TP 11826

# EVALUATION OF ABS TECHNOLOGY ON HIGHWAY B-TRAIN DOUBLE TANKER VEHICLES

Prepared for the
Transportation Development Centre
Policy and Coordination Group
Transport Canada

FINAL REPORT

December, 1994

BBL
Beauchemin - Beaton - Lapointe Inc.
CONSULTING ENGINEERS

2045, Stanley Street, Montréal, Québec H3A 2V4

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Un sommaire en français de ce rapport est inclus avant la Table des matières.

Transport Canada / Transports Canada

# PUBLICATION DATA FORM

| 1. Transport Canada Publication No. | 2. Project No. | 3. Recipient's Catalogue No. |
|---|---|---|
| TP 11826E | 7455 | |

**4. Title and Subtitle**

Evaluation of ABS Technology on Highway B-Train Double Tanker Vehicles

**5. Publication Date**

December 1994

**6. Performing Organization Document No.**

TDC 9058

**7. Author(s)**

Jacques R. Tourville

**8. Transport Canada File No.**

ZCD1465-543

**9. Performing Organization Name and Address**

Beauchemin-Beaton-Lapointe Inc.
Consulting Engineering
2045 Stanley Street
Montreal, Quebec
H3A 2V4

**10. DSS File No.**

XSD90-00159-(611)

**11. DSS or Transport Canada Contract No.**

T8200-0-0533/01-XSD

**12. Sponsoring Agency Name and Address**

Transportation Development Centre (TDC)
800 René Lévesque Blvd. West
6th Floor
Montreal, Quebec
H3B 1X9

**13. Type of Publication and Period Covered**

Final report (1991-1994)

**14. Project Officer**

Sesto Vespa

**15. Supplementary Notes (Funding programs, titles of related publications, etc.)**

Project partly funded by Transport Canada's Road Safety and Motor Vehicle Regulation Directorate and the Ontario Ministry of Transportation.

**16. Abstract**

The objectives of this project were to monitor and evaluate the performance and impacts of ABS systems installed on B-trains under actual fleet operating conditions. Vehicle monitoring, conducted in 1992-93, included real-time on-board recording of ABS system operation as well as collection of detailed records, to the extent of their availability, of maintenance and operational parameters potentially affected by the presence of ABS systems. These maintenance and operational records were compiled for similar vehicles with and without ABS, thus enabling comparisons and the quantification of the impact of the ABS systems.

The available ABS equipment was found to be remarkably reliable and maintenance free in the type of operation monitored. It has a marginal impact (less than 1%) on vehicle operating cost and a significant potential for increasing traffic safety through its test-track proven capacity to reduce stopping distances and to improve vehicle control during braking. It has been estimated that, for the vehicle operation observed during this evaluation project, a functioning ABS system would generate, in reaction to severe braking and/or slippery road conditions, approximately 100 major ABS events during 100 000 km of operation, out of which 20 would occur at speeds above 75 km/h. This is particularly significant for the pup trailer component of the B-train, which was found to generate ABS system activations 3 to 4 times more frequently than either the tractor or lead trailer components.

ABS technology was well received and readily accepted during this project. Vehicle drivers, unanimously, would rather drive ABS equipped vehicles. Fleet operators unanimously recommend that all new vehicles be equipped with ABS systems. The successful general introduction of ABS technology to the transportation industry will, however, require further efforts and investment by equipment suppliers to provide adequate training and familiarization programs for drivers, maintainers and operators to ensure the local availability of specialized support and maintenance services. They must also pursue further engineering development and improvement of specific system components. These necessary improvements do not reveal any basic equipment design flaws or shortcomings but are rather consistent with those that could be expected with the introduction of any new, relatively complex technology to the transportation industry.

| 17. Key Words | 18. Distribution Statement |
|---|---|
| ABS, antilock brakes, trucks, B-trains, monitoring, evaluation, performance, fleet, service conditions | Limited number of copies available from the Transportation Development Centre |

| 19. Security Classification (of this publication) | 20. Security Classification (of this page) | 21. Declassification (date) | 22. No. of Pages | 23. Price |
|---|---|---|---|---|
| Unclassified | Unclassified | — | xiv, 78, apps | — |

Transports Canada Transport Canada

# FORMULE DE DONNÉES POUR PUBLICATION

| 1. N° de la publication de Transports Canada | 2. N° de l'étude | 3. N° de catalogue du destinataire |
|---|---|---|
| TP 11826E | 7455 | |

**4. Titre et sous-titre**

Evaluation of ABS Technology on Highway B-Train Double Tanker Vehicles

**5. Date de la publication**

Décembre 1994

**6. N° du document de l'organisme exécutant**

TDC 9058

**7. Auteur(s)**

Jacques R. Tourville

**8. N° de dossier — Transports Canada**

ZCD1465-543

**9. Nom et adresse de l'organisme exécutant**

Beauchemin-Beaton-Lapointe Inc.
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Montréal, Québec
H3A 2V4

**10 N° de dossier — ASC**

XSD90-00159-(611)

**11. N° de contrat — ASC ou Transports Canada**

T8200-0-0533/01-XSD

**12. Nom et adresse de l'organisme parrain**

Centre de développement des transports (CDT)
800, boul. René-Lévesque Ouest
6e étage
Montréal (Québec)
H3B 1X9

**13. Genre de publication et période visée**

Rapport final (1991-1994)

