of the vehicle's kinetic energy which is utilized for 'launch assist', reducing the energy requirement for subsequent acceleration. The system is suitable as an adaptation to existing power trains, and an economic investment for fleets of light delivery trucks, taxis and buses. Offers little benefit for drive cycles that only include rare stops.	Expected to be commonly available by 2010.	Commercial introduction is likely in niche vehicle sectors such as urban delivery trucks. Currently being developed by Ford and Eaton for the F350 concept truck, the technology is relatively mature and of low technical risk.	13, 15, 34, 69, 70,71
6. Magneto-rheological brake actuator	Braking torque generated by shear forces in a magneto-rheological (MR) fluid controlled by an applied magnetic field.	This type of brake actuator uses a fluid as a the friction medium. The technology is proven for relatively low power density applications such as automotive suspension dampers, and controllable brakes for exercise machines. The critical performance characteristic for automotive braking applications is thermal management and high-temperature behavior of the MR fluid. Needs technical development to become practical, but offers significant advantages in terms of improved brake torque control and being environmentally friendly.	Not likely to be available on production vehicles before 2010 - if the technology is adopted, 2015-2020 is a likely timeframe for its introduction.	The use of MR fluid technology in suspension dampers suggests its adoption for braking systems is feasible. It is not a 'front runner' technology at present, but might become attractive if introduced in combination with other novel braking concepts - for example as a backup safety system for high capacity regenerative braking systems.	37, 72
7. Piezo-electric brake actuator	Piezo-electric elements are used to generate hydraulic pressure at each wheel; hydraulic pressure is maintained in one or more accumulators at each wheel, and brake torque is controlled via a conventional solenoid valve.	Piezo-electric actuators are becoming increasingly common, for example in diesel fuel injection systems. They are not appropriate for direct actuation of disk pads, but coupled to a hydraulic system as a novel electrical pump, the concept is feasible. Advantages are simplicity and high reliability of piezo-electric actuators, compatibility with brake-by-wire concepts, and compatibility with standard disk and caliper components.	Introduction not likely before 2010-2015	Technology may be attractive for brake-by-wire applications. The system is currently being researched, but as yet does not appear to be under serious prototype development by the automotive industry. The likelihood of commercial introduction is currently low.	32, 60, 73

Table IV. Emerging brake technologies, continued

Technology	Objective Technical Description	Qualitative Engineering Assessment	Estimated Timetable for Deployment	Likelihood of Commercial Introduction	References
8. Electronic Brake Assist (EBA)	Electronic system that incorporates estimation of driver intention, to recognize emergency brake application, and in this case increase brake system gain and or response speed	The system is effective in overcoming the common reluctance of drivers to apply full braking effort, even in the case of an emergency situation. The system detects rapid brake pedal action to initiate the brake assist. It is clearly capable of reducing braking distances in these situations. Because of the flexibility of the system, it is capable of adapting to different driving styles, and can be combined with other systems such as crash mitigation and collision avoidance.	Already deployed.	This type of system has been in commercial existence for over 5 years. First introduced by Mercedes-Benz, a number of car companies are now looking at implementing such a system.	3, 5, 16, 23, 65, 73
9. Mechanical Brake Assist (MBA)	Mechanical system that performs an identical function to EBA.	A cheaper alternative to EBA, the system uses a mechanical valve that responds to rapid pedal acceleration. This additional valve then triggers a rapid and increased braking system response. The device characteristics are fixed, and so this system lacks any possibility to be incorporated within an intelligent braking system, such as ESP, Crash Mitigation or Collision Avoidance.	Possible deployment within 2005-2010 timeframe	As a lower cost system than EBA, may fill a market gap up to around 2010. But is unlikely to gain a long term market acceptance	4, 6, 65
10. Vehicle Stability Control (VSC)	Single wheel braking is automatically triggered as a countermeasure for oversteer or understeer.	This system, also commonly known as Electronic Stability Program (ESP) uses a yaw rate sensing and sideslip estimation to compare with a reference vehicle model - where large discrepancies are found, brake application is applied to restore desired (reference) vehicle behavior. The primary purpose of brake actuation is to generate a yaw moment - changing the vehicles rotation about a vertical axis; reducing vehicle speed is a side-effect of the system.	Already deployed	Although the system is already available on more expensive passenger vehicles, there is continued scope for wider market penetration and greater system functionality, such as integration with crash mitigation and avoidance systems.	1,11, 65
11. Crash Mitigation System	System that detects likely frontal (and possibly lateral) impacts, e.g. using RADAR or LIDAR, may progressively warn the driver of a frontal crash and apply moderate braking effort (e.g. up to 0.3g deceleration) and finally apply maximum braking when impact appears inevitable.	This type of system may take partial control of the vehicle when a crash appears imminent. It may pre-deploy restraint systems and air bags/curtains, but of greatest relevance here is that partial or full braking will be deployed, independent of any driver decision. The concept is simply that a crash is inevitable, and that reducing vehicle speed will mitigate the effects.	likely deployment in the period 2008 - 2015	This type of system is very likely to be deployed in the US market. Currently it is commercially available in Japan (by Honda) and is under prototype/concept development at Ford. Bosch and Delphi have also published papers indicating their interest in the area.	2, 3 , 33
12. Collision Avoidance System	A collision avoidance system may support, warn or override the driver in an attempt to avoid a collision. Of relevance here is any sub-function that automatically deploys the brakes as part of the overall collision avoidance strategy	In the current context, this is any collision avoidance system that automatically applies the brakes to achieve this - as such, the system requires significant sensor data and signal processing to establish sufficient situational awareness to justify taking control away from the driver. Experience with collision warning systems indicates that precise situational awareness is not easily established from existing vehicle sensors. It may be that new communication systems (such as DSRC) are essential to future systems of this type. This type of system is very much in the research (as opposed to development) phase.	While warning systems may be introduced much earlier, collision avoidance systems that automatically deploy brakes (and possibly steering) to avoid a crash are not likely in the next 10 years (2015-2020 timeframe for introduction at the earliest)	Only likely if crash warning systems are seen be ineffective in the field, and crash fatality rates are not amenable to other measures. The main inhibitory factor in the USA is likely to be fear of adverse litigation.	2, 33, 47, 48, 49, 50, 65
13. Fault tolerant by-wire braking systems	An advanced system level concept for full electronic by-wire braking system, where no mechanical backup is available	By-wire braking is the most safety critical system being proposed for full electronic control on vehicles. Loss of by-wire throttle and steering control still leaves the driver some potential level of residual control to safely bring the vehicle to rest - differential braking can provide a steering function, and an integrated starter alternator damper can provide emergency drive torque. However no independent system would be available to compensate for the failure of a fully electronic by-wire braking system. Therefore new fault tolerant systems must be developed that deliver proven levels of reliability and fault tolerance. Particularly in the case of tolerance to software faults, performance in this area cannot be addressed by traditional safety testing procedures. Particularly significant in that the existence and performance of this type of system is almost entirely hidden within the electronic architecture of the vehicle	This type of system is an integral part of the design philosophy for safety-critical by-wire systems, and will be a highly significant safety factor with the introduction of electro-mechanical brake systems around 2010.	An essential aspect of by-wire braking systems. Introduction almost certain.	7, 8, 9, 17, 35, 43, 53, 59

C. Emerging Technologies

The discussions within the following subsection expand on the summary of search results presented in table IV. The numbers in brackets in the text refer to references listed at the end of this report. In many cases where references are indicated in the text, additional references on the subject appear in table IV.

Brake Application

Over most of the history of the automotive industry, the foundation brake system of passenger cars and light and medium trucks has been composed of mechanical friction brakes at the road wheels actuated via an hydraulic system that transmits, and often amplifies, the energizing forces applied by the driver to a brake pedal. Although application assistance (amplification) was supplied, decisions on when and how strongly to apply brakes were always the driver's, and the conversion of kinetic (or potential) energy was virtually always into heat expelled to the surroundings.

In recent years, the friction brake and the hydraulic actuation system have remained overwhelmingly dominant, but computer-controller "intelligent" systems and are being given increasingly important (and numerous) roles in deciding how and even when to apply brakes. This trend will continue and may lead to the demise of the traditional hydraulic system in favor of the so-called brake-by-wire systems: systems using electro-hydraulic actuation and, eventually, electro-mechanical actuation.[e.g., 1,7,10,12,22] Recently, regenerative brakes have appeared in small numbers (in hybrid and fully electric vehicles) to supplement the friction brake. The trend is likely to continue, albeit slowly. There may be some very long-term potential for reversal of these roles, i.e., motors acting as regenerative brakes supplying the primary braking effort with smaller friction brakes playing a supporting role.[15,34,44,45,57]

Computer-controlled brake application has become commonplace. Some of these systems modify braking initiated by the driver. *Anti-lock braking* systems (ABS) and *traction-control* systems apply (or release) hydraulic pressure to prevent excessive (positive or negative) wheel slip.[1,12,22,23,31,41,65] *Brake-assist* systems accelerate (in time), and may also raise the level of, brake application to improving emergency brake applications.[3-6,16,23,65,73] Current brake-assist systems do so by altering the behavior of the vacuum booster when the driver applies the brake more rapidly than normal.