**14. Agent de projet**

Sesto Vespa

**15. Remarques additionnelles (Programmes de financement, titres de publications connexes, etc.)**

Le financement de ce projet a été assumé en partie par la Direction de la sécurité routière et de la réglementation automobile de Transports Canada et par le ministère des Transports de l'Ontario

**16. Résumé**

L'objectif de ce projet consistait à surveiller et à contrôler des systèmes de freinage anti-blocage (ABS) installés sur des trains autoroutiers de type B à double citernes afin d'en évaluer la performance et les impacts dans des conditions opérationnelles normales. La collecte des données, effectuée en 1992-93, comportait l'enregistrement électronique en temps réel du fonctionnement des systèmes ABS ainsi qu'une série de données disponibles relatives aux paramètres d'entretien et d'opération des véhicules susceptibles d'être affectés par les systèmes ABS. Ces données sur l'entretien et l'opération ont été compilées pour des véhicules de même type avec et sans systèmes ABS, permettant ainsi de quantifier par comparaison les impacts des systèmes ABS.

L'équipement ABS actuellement disponible s'est avéré remarquablement fiable et durable, et il n'affecte que de façon marginale (inférieure à 1 %) les coûts totaux d'opération du véhicule. Il présente un potentiel significatif d'amélioration de la sécurité routière. Cette amélioration résulte essentiellement d'une réduction de la distance d'arrêt et d'un contrôle accru du véhicule lors d'un freinage d'urgence dans des conditions difficiles. Cet aspect est particulièrement significatif en rapport avec la composante remorque du véhicule qui génère environ de 3 à 4 fois plus d'activité du système ABS que les composantes tracteur ou semi-remorque. Il est estimé que, pour le type de véhicule et d'opérations observées durant cette évaluation, un système ABS générerait, en réponse à des freinages violents et/ou des conditions de chaussée glissante, approximativement 100 événements ABS majeurs durant des déplacements totalisant 100 000 kilomètres dont 20 à des vitesses particulièrement dangereuses supérieures à 75 km/h.

La technologie ABS a été bien accueillie et acceptée au cours de ce projet tant par les conducteurs, qui unanimement préfèrent conduire des véhicules équipés de freins ABS, que par les gestionnaires, qui à l'unanimité recommanderaient que tous les nouveaux véhicules soient équipés de systèmes ABS. Le succès de la vulgarisation de la technologie ABS au sein de l'industrie du camionnage exigera, toutefois, des efforts et des investissements additionnels de la part des fournisseurs d'équipement afin de mettre sur pied des programmes de formation et de vulgarisation s'adressant aux conducteurs, aux techniciens d'entretien et aux gestionnaires, d'assurer la disponibilité locale de services adéquats de support technique et d'entretien et de procéder à l'amélioration ou à la modification de certaines composantes du système. Ces améliorations et modifications nécessaires ne révèlent pas de fautes majeures dans la conception des équipements, mais doivent être considérées comme normales dans le cadre de l'introduction d'une nouvelle technologie relativement complexe à l'industrie du transport routier.

| 17. Mots clés | 18. Diffusion |
|---|---|
| ABS, freins antiblocage, camions, trains routiers de type B, contrôle, évaluation, performance, parc, conditions de service | Le Centre de développement des transports dispose d'un nombre limité d'exemplaires. |

| 19. Classification de sécurité (de cette publication) | 20. Classification de sécurité (de cette page) | 21. Déclassification (date) | 22. Nombre de pages | 23. Prix |
|---|---|---|---|---|
| Non classifiée | Non classifiée | — | xiv, 78, ann. | — |

**ACKNOWLEDGEMENTS**

Beauchemin-Beaton-Lapointe Inc. wishes to express its gratitude to the following persons and organisations:

- For guidance and support, to the members of the project Executive Committee:

  Mr John R. Billing, Ministry of Transportation of Ontario
  Mr M. Clark, Forest Engineering Research Institute of Canada
  Mr Ron Covello, Ministry of Transportation of Ontario
  M. Jean Grandbois, Ministère des Transports du Québec
  Mr Gordon Ferg, Shell Canada Products Ltd
  Mr Douglas Jacques, Transport Canada
  M. Jacques Richard, Société de l'assurance automobile du Québec
  Mr Peter Roy, Canadian Liquid Air Ltd
  Mr Sesto Vespa, Transportation Development Centre

- For collaboration and assistance, to the owners and operators of test vehicles:

  Shell Canada Limited
  Canadian Liquid Air Limited
  Harmac Transportation Inc.
  Transport R.M.T. Inc.
  Lévis Transport Limitée

  as well as to their maintenance contractors and subcontractors.

- For professional and technical contribution and participation, to:

  Robert Bosch Corporation
  Rockwell-Wabco Automotive
  Vehicle Monitor Corporation ( VMC )
  LDK Engineering Inc.

Mr Sesto Vespa of the Transportation Development Centre, Policy and Coordination Group, provided, as Project Officer, invaluable assistance and guidance to the project team by making available his vast expertise on research and development projects in the transportation field.

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## SUMMARY

The objective of this project was to monitor and evaluate the performance and impacts of ABS systems installed on highway B-Train double tanker vehicles under actual fleet operating conditions. The costs and benefits associated with use of ABS technology were to be included in the evaluation.