Other automatic systems apply the brake(s) on their own (as apposed to modifying driver-initiated braking). *Stability enhancement* systems apply individual wheel brakes to prevent pending yaw instability or can apply brakes generally to lower speed for the purpose of avoiding excessive lateral acceleration and, hence, rollover.[1,11,65] More recent versions of *adaptive cruise-control* (ACC) systems apply service brakes to adjust speed and maintain headway relative to a leading vehicle.[23,47,65] The future is likely to see expanded use of similar automatic brake application in the forms of various *crash-mitigation* and *crash-avoidance* systems.[2,3,33,47-50,65]

With the exception of some brake-assist systems, current and near-future automatic braking functions are and will be enabled by electro-hydraulic valves generally installed as augmentations to the traditional hydraulic system (and initially developed and installed for ABS). Typically these systems also require an auxiliary hydraulic pressure source, usually in the form of an hydraulic pump with attendant fluid reservoir and pressure accumulator. Such an hydraulic "source" may be a single, central source or may exist as an individual source at and for each brake.

The basic configuration of the actuation system is beginning to see major change. The presence of the new brake-system elements—hydraulic power, electro-hydraulic valves and the integrated computer control of both— immediately suggest the potential for abandonment of the base hydraulic application system in favor of a full *electro-hydraulic braking* system (EHB).[64,65,67] Such systems convert the displacement of the brake pedal (or, potentially, some other input device) to an electronic signal to be integrated with all the other electronic signals requesting brake application, ultimately actuating the friction brake through electro-hydraulic means, some of which may be very innovative relative to current approaches (including a proposed piezoelectric hydraulic pump/actuator).[32,60,73] Potentially, the traditional master cylinder and what is now the primary hydraulic system could completely go away. While such systems are being contemplated, EHB systems now in production maintain a portion of the traditional hydraulic circuit as a fail-safe backup to the primary electronic control.[64,65] Additionally, a remnant of the master cylinder is attractive as a means to maintain and/or simulate the traditional "brake-pedal feel."[9,10,13,38,63]

In the longer view, EHB is seen as only an intermediate step to *electro-mechanical braking* systems (EMB).[1,22,31,55] These systems could eliminate the hydraulic components altogether. The various electronic signals requesting brake action would be developed and integrated as with EHB, but the result would be used to activate electro-mechanical devices (motors of a sort) that would apply the traditional friction brakes. Further in the future (and perhaps less likely), the friction brake at each wheel could be replaced with higher power electro-mechanical devices for generating brake torques directly.[44,57] Such an approach would have the advantage of allowing *regenerative braking* with the primary (rather than an auxiliary) brake. Moreover, electro-mechanical actuators and/or brakes have potential advantages in various automatic systems as they generally have faster response times than hydraulic actuation systems.

Whether or not regenerative brakes are ever fitted as the primary brake in automobiles and trucks, they have already appeared as auxiliary systems in small numbers and are likely to become more prevalent.[13-15,34,69-71] Pressures for improved fuel economy and lower emissions are, of course, the motivations behind the emergence of these systems. Electric regenerative braking is a natural extension for gas/electric or diesel/electric hybrids or for fully electric vehicles. In these applications, the primary piece of hardware needed for regenerative braking is already present in the form of the electric motor(s) of the drive system. Turning this motor into a generator/alternator providing a regenerative braking function is largely a matter of proper electrical control. Thus, there is rather little cost or weight penalty for this auxiliary braking function. However, for vehicles without any electrical drive, regenerative braking generally requires new components that add both cost and weight. Nonetheless, one approach that may prove practical is hydraulic regenerative braking. During braking, an hydraulic pump/motor fitted to the drive train is used to charge a high-pressure accumulator. The energy so stored is later used, via the same pump/motor to help accelerate the vehicle. Prototypes have been demonstrated in light trucks and at least two suppliers are developing hydraulic regenerative systems for heavy vehicles with expectations of marketing them.[69-71]

Multiple systems using automated brake application on a single vehicle require integration and prioritization of multiple braking requests. Typically, to date the ABS CPU, the primary brake valve controller, houses this function, but it seems likely, as these systems become more numerous and complex, that process will migrate to a central processor for brake system control.

Sensors

Each of the automatic brake-application functions require some sensor or, more typically, a suite of sensors and subsequent signal processing to determine whether brake application is needed. The set of sensors and the data process become increasingly complex as automatic braking functions proliferate. Of course, the first of these sensors was the wheel-speed sensor, the core sensor of ABS systems. In modern vehicles, signals from the several wheel-speed sensors are directed to a central processor, where they not only serve the anti-lock function for the individual wheels, but in combination, provide the overall speed of the vehicle.

The brake-pressure boosting actions of brake-assist systems are typically triggered when the driver makes a faster-than-normal brake application.[3,5,16,23] Sensing such applications is accomplished by differentiating signals from electronic transducers that measure brake-pedal displacement or master-cylinder pressure. A less expensive, purely mechanical brake-assist system has been proposed that “senses” fast brake applications using only mechanical elements.[4,6]

Stability-enhancement systems process vehicle motion information to determine if corrective brake applications are needed. Vehicle speed is typically available through the ABS wheel-speed sensors; yaw rate may be sensed directly or be deduced by side-to-side comparison of wheel speeds. Steering-wheel angle may also be sensed. Lateral acceleration may be transduced directly, especially for roll-stability systems but it too can be deduced. For all systems where knowledge of the vehicle’s motion is required, sophisticated processing methods (Kalman filtering techniques) are often used as a means to obtain that information with a minimal set of sensory devices and/or to improve quality of, or confidence in, the resulting measurement.[50] In this context, vehicle components themselves may be employed as “sensors.” A specific example: using brake pressure, wheel speed and Kalman filtering techniques, the brake/wheel/tire assembly can be used as a road-friction “sensor.”[51]

ACC and the emerging crash avoidance systems introduce a new level in sensor complication in that they require not just information about the host vehicle, but also about its surroundings. The function of ACC is to maintain appropriate following interval between the host vehicle and a leading vehicle traveling at less than the selected cruise-control set speed of the host. Accordingly the primary information function is to identify and determine the range (distance to) and range rate (rate of change of distance to) the lead vehicle. The most commonly used base sensor is scanning radar but infrared laser range sensors are also used. In either case, however, the "sensor" package includes very sophisticated processing methods that interpret the raw signals in order to determine which represent the target vehicle and which do not. Information on the host vehicle's own motion (particularly speed and yaw rate) are typically incorporated to aid in this data processing.

At least three types of driver-assist systems that would apply brakes to avoid or mitigate crashes are being contemplated and exist at various levels of development. ("Development" includes work on similar *warning* systems: systems focused on the same crash-avoidance purposes but culminating in an alert to the driver rather than active vehicle control through brake application.) Forward-crash avoidance systems would seek to avoid head-on crashes of the host vehicle with objects ahead using ACC-like automatic braking, albeit with advanced sensing systems.[47,65] Road- (or lane-) departure avoidance systems would use selective braking similar to stability-control systems to redirect a vehicle about to depart the roadway (or its lane).[48-50,65] Another approach to avoiding road departure is embodied in a curve-speed control system. Such a system would "look ahead" at an electronic road map and slow the vehicle if it was "thought" to be approaching a curve to fast.

Much more than current systems, these systems will employ a suite of sensors whose several data streams will be merged in a so-called data-fusion process to enhance the quality of, and confidence in, the resulting measurements of the vehicle's surroundings. Thus, it is perhaps more useful to characterize these crash-avoidance systems as having integrated *sensor systems* rather than individual sensors. Forward-looking video cameras feeding pattern-recognition algorithms are basic to locating the road or lane ahead but can also contribute to obstacle identification; forward- and side-looking radar (or optical range detectors) are the basis for obstacle identification but the coordinated motion of multiple targets contributes to lane identification; on board GPS "senses" the host vehicle position, speed and heading in relation to electronic maps stored in on-board memory. Together they "sense" information about the road ahead, but can also contribute to obstacle identification. (E.g., the GPS/map system may indicate an overpass ahead, clarifying what might otherwise be confusing radar returns). Traditional sensors (wheel-speed, yaw rate, steering angle, etc.) add more information to the system.

Driver Interface

Traditionally, the primary control interface between the driver and the brake system has been the brake pedal: a mechanical link through which the driver energizes the hydraulic master cylinder with forces applied by the foot. A secondary control interface is the parking-brake actuator, usually a hand operated lever or another foot pedal. Dash mounted warning lights provide an interface by which the driver can monitor the health of the brake system and its auxiliary elements. Finally, the rear-mounted brake lights constitute and advisory interface with other drivers regarding braking activity of the host vehicle.

The introduction of automatic braking functions has already resulted in some changes to the behavior of these interfaces. The introduction of ABS effected the driver's primary interface with the brake system in that pressure pulses induced by the actions of some ABS systems are felt in the form of vibration or pulsation of the brake pedal. This was initially a source of some confusion for drivers but apparently has not been a major problem. *Brake-assist systems* now on the market also provide a distinctly different pedal feel when the system is activated as compared to pedal feel during normal applications.

Eventual introduction of brake-by-wire systems has the potential for major changes to the primary driver/system interface. In theory, brake-by-wire does not require any forceful actuation by the driver, thereby eliminating the basic reason for actuation via a foot pedal. While the primary actuator could certainly remain as a pedal with either a displacement or pedal-force transducer, it could just as well be a hand-operated lever (joystick) or button as has been demonstrated in some experimental systems. On the other hand, in the foreseeable future, it is apparent that manufacturers have no plans to launch such changes. Indeed, the greater concern seems to be the desire to maintain a traditional pedal feel as brake-by-wire systems evolve.[9,10,13,38,62] Moreover, manufactures will favor maintaining at least two-wheel hydraulic brake actuation as a fail-safe backup system for some time.[64,65] Thus, the master cylinder is likely to remain for some time as part of a backup system.