The B-Train double tanker vehicle was selected primarily because of its multi-trailer configuration and the type of operations it encompasses. It has specific braking problems since it is commonly driven partially loaded, in urban areas, with the second trailer lightly loaded. Under these conditions, the brakes will be applied frequently and its braking efficiency may be quite low. It is commonly used to carry dangerous goods and should therefore be a priority target for the application of ABS. It was determined to be the vehicle of choice for high gross weights in Canada through research conducted by the Roads and Transportation Association of Canada (RTAC) under its Vehicle Weights and Dimensions Study.

The project was initiated in 1991. Vehicle monitoring and data collection took place in 1992 and during the first half of 1993. Vehicle monitoring included real-time on-board recording of ABS system operation as well as collection of detailed records, to the extent of their availability, of maintenance and operational parameters potentially affected by the presence of ABS systems. These maintenance and operational records were compiled for similar vehicles with and without ABS thus enabling comparisons and the quantification of the impact of the ABS systems.

The available ABS equipment was found to be remarkably reliable and maintenance free in the type of operation monitored and has a marginal impact (less than 1%) on total vehicle operating cost. It has a significant potential for increasing traffic safety. The enhanced safety aspects flow from reduced stopping distance and improved vehicle control during emergency braking under adverse conditions. This is particularly significant for the pup trailer component of the B-Train which was found to generate ABS system activations 3 to 4 times more frequently than either the tractor or lead trailer units.

It is estimated that, for the type of vehicle and operation monitored under this evaluation project, a functioning ABS system would generate, in reaction to severe braking and/or slippery road conditions, approximately 100 major ABS events during 100 000 km of travel, out of which 20 would occur at especially dangerous speeds above 75 km/h.

ABS technology was well received and readily accepted. Vehicle drivers, unanimously, would rather drive ABS equipped vehicles. Fleet operators unanimously recommend that all new vehicles be equipped with ABS systems.

The successful general introduction of ABS technology to the transportation industry will, however, require further efforts and investment by equipment suppliers to:

- Provide adequate training and familiarization programs for drivers, maintainers and operators
- Assure the local availability of specialized support and maintenance services
- Provide further engineering development and improvements of specific system components such as:
    - the warning light arrangement which, by indicating the status of both trailer ABS systems by a single light, is sometimes confusing;
    - the wheel speed sensor assembly which easily goes out of adjustment, the friction secured component of the assembly can readily be pulled out of adjustment during a wheel change or other vehicle maintenance operations in the vicinity of the wheels as well as crooked wheels and worn or loose bearings, thus requiring frequent adjustments;
    - wheel speed sensor adjustment, which is too difficult and time consuming and which requires wheels to be pulled thus potentially leading to other problems;
    - the electrical power voltage requirement which is set too high.

These necessary improvements do not reveal any basic equipment design flaws or shortcomings but are rather consistent with those that could be expected with the introduction of any new, relatively complex technology to the transportation industry.

It is recommended that the use of ABS technology and its application to all heavy vehicles in the highway freight transportation industry be promoted and facilitated as much as possible. This recommendation particularly applies to double trailer combinations, such as the B-Train which has multiple articulation points and frequently operates under lightly loaded conditions.

## SOMMAIRE

L'objectif de ce projet consistait à surveiller et à contrôler des systèmes de freinage anti-blocage (ABS) installés sur des trains autoroutiers de type B à double citernes afin d'en évaluer la performance et les impacts dans des conditions opérationnelles normales. Les avantages-coûts reliés à l'utilisation de la technologie ABS devaient être compris dans cette évaluation.

Le choix du train routier de type B à double citernes a été motivé tout d'abord en raison de sa configuration multi-remorques et du type d'opérations qu'il est appelé à effectuer. Il accuse des problèmes de freinage particuliers résultant de son utilisation fréquente avec un chargement partiel, dans des zones urbaines et avec un chargement minimal de la remorque. Dans ces conditions, les freinages sont fréquents tandis que l'efficacité du freinage est susceptible d'être substantiellement réduite. Il est fréquemment utilisé pour le transport de matières dangereuses et devrait, par conséquent, constituer une cible prioritaire pour la mise en application de la technologie ABS. Il a été identifié comme véhicule lourd par excellence au Canada par l'Association des routes et transports du Canada (ARTC) à partir des résultats d'une étude antérieure sur les poids et dimensions des véhicules

Ce projet a été amorcé en 1991, tandis que la collecte des données a été effectuée en 1992 et durant la première moitié de 1993. L'information recueillie sur les véhicules comportait l'enregistrement électronique en temps réel du fonctionnement des systèmes ABS ainsi qu'une série de données disponibles relatives aux paramètres d'entretien et d'opération des véhicules susceptibles d'être affectés par les systèmes ABS. Ces données sur l'entretien et l'opération ont été compilées pour des véhicules de même type avec et sans systèmes ABS, permettant ainsi de quantifier par comparaison les impacts des systèmes ABS.

L'équipement ABS actuellement disponible s'est avéré remarquablement fiable et durable, et il n'affecte que de façon marginale (inférieure à 1 %) les coûts totaux d'opération du véhicule. Il présente un potentiel significatif d'amélioration de la sécurité routière. Cette amélioration résulte essentiellement d'une réduction de la distance d'arrêt et d'un contrôle accru du véhicule lors d'un freinage d'urgence dans des conditions difficiles. Cet aspect est particulièrement significatif en rapport avec la composante remorque du véhicule qui génère environ de 3 à 4 fois plus d'activité du système ABS que les composantes tracteur ou semi-remorque.