The electro-mechanical form of brake-by-wire also offers obvious motivation for altering parking-brake application. In many cases the same electro-mechanical device used to apply the wheel brake for service braking would be appropriate for applying the brake in emergency or parking situations. (Separate electric parking brake applicators have already been developed.[65]) With electric application, all of the numerous mechanical components associated with parking brake application could seemingly be replaced with little more than an electric switch and some wiring, implying very attractive weight and cost savings.

If we assume that "the brake system" encompasses all of the automated systems that apply brakes, the monitoring interface between the driver and that brake system is becoming far more extensive and complex. The common "ABS" warning light was the first small step in this progression. This warning light provides a simple binary message regarding the general health of the system: either the ABS is properly operational or it is not. On the other hand, ACC systems, for example, have rather elaborate dash-board displays that not only indicate general system health, but provide continuing information on the current operating state on a moment-to-moment basis. These visual displays may indicate various driver-selected settings as well as monitoring system status (e.g., target vehicle recognized/not recognized). Additional visual displays and/or audible warnings indicate that the driver must take over the braking task. As they become available, forward-crash avoidance, lane-departure avoidance and other such systems will presumably have similarly elaborate performance-monitoring interfaces.

Finally, vehicle brake systems interface not only with the driver of the vehicle on which they are mounted, but also with the driver(s) of following vehicles, i.e., with those drivers who observe the rear-mounted brake lights. Previously, the decision as to when to turn on brake lights was rather straight forward: when the driver applied the brakes. The means to do so was similarly simple: with a switch activated by initial brake-pedal motion or initial brake-pressure rise. Whether or not automatic brake application should be accompanied by brake-light actuation is not always so clear cut. (The advent of stability control systems required interpretation of this issue by NHTSA.[75]) The proliferation of automatic systems for applying brakes may raise this same question again in differing contexts. In any case, the means by which brake lights are actuated can not remain so simple. Some set of brake actuations must result in brake lights turning on; others must be filtered out so that do not cause the brake lights to illuminate.

D. Impediments to Emerging Technologies in the Current Standards

Neither FMVSS 105 or 135 appear to present any serious, near-term impediments to vehicle manufacturers in bringing emerging brake technologies to the automotive market, at least within the context of their existing plans. The representatives of both the vehicle manufacturer and the supplier who accepted our request for interviews said as much explicitly, and the literature reveals no explicit complaints on the subject.[77,78] To the extent that there have been, in recent years, questions regarding details of the application of the standards to new elements of braking systems, those interviewed believe that NHTSA's mechanism for resolving such questions and the resulting "letters of interpretation," have been both effective and appropriate.[76]

That is not to say that there will not be some confusion and/or need for clarification as new technologies come to market. Perhaps the most obvious possibility is related to parking brakes. The individual actuators of electro-mechanical brake systems could well have mechanical properties rendering them "self-locking" in the absence of an explicit "release" command. In this case, it would become very attractive for this same device to double as the parking-brake actuator. The elimination of all the separate mechanical elements of current parking-brake systems would provide significant cost and weight reductions. Moreover, the parking-brake system would easily and inexpensively activate all wheel brakes rather than just a selected subset making this system more effective when fully operational and providing an element of redundancy in the case of partial failure. While such a parking-brake system would be *applied* by and electro-mechanical device, it would nevertheless appear to be "a parking brake system of the friction type with solely mechanical means to *retain* engagement," as required by FMVSS 105 and 135. Presumably, such a parking-brake system would be activated by a simple electric switch or button operated by the driver. However, FMVSS 105 and 135 both limit parking brake application force, and, where that force is a hand force, the standards specify measurement procedures assuming conventional mechanical application devices. While the limit is obviously no problem, the measuring procedures are not applicable. Surely the more serious philosophical question regarding a parking brake system of this type relates to the replacement of the nearly completely redundant quality of the current mechanical application mechanisms with the partial redundancy of four separate applicators that, nevertheless, are also service-brake applicators. But the "bureaucratic" impediment of test methodology may be a minor impediment.

In the much longer term (and with an admittedly liberal evaluation of potential changes in brake systems), FMVSS 105 and 135 could present serious barriers to the emergences of "pure" electro-mechanical braking. That is, were electric vehicles to evolve in-wheel drive systems that, when operated regeneratively, could double as the primary braking system, essentially eliminating the friction brake (except, perhaps for moderate-power devices serving augmentation and zero-speed-holding/parking functions), such systems would find numerous obstacles in FMVSS 105 and 135, as many of the requirements, tests, and measurement methodologies assume that the primary brake is a friction brake.

E. Potential Shortcomings of the Current Standards

Examining the current standards, and particularly observing the manner in which they deal with specific existing brake technologies, suggests that FMVSS 105 and 135 may require modification in order to maintain a consistent effect as new technologies appear.

Regenerative Braking

The best single example to clarify this point might be with regard to hydraulic regenerative braking. Substantial attention is paid to (auxiliary) regenerative braking systems (RBS) within the standards (e.g., RBS are addressed in nine different sections of FMVSS 135). Broadly stated, the intent is to insure that tests are conducted with the RBS in an appropriate operational state (or range of states) and also that failure of the RBS is appropriately included in evaluations of partial-system failures. However, all of this is accompanied by explicit statements that limit requirements only to electric vehicles and only to electric regenerative braking. (Indeed, the standards' definitions of RBS specify an electrical system in an electric vehicle.) The philosophical intent of including RBS, however, would seem to apply equally to conventionally powered vehicles using regenerative braking of any description. Hydraulic regenerative braking appears to be a realistic commercial possibility, at least in heavy vehicles, in the relatively near future. If such systems meet with sales success, and depending on the future cost of petroleum fuels, they could rapidly migrate to lighter vehicles that typically use hydraulic brakes. Indeed, demonstration systems have been showcased in vehicles as light as the larger pickup trucks.

Brake Assist

Brake-assist systems present another near-term technology that might be considered for inclusion in the partial-failure requirements. Broadly speaking, the partial-failure requirements of FMVSS 105 and 135 aim to insure adequate braking performance under conditions where individual components of the system have failed. Some components considered are those that are fundamental to the braking system, but some are the technological "add-ons" that enhance braking performance; e.g., the standards make specific reference to both ABS and RBS regarding partial-system failure. It may become appropriate to consider brake-assist systems in the same manner. Brake assist is said to contribute to improved stopping distance. Moreover, the systems have already reached the "high-end" market and proposals exist in the literature for inexpensive systems that could become standard equipment.[4,73]

Fault-Tolerant Braking Systems

The overall task of insuring fail-safe performance in the face of the greater number and complexity of emerging brake and brake-related technologies is likely to become both an important and difficult issue particularly with regard to the need to integrate numerous x-by-wire systems on a vehicle (including multiple automatic braking functions).[42,54,58,59] The subject has become a point of concern in the literature.[7-9,17,35,43,53,59] The predictable need for regulatory clarity in the face of growing complexity of the systems was noted during interviews.[77]

There is a natural sensitivity to relying on electronic by-wire systems and, in particular, on a braking system having no mechanical link between the brake pedal and the brake actuator. Is it safe enough for lives to depend upon it? An intuitive response might be that a mechanical link must *always* be present, but this is not an objective perspective: mechanical systems fail, and their failure is not always easy to detect. The objective approach is to assess the risk of failure and determine how critical such failures are.

There are two objective safety differences between mechanical and electronic brake actuation: (a) the electronic system is subject to different sources of disruption, such as power failure and external electromagnetic radiation; (b) the electronic system contains significant software elements that may not be 100% reliable due, in part, to their complexity. In the latter case, faults may not even be localized; problems might arise through nearly unpredictable interaction with other vehicle electronic systems.

Under (a), the overall system reliability is not fundamentally different between mechanical and electronic by-wire brake systems. Fail-safe operation is traditionally delivered via component-level redundancy; an identical or equivalent component or sub-system is available in the event of a critical component failure. For example, traditional hydraulic braking systems are split diagonally to avoid catastrophic loss of braking in the event of hydraulic-system failure. For electronic brake-by-wire, the brake-pedal sensor is a critical component, which should be duplicated to reduce risk. There is also a need for electrical-power redundancy, and proof against external electromagnetic radiation from power lines etc. Overall, either type of system may be assessed using standard methods, as in Failure Mode Effects and Criticality Analysis (FMECA), or via a more quantitative Fault Tree Analysis of component failures.

Under (b), the by-wire systems are qualitatively different from the traditional mechanical systems: software cannot be completely proven as fail-safe and FMECA type analyses are not sufficient. How is it possible to be certain the brakes will work under all possible conditions of software execution? This is part of the overall problem of system complexity; it is generally impossible to predict the system response in all possible situations. One way to reduce risk due to complexity is to maintain redundancy at the system level through independent software and control hardware operating in parallel, and using a voting system to deploy control commands. This type of system is currently used in aerospace fly-by-wire applications, but it is almost certainly too expensive to be used in the automotive context.

A more appropriate option is to adopt a layered control architecture. In the event of a software fault in (say) the electronic stability program, the appropriate response is to alert the driver that the system is unavailable, and then revert to more basic 'lower level' function of standard braking. If the low-level function is deployed via a very simple and redundant micro-controller, the critical element is the system that detects and isolates the fault, and hence initiates the process of falling back to the low-level function. This implies the need for active fault diagnosis in which systems are constantly tested during operation, especially those redundant low-level micro-controllers that may not be used under normal vehicle operation.

The above discussion is intended to highlight the broad issues, not to define standards or solutions. In terms of braking system safety standards, the quality of the necessary fault tolerant behavior may not be amenable to the standard test procedure approach; it may be quite impossible to enumerate the possible system states, let alone test them. In the future, these issues could become of paramount importance to ensuring the safe operation of millions of vehicles fitted with by-wire braking systems, and they may demand a different, more analytical approach to insuring fail-safe performance. Such a view was expressed in our interviews.[77]

Monitoring Subsystems

The current FMVSS 105 and 135 require warning lights for monitoring brake-system health. Numerous reverences are made to warning lights for individual brake subsystems. As mentioned previously, evolving driving-assist systems that automatically apply brakes can have elaborate monitoring displays themselves, but as multiple systems are installed on individual vehicles, there are likely to be display-space problems and confusion over multiple messages. It may become worthwhile to either expand, or to generalize the requirements of the standards in this regard.

Other Topics

Additional topics of concern were revealed in the vehicle-manufacturer and component-supplier interviews.

Both the manufacturer and the component supplier expressed some concern over potential confusion as to when brake lights should be activated by automatic systems and when they should not.[77,78] Both organizations saw this as an important, practical subject with regard to implementing emerging automated system, indicating that the proliferation of multiple systems could make implementation difficult. Either in the context of FMVSS 105 and 135 or elsewhere (FMVSS 108), NHTSA might be well advised to promulgate an integrated, generalized requirement in this regard.

Although NHTSA has recently reviewed the issue of regulating after-market brake linings and has declined to do so, opinions were expressed that this should be done.[26,78] Brake designers are acutely aware that properties of the friction materials play heavily in their design efforts and influence the performance of the brake system overall and at the level of automated subsystems. On a similar point, there was support for the idea for regulating light-trailer braking systems.[27,78]

On the subject of the differences between FMVSS 105 and 135, it was suggested that justification for less stringent performance requirements for heavier vehicles is not as strong as it once was. Established advances in brake technology may allow heavier vehicles covered by FMVSS 105 to perform in many ways as well as passenger cars but that, because of commercial pressures, actual gains in commercial vehicle performance are not likely to be realized without more stringent regulation.[77] Little interest was expressed for adjusting the weight division between the standards. Moreover it was noted that if the vehicle is essentially intended to be a passenger vehicle, some manufacturers build to the more stringent requirements regardless of actual weight or regulatory category.[78]

Finally, although the scope of this project expressly excluded the issue of harmonization with other automotive regulations across the world, this nevertheless is an area of real concern to the industry. The strong trend toward the so-called *international platform*, and the difficulties of realizing the substantial economies it represents in the face of uncoordinated international regulations were noted in interviews.[77,78]

III. Project Conclusions

Over most of the history of the automotive industry, the foundation brake system of passenger cars and light and medium trucks has been composed of mechanical friction brakes at the road wheels actuated via an hydraulic system that transmits (and often amplifies) the energizing forces applied by the driver to a brake pedal. Decisions on when and how strongly to apply brakes were always the driver's, and the conversion of kinetic (or potential) energy was virtually always into heat expelled to the surroundings.

Today, brake systems are undergoing radical change. Decisions to apply (or release) brakes are being made automatically by computer-controlled systems (e.g., ABS and ACC). The type, complexity and shear number of such automatic systems is growing. To enabled automatic control, electro-hydraulic valves acting under computer control have been introduced to the traditional hydraulic systems. Electro-hydraulic brake-by-wire has been introduced, and in the foreseeable future, the brake application system is likely to become predominately electro-mechanical, largely doing away with hydraulic components.

The brake itself is also changing. Electric regenerative braking has been introduced as augmentation to the friction brake to improve the energy efficiency of electric and hybrid vehicles. Hydraulic regenerative braking may be introduced soon. In the long term, regenerative braking could become the primary braking mechanism.

FMVSS 105 and 135 as currently written do not appear to present serious impediments to emerging brake technologies in the near term (i.e., within the foreseeable plans of vehicle manufacturers). In the longer term, these regulations could inhibit the use of regenerative brakes as the primary vehicle brake.

Modification of FMVSS 105 and 135 may become appropriate due to emerging brake technologies. Primary among the issues involved is the increasing dominance and complexity of the electronic computer/software elements of the brake system and their integration with other computer/software systems on the vehicle. As a result, issues of fail-safe and partial failure performance, once concerned with rather simple, purely mechanical and hydraulic systems, are becoming highly complex. In the short term, additions to the standards for individual new systems may suffice. In the longer term, a new philosophical approach to insuring fault-tolerant braking systems may be required.

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   Most accidents can be attributed to driver error in recognition, judgment or vehicle operation. This paper presents an analysis of driver behavior characteristics in emergency situations that lead to an accident, focusing in particular on operation of the brake pedal. Based on the insights gained so far, we have developed a Brake Assist System with a Preview Function (BAP) designed to prevent accidents by helping drivers with braking actions.

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Abstract: This paper presents an enhanced anti-lock and/or anti-spin BBW (brake-by-wire) dispulsion sphere with electromechanical friction disc, ring and/or drum brakes for controlling not only the braking forces during normal riding and cornering but also the braking forces between the inner and outer M&GWs (motorized and/or generatorized wheels) in a hard turn independently.

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Abstract:As new smart systems for passenger cars are assisting the driver to handle maneuvers in critical and normal situations, brake systems are required to fulfill the compatibility and interface demands. These advanced brake systems will be operated in a remote mode during normal braking and for autonomous brake interventions. Bosch is developing a brake-by-wire system on a hydraulic basis, called "Electrohydraulic Brake EHB". Brake pressure build-up is supplied by a high pressure accumulator. Generation of the high pressure is done by an electric motor driven pump, similar to current ABS systems. Pressure at the wheel brakes is individually controlled by closed-loop pressure control, consisting out of inlet, and outlet valves, pressure sensor and corresponding algorithm. It is specified, that this control must be completely noiseless, proportional, fast, and highly accurate. To raise the acceptance of such a system, it will be introduced with a conventional hydraulic backup. The backup actuates the front wheel brakes. In the normal operating mode the master cylinder is switched to a hydraulic pedal travel simulator to give the right feeling and sensitivity at the brake pedal. The system comes together with ABS, ASR, and VDC functions, optimized by using the wheel brake cylinder pressure information and proportional brake pressure control. It incorporates electronic brake force distribution between front and rear and even left and right thus improving stopping distances and stability, making better use of the rear brakes than conventional systems. It can be shown that ABS and other regulations can be done fully hidden for the driver. No noise from the pressure control or pedal reactions are noticed. Autonomous vehicle guiding systems, such as advanced cruise control, collision avoidance (assist) systems, necessary for Intelligent Vehicle Highway System IVHS, and functional upgrading like hill-holder systems, and parking aids will have an ideal brake basis to act on. Further concepts of integrating various other drivetrain and comfort systems will have a brake system that fulfills their needs. Functional enhancement can be added to the brake system with minimal hydraulic modifications.

13. Otomo, A., Sakai, A., Takasu, T., and Nakamura, K., "Development of regenerative braking system for hybrid vehicle." Report No. SAE 1999-10-0062, Manufacturing Future Mobility, Melbourne, Australia, May 1999.

Abstract: We have developed an innovative braking system, which is highly efficient and provides a natural brake feel, for hybrid vehicle application. The linear-control solenoid valve, which is a constituent element of this system, is expected to become the core hydraulic unit for future brake control systems. This paper reports on a liquid pressure-regenerative braking cooperative system that we have commercialized. It maximizes the efficiency of the regenerative braking system without deteriorating the brake feeling in a vehicle such as a hybrid EV (Electric Vehicle) in which the regenerative brake torque is frequently changed by a motor.

14. Nakamura, E., Soga, M., Sakai, A., Otomo, A., and Kobayashi, T., "Development of electronically controlled brake system for hybrid vehicle." Report No., SAE 2002-01-0300, SAE 2002 World Congress, Detroit, MI, March 2002.

15. Kepner, R. P., "Hydraulic power assist – A demonstration of hydraulic hybrid vehicle regenerative braking in a road vehicle application." Report No., SAE 2002-01-3128, SAE International Truck and Bus Meeting and Exposition, Detroit, MI, Nov. 2002.

Abstract: With the desire for improved fuel economy for road vehicles, there has been increased interest in Hydraulic Hybrid Vehicle (HHV) technology. The inherent power density of HHV makes significant benefits from regenerative braking possible in higher-mass vehicles. Other advances in hydraulic components make HHV practical in a passenger vehicle. A vehicle to demonstrate Hydraulic Power Assist (HPA), a type of HHV using primarily regenerative braking, was built by Ford Motor Company Advanced Powertrain working jointly with the United States Environmental Protection Agency (USEPA) Advanced Technology Division, in the context of a Cooperative Research and Development Agreement (CRADA). A full-size Sport Utility Vehicle was fitted with a hydraulic pump/motor and valve block provided by Ifield Technologies, and carbon fiber accumulators developed by the US EPA. The pump/motor was connected to the vehicle driveshaft in parallel with the conventional powertrain, and a development control system integrated the hydraulic system with the powertrain and braking systems. The vehicle demonstrated the ability to improve fuel economy on a start/stop city- typical driving cycle. It also demonstrated the ability to smoothly integrate hydraulic power with friction braking and with the conventional engine-based powertrain, and to achieve reasonable noise levels. This report includes a description of the system, and initial fuel economy, performance and noise results.