Il est estimé que, pour le type de véhicule et d'opérations observées durant cette évaluation, un système ABS générerait, en réponse à des freinages violents et/ou des conditions de chaussée glissante, approximativement 100 événements ABS majeurs durant des déplacements totalisant 100 000 kilomètres dont 20 à des vitesses particulièrement dangereuses supérieures à 75 km/h.

La technologie ABS a été bien accueillie et acceptée au cours de ce projet tant par les conducteurs, qui unanimement préfèrent conduire des véhicules équipés de freins ABS, que par les gestionnaires, qui à l'unanimité recommanderaient que tous les nouveaux véhicules soient équipés de systèmes ABS.

Le succès de la vulgarisation de la technologie ABS au sein de l'industrie du camionnage exigera, toutefois, des efforts et des investissements additionnels de la part des fournisseurs d'équipement afin de :

- Mettre sur pied des programmes de formation et de vulgarisation s'adressant aux conducteurs, aux techniciens d'entretien et aux gestionnaires.
- Assurer la disponibilité locale de services adéquats de support technique et d'entretien.
- Procéder à l'amélioration ou à la modification de certaines composantes du système, telles que :
    - le module de lumières d'avertissement qui, en indiquant par une seule lampe l'état de fonctionnement des systèmes des deux remorques, engendre parfois de la confusion;
    - le mécanisme de mesure de vitesse installé aux roues du véhicule perd son ajustement trop facilement. En effet, la composante du mécanisme maintenue en place par simple friction peut facilement être déplacée lors d'un changement de pneu ou de tout autre opération d'entretien à proximité de la roue ainsi que sous l'effet d'une jante tordue ou d'un roulement défectueux. Il en résulte la nécessité d'ajustements fréquents;
    - l'ajustement du mécanisme de mesure de vitesse aux roues est trop compliqué et exige trop de temps. Il nécessite l'enlèvement de la roue ce qui souvent génère des problèmes additionnels d'ajustement;
    - le voltage d'alimentation électrique requis pour l'opération du système ABS semble être trop élevé.

Ces améliorations et modifications nécessaires ne révèlent pas de fautes majeures dans la conception des équipements, mais doivent être considérées comme normales dans le cadre de l'introduction d'une nouvelle technologie relativement complexe à l'industrie du transport routier.

Il est donc recommandé que l'utilisation de la technologie ABS, de mème que ses applications à tous les véhicules lourds, au sein de l'industrie du camionnage autoroutier, doivent être encouragées et facilitées le plus possible. Cette recommandation s'adresse tout particulièrement aux combinaisons de remorques doubles, telles que le train routier de type B qui possède plusieurs points d'articulation et qui opère fréquemment avec des charges légères.

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## 1.0 INTRODUCTION

This document constitutes the final report resulting from a project titled "Evaluation of ABS Technology on Highway B-Train Double Tanker Vehicles" conducted by Beauchemin-Beaton-Lapointe, Consultants, between 1991 and 1994. It is being submitted to the Transportation Development Centre as the executing agency representing the co-sponsors of the project, Transport Canada and the Ministry of Transportation of Ontario.

The subsequent chapters of this report provide:

- A description of the project in terms of: its background and objectives; the participation and collaboration of two vehicle fleet operators; the implemented data collection plan.

- Descriptions of project details and parameters with respect to: vehicle characteristics and operations for both participating fleets (Shell Canada and Canadian Liquid Air); ABS systems characteristics and installation for both suppliers of evaluated systems (Bosch and Rockwell-Wabco); electronic on-board monitoring equipment provided by the Vehicle Monitor Corporation.

- Analyses of the collected data and the corresponding project findings in terms of:

    - ABS systems performance: operation, reliability, maintenance requirements and user perception;

    - ABS systems impact on vehicle operation: tire wear and replacement, braking system maintenance and safety record;

    - ABS systems cost impact: system installation and maintenance costs, vehicle maintenance cost and overall vehicle operating cost.

- An assessment of the above project findings through comparisons with those reported in National Highway Traffic Safety Administration (NHTSA) and Society of Automotive Engineers (SAE) publications of the results of similar and/or comparable ABS evaluation projects.

- The conclusions and the recommendations derived from the results and findings of this project.

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## 2.0 PROJECT DESCRIPTION

The "Evaluation of ABS Technology on Highway B-Train Double Tanker Vehicles" project is part of an ongoing cooperative program, co-sponsored by Transport Canada and the Ministry of Transportation of Ontario, designed to address vital issues in highway freight transportation. The approach favoured in addressing these issues is to undertake studies and projects which actively involve, through a cooperative effort, the federal and provincial governments as well as selected representatives of the transportation industry.

### 2.1 BACKGROUND

The present project is set against a background of studies and reports from various sources in Canada and the United States, which have investigated heavy articulated vehicle dynamic stability issues and improvements. One particular area of investigation has been Anti-lock Brake Systems, which have been shown to provide improved stability and performance during braking.

#### 2.1.1 NHTSA Study

The NHTSA of the United States is considering mandating ABS on new heavy commercial vehicles. It is possible that ABS will be mandated for such vehicles in the U.S. starting in 1996.