16. Hara, M.; Ohta, M.; Yamamoto, A.; Yoshida, H. 1998. "Development of the brake assist system." Toyota Motor Company, Ltd. (Japan) 5 p. International Technical Conference on Experimental Safety Vehicles. Sixteenth. *Proceedings.* Volume I. Washington, D.C., NHTSA, 1998, p. 497-501. Report No. 98-S2-P-17.

17. Duboka, Arseni, and Todorovi, J., "Innovation of reliability requirements in braking regulations." Report No. SAE 945157, 25th FISITA Congress~Automobile in Harmony with Human Society, Beijing, China, Oct. 1994.

Abstract: Reliability is the ability of a system to perform function in designated environment within specified time interval or amount of work. Reliability of a system comprising less elements is higher than in a system with more elements for the same reliability of elements. Besides, system reliability in series is lower than in parallel configurations. If so, what is the reliability of braking systems today? Braking systems are under permanent improvement. Three directions are recommended: (i) improvements in component characteristics of existing systems, (ii) introduction of new devices (like ABS) in existing systems and (iii) development of new systems, like EBS - Electronic Braking Systems. Intensive development of standards and national/international braking regulations is also evident. Full attention is paid to the performance of vehicle under braking systems themselves, showing significance of the cases that provoke "catastrophic" implications ("Full failures" of a part of system and fade). It means that deterministic approach is presented. Monotonous processes (deformations, wear, aging, corrosion) are less covered. The same applies to reliability and/or maintainability items, and the real stochastic nature of usage conditions and braking system loads is not sufficiently respected. This amy be understood for braking systems comprising mechanical components only. However, the recent comprehensive application of electrical and electronic components requires innovations in braking regulations with respect to reliability requirements. State of the art attempts in the braking technology are analyzed in the paper, with particular emphasize of the newly developed systems. Impacts on reliability characteristics of the system composed with electrical and electronic components is considered. Innovation of braking regulations for more accurate presentation of components and systems reliability requirement is proposed.

18. Gormley, J., Schink, W.A., "Technology innovation 'the industry high wire walk'." Report No., SAE 94C001, Leading Change: The Transportation Electronic Revolution Meeting, Dearborn, MI, Oct., 1994.

Abstract: Development of creative and innovative products is critical to success and long-term survival in the global automotive market. Technology innovation requires a balance of "Visionaries" and "Savants" (specialists) that can balance technology and customer needs. Major inhibitors to an effective innovation process are: low customer value (improper anticipation of customer wants); lack of strategic company objectives;

ineffective product development process; insufficient business and technical capability and external factors (e.g., government regulations). Improvements are suggested along with the enablers, such as the systems engineering approach to effect improvement. A predictive process to assess the merits of innovations is described with examples.

19. Dan McCosh, "Multidisc brakes." *Popular Science*. New York: Jun 1998. Vol. 252, Iss. 6; p. 29.

20. Mellersh, Dennis, and Weber, Doug, "Brakes & clutches [Special report]." *Design Engineering*. Toronto: Oct 1997. Vol. 43, Iss. 10; p. 21

Abstract: Most manufacturers tell us that brakes and clutches are essentially a mature technology. However, there is a "new" product emerging from some suppliers.

21. "Innovation advances mature technology." *Design Engineering*. Toronto: Apr 1996. Vol. 42, Iss. 4; p. 27.

22. McCosh, Dan, "Brake-by-wire." *Popular Science*. New York: Jul 1995. Vol. 247, Iss. 1; p. 31.

A series of innovative brake technologies, most of them advances in antilock braking systems, are being tested by ITT's automotive division. Traction control and antilock brakes are commonplace today. Both rely on a computer precisely monitoring wheel speed and intervening at each wheel either to apply a brake to a spinning wheel, or releasing pressure to avoid a lockup.

An experimental Mercedes-Benz and Audi are fitted with a system that uses the brake pedal only as a signal generator to a computer that directs braking strategy. A simplified system on the Mercedes actuates ABS without the characteristic "chatter"--the brake pedal is isolated from the hydraulics. The Audi's brakes are actuated not by the pedal, but by a tiny knob on the gearshift lever--demonstrating that the pedal is no longer necessary.

Neither system is practical for a production car, but the elements can be developed to allow computer-controlled brakes that detect whether a stop is a "panic" and needs full braking, or that combine with forward-seeking radar for an active cruise control. ITT anticipates that for brake-by-wire to be fully effective, the company will eliminate hydraulics as well, using a completely electromechanical braking system.

At the other end o the spectrum of complexity, a low-cost ABS suitable for small cars eliminates the pump on most ABSs. Instead, reserve hydraulic fluid in an oversize reservoir actuates the system.

23. Scott, David, "Assist for antilock brakes." *Popular Science*. New York: Apr 1995. Vol. 246, Iss. 4; p. 41

In a panic situation you slam your foot on the brake, but probably not hard enough to apply the car's full braking force, nor activate the anti-lock braking system. That's the joint finding of Britain's Lucas Automotive and Mercedes-Benz in Germany, which report that only 30 percent of typical drivers follow speedy reaction with full thrust on the brake. Their answer is a electronic brake servo system planned for some Mercedes cars next year. Called EAS (Electronic Actuation System), it's the biggest advance in braking technology since ABS, says Lucas.

Any abnormally fast pedal movement, regardless of how short a distance the brake pedal actually travels, is detected by a speed sensor. This triggers an electronically controlled solenoid air valve that operates the standard vacuum servo to apply maximum braking force and stop the car. During normal braking in traffic and when cruising on the highway, the EAS is dormant but alert, ready to pounce if it detects another abnormally fast pedal movement.

This EAS concept is easily integrated with other electronic facilities in the car for added safety benefits. It could combine naturally with intelligent cruise control, for example, where safe driving distances between cars are gauged by radar or other sensors, and held by electronic braking as well as by throttling back to the engine. Even with conventional cruise control the EAS could maintain the set speed on long steep descents when engine drag alone is insufficient.

EAS could also function as an automatic "hill holder" when the car is stopped on a gradient, say, at a traffic light or in stop-and-go traffic. The brake would automatically release when the accelerator is pressed.

EAS is a natural for traction control combined with ABS as well, where wheelspin on slick or loose surfaces is prevented and grip restored by selective braking. Active driving stability on fast corners would carry traction control a stage further, restraining tail-slide by judicious braking of the outside wheel on a bend.

In both of these cases, the automatic brake pressure would be applied by tie vacuum servo instead of separately by the usual ABS hydraulic pump, thus simplifying the installation.

24. “Braking new ground with innovative designs.” *Design Engineering*. Toronto: Dec 1994. Vol. 40, Iss. 12; p. 17.

25. “Closed loop clutch/brake positioning control.” *Design Engineering*. Toronto: Dec 1993. Vol. 39, Iss. 12; p. 14.

26. Roger Gilroy, “NHTSA Sees No Need for Rule on Friction Ratings.” *Transport Topics*. Alexandria: Mar 22, 2004. p. 53.

27. Bob Kovacik, “Trailers of tomorrow.” *Trailer Boats*. Carson: Jan 2000. Vol. 30, Iss. 1; p. 82.

28. Anna Wilde Mathews, “U.S. Develops Broad System to Rate Autos' Safety.” *Wall Street Journal* (Eastern edition). New York, N.Y.: Dec 2, 1999

29. Alex Binkley, “Braking in Canada.” *Traffic World*. Newark: Mar 1, 1999. Vol. 257, Iss. 9; p. 47.

30. Evarts, Eric C., “More friction over merits of antilock brake systems.” *Christian Science Monitor.* Boston, Mass.: Feb 6, 1996. p. 3.

31. Kees, M. (Coventry University) ;Burnham, K.J. ;Lockett, F.P. ;Tabor, J.H. ;Williams, R.A. “Hydraulic actuated brake and electromechanically actuated brake systems.” *IEE Conference Publication ,* n 483, 2001, p 43-47. International Conference on Advanced Driver Assistance Systems, Sep 17-18 2001, Bormingham, United Kingdom.

    Absract: Hydraulic actuated brakes (HAB) and electromechanically actuated brake (EMB) systems were studied. The investigation and simulation studies were carried out on a half-car model using the Simulink environment. Antilock-brake system (ABS) control strategies utilizing HAB and EMB technologies were evaluated and compared. The results showed that a front wheel tends to lock up before a rear wheel which was essential for vehicle stability. The overall vehicle behavior of the HAB was similar to real data test set achieved from an ABS manoeuvre under similar conditions.

32. Konishi, Katunobu (Department of Mechanical Engineering, The University of Tokushima) ;Kimura, Masaharu ;Lan, Lin.Nippon Kikai Gakkai Ronbunshu, C Hen. “Disk brakes driven by piezoelectric elements.” *Transactions of the Japan Society of Mechanical Engineers,* Part C , v 69, n 4, April, 2003, p 882-889 Language: Japanese

    Absract: This paper deals with a brake device attached to each wheel of small cars as a component of brake-by-wire system. The brake device consists of a disk brake, a piezoelectric pump, two accumulators and a three position solenoid valve. Mathematical model of the brake device, an approximation formula of the clamping force (CF), and a control scheme of the CF are presented. Simulation results show that (1) the CF large enough for small cars is generated by using a multilayered piezoelectric element of 40 mm diameter, (2) the rise time of the CF is about 0.1 second including the time to contact the disk pad with the disk plate. (3) the formula gives close approximation to the simulated value of CF,

and (4) the feedback control of the CF is achieved by using the disturbance observer. (8 refs.)

33. Yi, K. (School of Mechanical Engineering, Hanyang University) ;Chung, J. "Nonlinear brake control for vehicle CW/CA systems." IEEE/ASME *Transactions on Mechatronics* , v 6, n 1, March, 2001, p 17-25

Absract: A brake control law for vehicle collision warning/collision avoidance (CW/CA) systems has been proposed in this paper. The control law has been designed for optimized safety and comfort. A solenoid-valve-controlled hydraulic brake actuator system for the CW/CA systems has been investigated. A nonlinear computer model and a linear model of the hydraulic brake actuator system have been developed. Both models were found to represent the actual system with good accuracy. Uncertainties in the brake actuator model have been considered in the design of the control law for the robustness of the controller. The effects of brake control on CW/CA vehicle response has been investigated via simulations. The simulations were performed using a complete nonlinear vehicle model. The results indicate that the proposed brake control law can provide the CW/CA vehicles with an optimized compromise between safety and comfort.

34. Yeo, H. (School Mechanical Engineering, Sungkyunkwan University) ;Kim, H. "Hardware-in-the-loop simulation of regenerative braking for a hybrid electric vehicle." *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering* , v 216, n 11, 2002, p 855-864

Absract: A regenerative braking algorithm and a hydraulic module are proposed for a parallel hybrid electric vehicle (HEV) equipped with a continuous variable transmission (CVT). The regenerative algorithm is developed by considering the battery state of charge, vehicle velocity and motor capacity. The hydraulic module consists of a reducing valve and a power unit to supply the front wheel brake pressure according to the control algorithm. In addition, a stroke simulator is designed to provide a similar pedal operation feeling. In order to evaluate the performance of the regenerative braking algorithm and the hydraulic module, a hardware-in-the-loop simulation (HILS) is performed. In the HILS system, the brake system consists of four wheel brakes and the hydraulic module. Dynamic characteristics of the HEV are simulated using an HEV simulator. In the HEV simulator, each element of the HEV powertrain such as internal combustion engine, motor, battery and CVT is modelled using MATLAB SIMULINK. In the HILS, a driver operates the brake pedal with his or her foot while the vehicle speed is displayed on the monitor in real time. It is found from the HILS that the regenerative braking algorithm and the hydraulic module suggested in this paper provide a satisfactory braking performance in tracking the driving schedule and maintaining the battery state of charge.

35. Belschner, R. ;Hedenetz, B. ;Heni, A. ;Nell, J. ;Willimowski, P. ;Kopetz, H. "Brake-by-wire by using a TTP/C communication network." *VDI Berichte* , n 1789, 2003, p 703-722.

Absract: The focus of this paper is the realisation of fault-tolerant electronic architectures for distributed real-time systems in order to replace conventional mechanical or hydraulic backup and fail-safe systems, especially for x-by-wire applications. It is shown by means of the example of brake-by-wire that the safe communication system will play the key role for pure electronic driven systems in future vehicles. Because of the distribution of the system throughout

the car and the very high safety requirements, (class C according to SAE classification) brake-by-wire or steer-by-wire without mechanical or hydraulic backup is very difficult to realise without this key component. Daimler-Benz research designed a brake-by-wire research car without mechanical backup in cooperation with ITT Automotive by using a TTP/C communication network (DB/TU Vienna) for the first time in order to control electromechanical brake actuators (ITT). Since October 1997 the brake-by-wire research car has been used for feasibility study of the brake-by-wire without hydraulic backup, and in particular for the validation of the TTP-C electronic system as well as for the specification of the safety requirements and performance of the electromechanical brake actuators and the power supply.

36. Stolzl, S. (Continental Teves AG and Co. OHG) ;Schmidt, R. ;Klina, W. ;Sticher, T. ;Fachinger, G. ;Klein, A. ;Giers, B. ;Fennel, H. “The electro-hydraulic brake system from Continental Teves; A new challenge for system and method series development.” *VDI Berichte* , n 1789, 2003, p 3457-3472.

    Absract: Sensor-based and electronic brake systems increase the range of functionalities in vehicles and improve driving safety. This is realized by isolating the driver from the wheel brakes and the higher customer value is based on software. The Electrohydraulic brake system (EHB) is the next generation of these intelligent brake systems which will soon be introduced in series production. This paper describes the operation of EHB by Continental Teves and shows the new exciting challenges, as a result for system and product developmet.

37. Huang, J. (Department of Engineering Mechanics, Chongqing University) ;Zhang, J.Q. ;Yang, Y. ;Wei, Y.Q. “Analysis and design of a cylindrical magneto-rheological fluid brake.” *Journal of Materials Processing Technology* , v 129, n 1-3, Oct 11, 2002, p 559-562.

    Absract: A magneto-rheological (MR) fluid brake is a device to transmit torque by the shear force of an MR fluid. An MR rotary brake has the property that its braking torque changes quickly in response to an external magnetic field strength. In this paper, the design method of the cylindrical MR fluid brake is investigated theoretically. The equation of the torque transmitted by the MR fluid within the brake is derived to provide the theoretical foundation in the cylindrical design of the brake . Based on this equation, after mathematical manipulation, the calculations of the volume, thickness and width of the annular MR fluid within the cylindrical MR fluids brake are yielded.

38. Hildebrandt, A. (Department of Control Engineering, Technische Universitat Ilmenau) ;Sawodny, O. ;Trutschel, R. ;Augsburg, K. “Nonlinear control design for implementation of specific pedal feeling in brake-by-wire car design concepts.” *Proceedings of the American Control Conference* , v 2, *Proceedings of the 2004 American Control Conference* (AAC) , 2004, p 1463-1468.

    Absract: Brake-By-Wire means that the direct mechanical link between brake pedal and braking cylinder is completely replaced by an electromechanical braking system. This concept, originally used for aircraft and military only, has massive advantages for implementing in new car designs. As a consequence, the pedal movement can be generated arbitrarily. Ideally, the pedal should behave like a conventional brake . In the paper a simplified model for the desired dynamical behavior of the pedal unit is presented, which can be tuned for specific requirements like pedal force, and pedal movement. Its numerical solution leads, due to the pedal force, to the desired time-indexed trajectory of the pedal. Secondly there is presented a closed loop control strategy for a hydraulic driven pedal consisting of an electric pump, servo valve and a differential cylinder in order to track the reference trajectory. Experimental results show the efficiency of the presented controller for the movement of brake pedals in brake-by-wire car design concepts as pedal simulator.

39. Stoll, Ulrich (DaimlerChrysler AG). "Sensotronic Brake Control (SBC) - The electro-hydraulic brake from Mercedes-Benz." *VDI Berichte* , n 1789, 2003, p 675-685.
    Absract: With SBC (Sensotronic Brake Control), the engineers from DaimlerChrysler and the system supplier Robert Bosch have had success in developing a new type of brake system that completely meets the demands in driving dynamics and comfort. Because of high dynamics and the precise sensor-supported control, it has also been possible to further improve the performance of the integrated safety systems ESP (Electronic Stability Program) and BAS (Brake Assist). SBC will be installed as standard equipment in the new Mercedes SL-class for the first time.

40. Park, Kihong (Grad. Sch. of Automotive Engineering, Kookmin University) ;Heo, Seung-Jin. "A study on the brake-by-wire system using hardware-in-the-loop simulation." *International Journal of Vehicle Design* , v 36, n 1, 2004, p 38-49.

41. Anwar, Sohel (Chassis Advanced Technology Dept., Visteon Corporation). "An anti-lock braking control system for a hybrid electromagnetic/electrohydraulic brake-by-wire system." *Proceedings of the American Control Conference* , v 3, *Proceedings of the 2004 American Control Conference (AAC)* , 2004, p 2699-2704.
    Absract: This paper presents a nonlinear sliding mode type controller for slip regulation in a braking event for a hybrid electromagnetic-electrohydraulic brake-by-wire system. The ABS controller modifies the brake torque command generated by a supervisory controller based on driver's command via brake pedal sensor. The brake torque command is then generated by closed loop actuator control algorithms to control the eddy current brake (ECB) and electrohydraulic brake (EHB) systems. The proposed control algorithm shows very good slip regulation in a braking event on low friction coefficient surfaces when compared with non-ABS braking . Usage of ECB resulted in a smooth ABS stop minimizing the NVH of current hydraulic ABS systems.

42. Trachtler, Ansgar (Robert Bosch GmbH, Corporate Research Development, Chassis Systems). "Integrated vehicle dynamics control using active brake, steering and suspension systems." *International Journal of Vehicle Design* , v 36, n 1, 2004, p 1-12.
    Absract: Active chassis systems like brake , steering, suspension and propulsion systems are increasingly entering the market. In addition to their basic functions, these systems may be used for functions of integrated vehicle dynamics control. A global architecture is required to prevent negative interference, for an optimised functionality and for managing system complexity. Several approaches are known under names like Integrated or Global Chassis Control and Integrated Vehicle Dynamics Control. Vehicle Dynamics Management (VDM) is the Bosch approach for co-ordinating vehicle dynamics functions by integrated control of active chassis systems. Its essential features are a clearly structured, extensible functional architecture with appropriate control structures and system interfaces with physical meaning.

43. Isermann, Rolf (Inst. fur Automatisierungstechnik, Tech. Universitat Darmstadt). "Fault tolerant components for drive-by-wire systems." *VDI Berichte* , n 1789, 2003, p 5057-5083.