Antilock braking equipment has improved dramatically since 1975 when mandatory use of ABS was introduced in the U.S. under Federal Motor Vehicle Safety Standard (FMVSS) 121. The braking systems developed at that time were found to be unreliable and were reportedly responsible for causing accidents. One of the main problems was determined to be frequent malfunctions caused by electromagnetic interference. As a result, a 1978 court decision struck down the stopping distance requirement that resulted in mandatory use of ABS.

NHTSA realised that it would have to proceed on the basis of independent testing before making any decision on mandating ABS again. NHTSA undertook a durability testing program in consultation with industry wherein 200 tractors were placed in service with ABS, 40 with each of the following five systems:

- WABCO
- Bosch
- Midland
- Rockwell
- Bendix.

The NHTSA program, started in March 1989 with the first tractor in service in September 1989, extended over three years with its final report[1] issued in March 1992. NHTSA worked with seven truck manufacturers and 17 fleets in six different cities to put the program together. The Southwest Research Institute was the prime program contractor who managed the work and retained subcontractors as required, particularly to collect data from the various sites from which the test vehicles were operated. In addition, NHTSA had representatives in the field who make two to four visits per year to each fleet location in order to maintain the necessary levels of cooperation and participation.

### 2.1.2 Transport Canada and Ontario Ministry of Transportation Program

The intent of this "ABS Technology Demonstration" program[2], which was developed and funded by Transport Canada and the Ontario Ministry of Transportation, does not involve further development of ABS technology. Rather, it is meant to give this technology a higher profile and provide industry with information on the costs, benefits, general performance, and durability (including maintainability and reliability) based on operational experience in Canada. It is further intended to promote the treatment of ABS technology as a vehicle system by involving both tractor and trailer manufacturers, to assist in the introduction of ABS to trailer applications and to help to make ABS an easily available option on new heavy vehicles. The program also provided data for consideration in cost-benefit assessments of possible future regulations in this area.

The Canadian research initiative is intended to complement rather than repeat on-going work in the U.S. This project is included under the TC/US DOT Memorandum of Understanding Covering Research and Development in Transportation (Addendum no. 5 - Traffic and Motor Vehicle Safety Research) known as the Volpe/Jamieson agreement. The various projects and studies conducted under this program have already generated a number of reports amongst which the following are most closely related to this project and/or are used as references in the present report.

- A technical paper[3], presented by Mr Sesto Vespa of TDC in June 1992 at the CSME Forum held in Montreal, which discusses the braking performance of large trucks and the contribution of antilock systems.

- Reports[4,5] of track tests conducted by ABS systems manufacturers at the Centralia test facilities of the Ministry of Transportation of Ontario. The results of both tests, as reported, demonstrate the very significant contribution of the systems in reducing stopping distance as well as increasing vehicle stability and control during braking and lane change manoeuvres on various pavement surface conditions.

    - Robert Bosch Corporation report[4] of track testing, conducted in September 1990, of one of its ABS systems installed on a Shell Canada Limited B-Train.
    - Rockwell-Wabco Automotive report[5] of track testing, conducted in June 1992, of one of its ABS systems installed on a Canadian Liquid Air Limited B-Train.

- A report[6] on an evaluation project of an antilock braking system and automatic slip regulation installed on a log-hauling truck and monitored over a one-year in-service operation under severe terrain and weather conditions in British Columbia.

- A report[7], published by the Ontario Ministry of Transportation, of the results of a testing program of an antilock braking system installed on an A-Train vehicle.

## 2.2 OBJECTIVES

The objectives of this demonstration project were to determine:

- The operational performance characteristics, reliability, durability and maintainability of ABS systems, installed on several complete train units, under actual operating conditions.

- The impact of ABS systems on vehicle operation in terms of costs, safety and availability and maintenance.

In order to achieve these general objectives, the following project goals[2] were initially formulated by the project sponsors for this project:

- To install ABS systems on a fleet of ten B-Train double tanker vehicles in normal service.

- To install electronic data recorders on each vehicle equipped with ABS.

- For comparative purposes, to select a control fleet of ten non-ABS B-Train double tanker vehicles with comparable operating and equipment characteristics for participation in the evaluation.

- Data gathering to be consistent with that undertaken by NHTSA and to be continuous over a period of not less than twelve months.

## 2.3 VEHICLE TYPE

The B-Train double tanker vehicle was selected for this ABS evaluation project for a variety of reasons:

- It was determined to be the vehicle of choice for high gross weights by the Vehicle Weights and Dimensions Study.

- It has specific braking problems since it is commonly driven partially loaded, in urban areas, with the second trailer lightly loaded. Under these conditions, the brakes will be applied frequently and its braking efficiency may be quite low.

- It is commonly used to carry dangerous goods and should therefore be a priority target for the application of ABS.

The B-Train double tanker is generally operated in ways that make it particularly suited for evaluation. It is usually operated as a train married with a tractor, operating from a fixed base. Married pair operation facilitates testing and evaluation as it permits the use of a smaller fleet of trailers, reduces potential equipment problems due to coupling and uncoupling, and reduces variation in vehicle characteristics, thus highlighting ABS contribution to performance.

The operation of B-Trains as married units also avoids problems associated with the use of a non-standard electrical connector between tractor and trailers. These vehicles are also commonly used by knowledgeable operators with good safety records, who follow good operating, maintenance and record keeping practices. This facilitates data collection and analysis.

## 2.4 FLEET PARTICIPATION

The selection of participating fleet operators took into account the following criteria:

- Since ABS retrofit may result in excessive costs and less than ideal performance, selected fleets preferably had to offer vehicles with factory installed ABS systems.

- Since uncontrolled variables, such as vehicle age and condition, had to be minimised to better allow ABS-related parameters monitoring, selected fleets preferably had to offer new vehicles which could be monitored from their initial service date.

- Since non-ABS reference vehicles were required to quantify ABS system impact on operation parameters, selected fleets had to operate comparable ABS and non-ABS units from the same location and on similar service.

The above selection criteria significantly restricted the number of potential fleet operators which qualified for participation in the project. Furthermore, since B-Train double tankers are not generally acquired in large numbers, several operators had to be selected to provide the required sample size for the project.

The selected fleet operators entered into an agreement with the project sponsors through which:

- The operators would conduct an evaluation of available ABS equipment and make their own selection for installation on their vehicles.

- The operators would order their new vehicles with factory installed ABS systems.

- The project sponsors would cover the marginal cost to the operators related to the ABS systems which would remain on the vehicles at the end of the project.

- The operators would facilitate and participate in vehicle monitoring and data collection during the project.

### 2.4.1 Shell Canada Limited

Shell Canada Limited agreed to provide six ABS-equipped vehicles and six non-ABS reference vehicles operated from four different locations:

- Hamilton : 1 ABS unit + 1 reference unit
- Toronto : 2 ABS units + 2 reference units
- Montreal : 2 ABS units + 2 reference units
- Ottawa : 1 ABS unit + 1 reference unit.

### 2.4.2 Canadian Liquid Air Limited

Canadian Liquid Air Limited (CLA) agreed to provide maintenance data and operator comments. CLA operated four ABS-equipped and 2 non-ABS units under relatively well controlled conditions from its Midale (Saskatchewan) facility as well as one ABS-equipped unit out of Moncton (New-Brunswick).

## 2.5 DATA COLLECTION PLAN

The original project plan specified three specific areas of data collection, as outlined hereafter and on Figure 1, to enable the subsequent analyses required by the study objectives.

### 2.5.1 ABS Monitoring

The ABS systems installed on the B-Trains were subjected to two types of monitoring:

- Through an electronic monitoring system installed on each vehicle which recorded on a continuous real-time basis the status and operational parameters of the ABS system, thus providing basic data on the performance and reliability of the system.

- Through the detailed maintenance records of each vehicle and ABS system to determine and quantify the reliability and maintainability of the system.

### 2.5.2 ABS Impact on Vehicle Operation

The operation records of each ABS-equipped unit and each non-ABS reference unit were collected and analysed with respect to parameters on which the ABS systems may have had an impact such as:

- Safety record.

- Tire tread wear and replacement, in terms of both rates and costs.

- Braking system wear and repairs, in terms of both rates and costs.

### 2.5.3 ABS Perception

Interviews were conducted with ABS-equipped vehicle drivers, maintainers and operators/owners in order to determine their perception of ABS systems as they may affect:

- Safety and driving habits.

- Overall vehicle maintenance and related costs.

- Overall impact on vehicle operation and costs.

**Figure 1**

**SUMMARY OF DATA COLLECTION PLAN**

| TYPES OF DATA | SOURCES OF DATA |
|---|---|
| **ABS MONITORING** | |
| • ABS System Performance & Reliability | • Electronic continuous real-time recordings of ABS system status and operations through on-board equipment installed in parallel with the ABS system on each vehicle |
| • ABS System Maintainability | • Maintenance records of vehicles and ABS systems, particularly warranty service records, to establish type, frequency and cost of ABS system maintenance |
| **ABS IMPACT ON VEHICLE OPERATION** | |
| • ABS System Impact on Safety | • Safety records and accident reports for both ABS-equipped and non-ABS reference vehicles |
| • ABS System Impact on Tire Wear and Replacement | • Tire tread depth measurements recorded on periodic inspection reports for both ABS-equipped and non-ABS reference vehicles to establish impact in terms of wear rate, replacement frequency and cost |
| • ABS System Impact on Braking System Wear and Repairs | • Maintenance records of both ABS-equipped and non-ABS reference vehicles to establish impact in terms of rate, frequency and cost |
| **ABS PERCEPTION** | |
| • Driver Perception in Terms of Safety and Driving Habits | • Individual personal or telephone interviews with the drivers normally assigned to ABS-equipped vehicles |
| • Maintainer Perception in Terms of Maintainability and Cost | • Individual personal interviews with maintenance foremen to obtain opinions on both the maintainability of the ABS systems and their impact on general vehicle maintenance and related costs |
| • Operator Perception in Terms of Vehicle Operation and Cost | • Individual personal interviews with fleet operation managers to obtain opinions on ABS systems as they may impact vehicle operation, availability and cost |

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# 3.0 PROJECT DETAILS AND PARAMETERS

This chapter provides specific project details and parameters related to:

- Vehicles monitored for data collection
- ABS systems installed on the monitored vehicles
- On-board electronic ABS monitoring equipment installed on the vehicles
- Availability of data on vehicle operation

It also describes the implementation of the original data collection plan and its modifications, during the course of the project, imposed by conditions and decisions which were as much unforeseeable as they were beyond the control of the management and technical personnel conducting the data collection phase of the study.