Absract: After considering electronic driver assisting systems such as ABS, TCS, ASR, ESP, BA the developments towards drive-by-wire systems with and without mechanical or hydraulic backup are considered. For the design of drive-by-wire systems safety integrity methods like reliability, fault tree, hazard analysis and risk classification are required. Different fault tolerance principles with various forms of redundancy are considered resulting in fail-operational, fail-silent and fail-safe systems. Fault-detection methods are discussed for use in low-cost components. This is followed by some principles for fault-tolerant design of sensors, actuators and communication. A fault tolerant electrical throttle valve and a brake-by-wire system with electronic pedal and electrical brakes are then considered as examples.

44. Sakai, Shin-Ichiro (Inst. Space and Astronautical Sci.) ;Hori, Yoichi . "Advantage of electric motor for anti skid control of electric vehicle." *EPE Journal (European Power Electronics and Drives Journal)* , v 11, n 4, September/November, 2002, p 26-32.

Absract: Electric vehicles (EVs) are driven by motor, which is an excellent actuator for motion control compared to combustion engines or hydraulic braking systems. One essential advantage of motor is its fast and precise torque response. Thus, for EVs, fast feedback control can be applied in EVs. In this paper, such fast feedback control with motor is applied for anti skid control. Some experimental results show the anti skid effect of motor feedback controller, which attempts to increase the equivalent wheel inertia. Then the influence of actuator's response delay is evaluated, resulting that such feedback control is difficult with slow actuator like hydraulic braking system. These discussions indicate the advantages of motor, however, the actual braking systems in most EVs and hybrid EVs (HEVs) are not pure electric ones at this moment. Therefore, regenerative braking control cooperating with hydraulic braking is also proposed and discussed. It reduces the braking distance by 20% in the simulations.

45. Cikanek, S.R. (Ford Research Laboratory) ;Bailey, K.E. "Regenerative braking system for a hybrid electric vehicle." *Proceedings of the American Control Conference*, v 4, 2002, p 3129-3134

Absract: This paper discusses a Regenerative Braking System (RBS) for a Parallel Hybrid Electric Vehicle (PHEV) that performs regenerative energy recovery based on vehicle attributes, thereby providing improved performance, efficiency and reliability at minimal additional cost. A detailed description of the regenerative braking algorithm will presented along with simulation results from a dynamic model of the PHEV exhibiting the regenerative braking performance.

46. "Brakes of the future." *Automotive Engineer*. 1998/09. 23(8) P79.

Absract: The new ultrafast electro-hydraulic brake (EHB) system, developed by Daimler-Benz, could save thousands of lives. Its brakes have already been tested and can reduce a car's stopping distance by several metres; they could be fitted on production cars within a few years. In the EHB system, a new central hydraulic brake unit replaces the conventional brake booster, and an electric pump and high-pressure accumulator are added. Electronically adjustable valves mean that maximum braking pressure can be applied much more quickly than in conventional servo-assisted braking systems. Sensors on the brake pedal detect exactly how much brake pressure is needed, and convert this to braking commands within a fraction of a second. The system can apply precisely the correct braking force to each wheel in an instant. It can even detect when a brake pipe is faulty and then act appropriately. The EHB system could eventually lead to a safe self-driving car, which the driver would not have to steer or brake.

47. "Automotive collision avoidance system field operational test: ACAS/FOT Third annual report." General Motors Corporation, Warren, Mich./ Delphi Delco Electronics Systems, Kokomo, Ind./ Delphi Chassis Systems, Dayton, Ohio/ Hughes Research Laboratories, Malibu, Calif./ HE Microwave, Tucson, Ariz./ Michigan University, Ann Arbor, Transportation Research Institute. 112 p. Sponsor: National Highway Traffic Safety Administration, Washington, D.C. Report No. DOT HS 809 600.

Abstract: In June of 1999, the National Highway Traffic Safety Administration entered into a cooperative research agreement with General Motors to advance the state-of-the-art of rear-end collision warning technology and conduct a field operational test of a fleet of passenger vehicles outfitted with a prototype rear-end collision warning system and adaptive cruise control. The goal of the research program was to demonstrate the state-of-the-art of rear-end collision warning systems and measure system performance and effectiveness using lay drivers driving on public roads in the United States. The five-year program consists of a 2 1/2 year development phase during which refinement of component technologies will continue and be integrated into a prototype test vehicle. In the three-year period of the second program phase, a fleet of ten vehicles will be constructed and outfitted with rear-end collision warning and adaptive cruise control systems and given to volunteer drivers to drive over a period of several weeks. Data collected from on-board vehicle instrumentation will be analyzed and used to estimate potential safety benefits, obtain information on the driving experiences of the volunteer drivers and their acceptance of this next-generation safety technology. The operational test will last approximately one year. This document reports on the activities and results from the end of the first program year of Phase II of this research project.

48. Palkovics, Laszlo (Knorr-Bremse R&D Inst) ;Kovacs, Gabor ;Gianone, Laszlo ;Bokor, Jozsef ;Szell, Peter ;Semsey, Akos. "Vision system for avoidance of lane-departure." *Vehicle System Dynamics* , v 33, n Suppl, *The Dynamics of Vehicles on Roads and on Tracks*' 2000, p 282-292.

Abstract: The paper presents an experimental system for detection and prevention of the unintended lane- departure of road vehicles. The system is realized by a co-operation of a drive stability system and a computer vision system. The detection algorithm does not depend on the type of the lane-boundaries (lane-marks, paved lane-boundary, transition from asphalt to grass) and filters out information marks which do not signalize lane-boundaries. If lane- departure is predicted, then intervention to the vehicle's motion is applied by unilateral braking. A control algorithm is presented which calculates the necessary torque to bring the vehicle back to the lane.

49. Risack, R. (Fraunhofer-Inst) ;Moehler, N. ;Enkelmann, W. "Video-based lane keeping assistant." *IEEE Intelligent Vehicles Symposium, Proceedings* , 2000, p 356-361, Dearbon, MI, USA.

Abstract: We propose a lane keeping assistance system which warns the driver on unintended lane departures . Based on an existing robust video-based lane detection algorithm we compare different methods to detect lane departure . A number of assumptions on driver behaviour in certain situations have been integrated to distinguish between intended and unintended lane departures . We integrated our lane keeping assistant in an experimental car and performed systematic experiments in real traffic situations.

50. Mudaliar, Nikhil; Leblanc, David ; Peng, Huei . "Linear estimator for road departure warning systems." *Proceedings of the American Control Conference*, v 3, *Proceedings of the 2004 American Control Conference (AAC)* , 2004, p 2104-2109

Abstract: Most single vehicle road departure accidents in America occur due to either loss of control or road /lane departure caused by speeding or driver inattentiveness. Many active safety systems currently in use or under development are aimed at preventing accidents either by countering vehicle instability or by trying to prevent road departure . In either case these active safety systems need clean and reliable real-time vehicle dynamics variables to accurately assess the threat levels. Since it is not always feasible to measure the required information, estimation techniques are commonly used to fill in the gap. In this paper, we developed a Kalman filter to estimate two vehicle handling variables that are costly to measure - lateral velocity and relative heading angle. It is shown that it is critical to first obtain an accurate estimation of road super-elevation (bank angle) before those two states can be accurately estimated. By properly assigning the Kalman filter observer gains, we achieved robust estimation performance across a wide array of uncertain conditions. The work reported here will be used to support the data analysis for the Road Departure Crash Warning (RDCW) Field Operational Test, to be carried out at the University of Michigan Transportation Research Institute (UMTRI).

51. Liu, Chia-Shang (Univ of Michigan) ;Peng, Huei . "Road friction coefficient estimation for vehicle path prediction." *Vehicle System Dynamics* , v 25, n Suppl, *Proceedings of the 1995 14th IAVSD Symposium on the Dynamics of Vehicles on Roads and Tracks*, Aug 21-25 1995, Ann Arbor, MI, USA

Abstract: The basic concept of lane departure warning system is to project vehicle trajectory, and compare with the perceived road geometry to calculate a performance metric termed time to lane crossing (TLC). When the calculated TLC is less than a threshold value, the control system will either issue warning signals or take intervention actions. Online estimation of road /tire characteristics is crucial for TLC calculation and the overall lane departure warning system. A disturbance observer has been developed which identifies the road surface friction coefficient. The effect of road surface condition on vehicle path prediction is the main performance evaluation metric. (12 refs.)

52. Jonner, W. D.; Winner, H.; Dreilich, L., and Schunck, E., "Electrohydraulic brake system - the first approach to brake-by-wire technology," SAE Special Publication *Current and Future Developments in ABS/TCS and Brake Technology*, Proceedings of the 1996 SAE International Congress & Exposition, Detroit, MI, Feb. 1996.

53. Dominguez-Garcia, Alejandro D., Kassakian, John G., Schindall, Joel E., "A backup system for automotive steer-by-wire, actuated by selective braking." IEEE Annual Power Electronics Specialists Conference, v 1, 2004 IEEE 35th Annual Power Electronics Specialists Conference, PESC4, 2004, p 383-388.

Abstract: In this paper we propose an alternate approach to improve Steer-by-Wire (SbW) reliability in which we utilize Brake-Actuated Steering (BAS) as an independent secondary backup steering system. In SbW systems, component and module redundancy is the common approach used to maintain the steering function when a failure occurs. Unfortunately this adds a significant amount of complexity and cost and, what is more important, it is not possible to overcome unanticipated and common mode failures of the SbW system. BAS utilizes the torque generated by selective wheel braking and/or acceleration to actuate the steering mechanism. With this approach, if the primary steering system (SbW) fails uncovered or there is a common mode failure, the steering rack is decoupled from the primary steering actuator and the wheels are instead steered by the torque generated by application of asymmetric braking (or acceleration). BAS, as well as SbW, will be a heavy user of power electronics, electrical actuators, sensors and sophisticated control systems, many of which are already available from electronic stability systems (e.g., ESP), which are becoming more common in passenger cars. In this paper we detail the characteristics of the BAS system and provide the models necessary for designing appropriate power electronics and control systems.