## 3.1 VEHICLES

The B-Train double tanker vehicles monitored during the data collection phase of this project are illustrated on Figure 2 in both the Shell Canada and Canadian Liquid Air configurations and liveries.

It should be noted that this study was initiated in the early part of 1991 as the Canadian economy was experiencing a general downturn which prompted the two selected fleets to review their hauling needs and procedures. These revisions resulted in substantial modifications to the planned numbers and characteristics of monitored vehicles as well as to fleet operations and availability of data. The following vehicle descriptions for each fleet highlight these modifications while their impact is reflected in Chapter 4 - Data Analysis and Project Findings.

### 3.1.1 Shell Canada Fleet

Shell Canada contributed twelve double tanker B-Trains, six each of ABS-equipped and non-ABS reference units, operated out of four regional plants located in Hamilton, Toronto, Montreal and Ottawa. These vehicles were used to deliver bulk quantities of petroleum products such as gasoline, diesel fuel and heating oil. They operated both in urban areas and on intercity highways over a yearly average distance of approximately 100 000 kilometres each thus providing an excellent representation of diversified operating conditions for the evaluation purposes of this project.

Figure 2

**CONFIGURATIONS AND LIVERIES OF MONITORED B-TRAINS**


**Shell Canada Limited**


**Canadian Liquid Air Limited**

#### 3.1.1.1 Vehicle Characteristics

Each Shell Canada unit consisted of the following three components:

- A tractor mounted on ten tires arranged as two on the front steer axle and four each on the two drive rear axles
- A lead trailer, having a capacity of approximately 30 000 litres (capacity varied slightly between the different units) stored in four separate compartments, mounted on eight tires on two axles plus an additional two or four tires on a lift-axle present on some units
- A pup trailer also having a capacity of approximately 30 000 litres in four compartments and mounted on eight tires on two axles.

The general characteristics of the twelve Shell Canada units are listed in Table 1 which highlights the divergence between the actual study vehicles characteristics and the original selection criteria of factory installed ABS systems, new vehicles to be monitored from their initial service date, uniformity of configuration and characteristics of all ABS-equipped and non-ABS reference vehicles.

It should also be noted that, of these twelve vehicles, the following two contributed only partially to the data collection effort:

- The ABS-equipped unit operated out of Hamilton was involved in a major non-braking related accident and was completely destroyed by fire approximately seven months into the data collection year
- A non-ABS reference unit operated out of Montreal suffered numerous mechanical breakdowns and, since hauling capacity requirements were declining, was used very sparingly during the data collection year.

#### 3.1.1.2 Fleet Operation

Shell Canada Limited took two corporate decisions relative to vehicle maintenance and ownership, immediately prior to and during this project, which had major impacts on the data collection effort:

- At the end of 1991 vehicle maintenance, which had been performed by Shell employees in garage facilities at each plant, was contracted out to specialised firms which in turn sub-contracted specific maintenance items, such as tires and braking systems, to other more specialised firms. This obviously multiplied the number of

**Table 1**

**SHELL CANADA LIMITED FLEET - CHARACTERISTICS OF VEHICLES**

| VEHICLE IDENTIFICATION | | VEHICLE CHARACTERISTICS | | | ABS SYSTEM CHARACTERISTICS | | |
|---|---|---|---|---|---|---|---|
| Ref. No | Location | Component | Make | In-Service Date | Make | Installation Type | Date of Installation |
| **ABS-EQUIPPED UNITS** | | | | | | | |
| ABS-1 | Hamilton | Tractor | Kenworth | May '90 | Bosch | Original | |
| | | Trailers | Hutchinson | July '82 | Bosch | Retrofit | October '90 |
| ABS-2 | Toronto | Tractor | Kenworth | May '90 | Bosch | Original | |
| | | Trailers | Hutchinson | January '87 | Bosch | Retrofit | September '90 |
| ABS-3 | Toronto | Tractor | Kenworth | May '90 | Bosch | Original | |
| | | Trailers | Hutchinson | January '87 | Bosch | Retrofit | October '90 |
| ABS-4 | Montreal | Tractor | Kenworth | April '90 | Bosch | Original | |
| | | Trailers | Remtec | March '90 | Bosch | Retrofit | February '91 |
| ABS-5 | Montreal | Tractor | Kenworth | April '90 | Bosch | Original | |
| | | Trailers | Remtec | March '90 | Bosch | Retrofit | February '91 |
| ABS-6 | Ottawa | Tractor | Kenworth | June '90 | Bosch | Original | |
| | | Trailers | Hutchinson | January '82 | Bosch | Retrofit | October '90 |
| **NON-ABS REFERENCE UNITS** | | | | | | | |
| REF-1 | Hamilton | Tractor | Kenworth | May '90 | | | |
| | | Trailers | Hutchinson | June '82 | | | |
| REF-2 | Toronto | Tractor | Kenworth | May '90 | | | |
| | | Trailers | Hutchinson | January '87 | | | |
| REF-3 | Toronto | Tractor | Kenworth | May '90 | | | |
| | | Trailers | Hutchinson | January '87 | | | |
| REF-4 | Montreal | Tractor | Kenworth | July '88 | | | |
| | | Trailers | Remtec | August '83 | | | |
| REF-5 | Montreal | Tractor | Kenworth | July '88 | | | |
| | | Trailers | Westank | June '87 | | | |
| REF-6 | Ottawa | Tractor | Kenworth | May '90 | | | |
| | | Trailers | Hutchinson | January '82 | | | |

sources and formats of vehicle maintenance data as well as reduced the uniformity of maintenance standards and procedures. Furthermore a number of these contractors and sub-contractors were retained on per-kilometre rates and considered their actual detailed operations and costs as confidential and commercially sensitive information

- In the summer of 1992, Shell Canada sold all its B-Trains to independent trucking firms with which it then entered into hauling service contracts. This decision introduced to the data collection effort additional variables in term of sources, format and reliability of data as well as dependence on the cooperation of new vehicle owners who were neither informed about nor committed to the project and its objectives.