54. Shaheen, S., Heffernan, D., Leen, G., "A comparison of emerging time-triggered protocols for automotive X-by-wire control networks," *Proceedings of the Institution of Mechanical Engineers*, Part D: *Journal of Automobile Engineering*, v 217, n 1, 2003, p 13-22.

Abstract: This paper compares the emerging time-triggered protocols that will find use in automotive control networks. At present there is no de facto standard in the automotive industry for in-vehicle networking based on the time-triggered model. As the industry is pushing towards incorporating X-by-wire technology (X standing for steer, brake, shift, etc.) for future cars, car manufacturers are working towards agreeing industry standards for X-by-wire control system applications. Currently there are four protocols based on the time-triggered paradigm which are competing for the X-by-wire automotive market. These protocols are TTCAN, TTP/C, FlexRay and Byteflight.

55. Kobe, Gerry, "Fluidless brakes." *Automotive Industries AI*, v 177, n 3, Mar, 1997, p 65-66.

Abstract: Today, it seems that every manufacturer has a program in place to move from conventional hydraulic, to fluidless, electronic braking. Brake manufacturers agree that brake-by-wire (BBW) will evolve in stages. The first step will be electro-hydraulic (E-H) braking to help manufacturers gain experience with the technology. Fluidless BBW technology is also coming. In fact, one manufacturer, Delphi Chassis Systems already have a fluidless brake on the rear of the GM EV1.

56. Schwarz, R., Isermann, R., Bohm, J., Nell, J., and Rieth, P., "Modeling and control of an electromechanical disk brake." *Proceedings of the 1998 SAE International Congress & Exposition*, Feb, 1998, Report No. SAE 980600,

Abstract: In the scope of a research collaboration, ITT Automotive Europe and Darmstadt University of Technology are developing control strategies for a low-cost Brake-by-Wire system. The development environment described in this paper includes simulation models for both the electromechanical brake and the vehicle as well a brake test bench and test vehicle. Different approaches for clamping-force, peripheral-force and brake-torque sensing are also compared.

57. Bray, J.T., Walker, G.R., Simpson, A.G., Greaves, M.C., and Guymer, B.D., "Brake system performance requirements of a lightweight electric/hybrid rear wheel drive vehicle." *International Journal of Vehicle Autonomous Systems*, v 1, n 3-4, 2003, p 436-

Abstract: This paper investigates the braking performance requirements of the UltraCommuter, a lightweight series hybrid electric vehicle currently under development at the University of Queensland. With a predicted vehicle mass of 600 kg and two in-wheel motors each capable of 500 Nm of peak torque, decelerations up to 0.46 g are theoretically possible using purely regenerative braking. With 99% of braking demands less than 0.35 g, essentially all braking can be regenerative. The wheel motors have sufficient peak torque capability to lock the rear wheels in combination with front axle braking, eliminating the need for friction braking at the rear. Emergency braking levels approaching 1 g are achieved by supplementation with front disk brakes. This paper presents equations describing the peak front and rear axle braking forces which occur under straight line braking, including gradients. Conventionally, to guarantee stability, mechanical front/rear proportioning of braking effort ensures that the front axle locks first. In this application, all braking is initially regenerative at the rear, and an adaptive 'by-wire' proportioning system presented ensures this stability requirement is still satisfied. Front wheel drive and all wheel drive systems are also discussed. Finally peak and continuous performance measures, not commonly provided for friction brakes, are derived for the UltraCommuter's motor capability and range of operation.

58. Masayuki, S., Shimada, M., Sakamoto, J. I., and Otomo, A., "Development of vehicle dynamics management system for hybrid vehicles: ECB system for improved environmental and vehicle dynamic performance." *JSAE Review*, v 23, n 4, October, 2002, p 459-464.

Abstract: In anticipation of the increased needs to further reduce exhaust gas emissions and improve fuel consumption, a new brake-by-wire system called an "electronically controlled brake" system (hereafter referred to as "ECB") has been developed. With this brake system, which is able to smoothly control the hydraulic pressure that is applied to each of the four wheel cylinders on an individual basis, functional enhancements can be added by appropriately modifying its software. This paper discusses the necessity of the ECB, the system configuration and the results of its application on hybrid vehicles.

59. Fijalkowski, B., "Very advanced automotive powertrains with the crankless prime movers." *Automotive and Transportation Technology Congress and Exhibition*, Report No. SAE 2001-01-3421, Barcelona, Spain, Oct. 2001

Abstract: Comprehensive background and feasibility studies have been performed that show a novel very advanced automotive crankless prime mover, that is, a 2-, 4- or even 5-stroke thermodynamic cycle, twin-opposed-piston, crankless internal combustion engine (ICE), called the Fijalkowski engine-generator/motor (FE-G/M), has a great deal of potential in meeting and exceeding requirements for ride- by-wire (RBW) or x-by-wire (XBW) automotive mechatronic control system, comprising drive-by-wire (DBW) all-wheel- drive-able (AWD) propulsion as well as brake-by-wire (BBW) all-wheel-brakeable (AWB) dispulsion mechatronic control hypo-systems for smart automotive vehicles (AV), most of all, for hybrid electric vehicles (HEV). The paper is focusing on main innovations and trends for a ride-by-wire (RBW) or x-by-wire (XBW) automotive mechatronic control system, comprising drive-by-wire (DBW) all-wheel- driveable (AWD) propulsion as well as brake-by-wire (BBW) all-wheel-brakeable (AWB) dispulsion mechatronic control hyposystems, and magneto-rheological fluid (MRF) mechatronic translational-motion-to-rotary- motion (TM-RM) & rotary- motion-to-rotary-motion (RM-RM) commutator prime mover, that is, the FE-G/ M.

60. Wilkie , W., High, J. and Bockman, J.., "Reliability Testing of NASA Piezocomposite Actuators." *Langley Technical Reports*, NASA Langley Research Center, Hampton, Virginia, USA,. 2002.

Abstract: NASA Langley Research Center has developed a low-cost piezocomposite actuator which has application for controlling vibrations in large inflatable smart space structures, space telescopes, and high performance aircraft. Tests show the NASA piezocomposite device is capable of producing large, directional, in-plane strains on the order of 2000 parts-per-million peak-to-peak, with no reduction in free-strain performance to 100 million electrical cycles. This paper describes methods, measurements, and preliminary results from our reliability evaluation of the device under externally applied mechanical loads and at various operational temperatures. Tests performed to date show no net reductions in actuation amplitude while the device was moderately loaded through 10 million electrical cycles. Tests were performed at both room temperature and at the maximum operational temperature of the epoxy resin system used in manufacture of the device. Initial indications are that actuator reliability is excellent, with no actuator failures or large net reduction in actuator performance.

61. Jansson, J., Johansson, J., and Gustafsson, F., "Decision Making for Collision Avoidance Systems." SAE 2002 World Congress, Detroit, MI, March 2002, SAE Report No. 2002-01-0403.

Abstract: Driver errors cause a majority of all car accidents. Forward collision avoidance systems aim at avoiding, or at least mitigating, host vehicle frontal collisions, of which rear-end collisions are one of the most common. This is done by either warning the driver or braking or steering away, respectively, where each action requires its own considerations and design. We here focus on forward collision by braking, and present a general method for calculating the risk for collision. A brake maneuver is activated to mitigate the accident when the probability of collision is one, taking all driver actions into considerations. We describe results from a simulation study using a large number of scenarios, created from extensive accident statistics. We also show some results from an implementation of a forward collision avoidance system in a Volvo V70. The system has been tested in real traffic, and in collision scenarios (with an inflatable car) showing promising results.

62. Zehnder, J.W.; Kanetkar, S.S.; Osterday, C.A. "Variable rate pedal feel emulator designs for a brake-by-wire system." SAE 1999 World Congress, Detroit, MI, March 1999, SAE Report No. 1999-01-0481.
    Abstract: An important element of a brake-by-wire system is the pedal feel emulator. This device is tuned for each vehicle application to provide the desired pedal force/travel relationship while operating the brake system in the normal powered mode. The two designs examined apply to a hydraulic-based, brake-by-wire system and are used in conjunction with a master cylinder to meet failed power braking requirements. Both designs use uniquely different spring technologies to provide a variable rate curve to simulate the pedal feel characteristics of conventional vacuum-boosted brake system.

63. Mao, Y.J. (Department of Mechanical Engineering, National Chiao Tung University) ;Tseng, C.H. "A study of a pressure regulator for an anti-lock braking system for low-powered vehicle." *Proceedings of the Institution of Mechanical Engineer*s, Part D: *Journal of Automobile Engineering* , v 218, n 8, August, 2004, p 793-803.
    Absract: This study proposes an innovative design of a hydraulic pressure regulator for an anti-lock braking system, called EconABS, for extremely low-powered vehicles. This system utilizes the braking force generated at the caliper as the energizing force to reduce the pressure in the caliper and to prevent over-braking . This approach limits power consumption and means that only minimal electric power is manipulated to supply the electric circuit and logic valve. The mathematical model is derived and the operating performance is simulated. Experimental results for the static situation are retrieved using a test rig. The experimental results represent consistency with the simulations as the design parameters are modified. The regulator design is shown to be a feasible solution for extremely low-powered vehicles.

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