### 3.1.2 Canadian Liquid Air Fleet

In late 1991, immediately prior to the inception of the data collection phase, Canadian Liquid Air, which was to contribute two ABS-equipped and two non-ABS reference units to the project, terminated the use of B-Trains from its originally proposed Varennes operation. A single ABS-equipped unit has been utilised regularly to haul refrigerated liquid oxygen between Montreal and Moncton with its maintenance base in Moncton. It has generated minimal vehicle maintenance data and it has not experienced a single ABS-related maintenance problem. Furthermore, meaningful data analysis is not possible in the absence of a similar non-ABS vehicle operated under similar conditions which could serve as a reference unit for comparison purposes.

Canadian Liquid Air, however, has been operating six identical B-Trains, four with ABS systems and two without, on one route out of their Middle operation since March 1992. The maintenance records of these vehicles provide an excellent source of statistically valid data since internal variables have been minimised through the application of uniform and constant maintenance procedures and standards. Vehicle maintenance data from these six units, although not part of the original data collection plan, have been included in this report because of its relevance and availability.

#### 3.1.2.1 Vehicle Characteristics

The more significant characteristics, in terms of this evaluation project, of the vehicles operated by Canadian Liquid Air out of Midale are the following:

- All six tractors and four of the trailer pairs are equipped with factory-installed Rockwell-Wabco ABS systems and were placed in service between September 1991 and March 1992.

- Two trailer pairs are non-ABS and have been in service since 1989.

The Moncton based B-Train was retrofitted with Rockwell-Wabco ABS systems during a general re-build operation and placed back into service in March 1992.

#### 3.1.2.2 Fleet Operation

This Canadian Liquid Air Midale fleet of B-Trains is used exclusively to haul liquefied carbon dioxide, on a continuous twenty-four-hour-per-day basis, between the CLA plant in Midale and oil extraction operations in Medicine Hat a distance of approximately 600 kilometres. The vehicles accumulate approximately 300 000 kilometres per year each of mostly highway travelled distance.

The vehicles are maintained, under a fixed "per-kilometre-travelled" cost contract in Midale by a specialised firm which provided some detailed information on its overall maintenance operations and costs.

The lead and pup trailers are operated as "married pairs" but the tractors form a "pool" from which units are assigned to trailer pairs on a random basis.

These fleet operation characteristics combined with the vehicle characteristics result in a test sample which significantly differs from the original selection criteria and introduce data variables and parameters which are quite different from those of the initial data collection plan. Their data are not readily comparable with that collected from the Shell Canada vehicles. Consequently, the vehicles were never closely monitored by the project team. However, they are closely monitored by their operator and maintainer and their data contribution to this project was in terms of providing general maintenance data as well as driver, maintainer and operator perception of ABS.

Due to changing Shell and CLA fleet operations resulting from market conditions and their resulting impacts on project costs and schedules, it was decided not to electronically monitor the CLA vehicles. At the time that the decision had to be taken on whether to equip the CLA vehicles with an electronic monitoring system, data already in hand from the Shell vehicles indicated that this electronic monitoring would not be necessary.

## 3.2 ABS SYSTEMS

The intent of this section of the report is not to provide a detailed description of the ABS systems installed on the monitored vehicles as this is more aptly available from the technical specifications published by each system manufacturer. It is, however, meant to convey basic and general information on system configuration, components and installation required for meaningful understanding of the monitoring conducted and the findings of this study.

Substantially more information is provided on the Bosch ABS system installed on the Shell Canada vehicles. These were electronically monitored and periodically inspected during the data collection year by the project team. The Rockwell-Wabco ABS system installed on the Canadian Liquid Air vehicles operated out of Midale and these were neither monitored nor inspected by the project team for schedule and cost reasons as discussed previously. CLA and its maintenance contractor provided the data in this report concerning the CLA vehicles and the Rockwell-Wabco ABS system.

### 3.2.1 Robert Bosch Corporation

The Robert Bosch Corporation was selected by Shell Canada Limited to supply the ABS systems to be installed on the double tanker B-Train vehicles which were assigned to participate in this evaluation project.

The initial installation of the ABS systems entailed the following:

- The ABS-equipped tractors, manufactured by Kenworth, were delivered to Shell between May and July of 1990 with the 4S/4K ABS factory-installed systems where 4S/4K means 4 wheel speed sensors and 4 modulation valves.

- The ABS-equipped lead trailers were retro-fitted with 6S/4K ABS systems (speed sensors at 6 wheels and 4 channels controlling brake modulation valves) between September 1990 and February 1991.

- The ABS-equipped pup trailers were retro-fitted with 4S/2K ABS systems (speed sensors at 4 wheels and 2 channels controlling brake modulation valves) during the same period.

- The six tractors were equipped with ABS systems Model Gamma IIE and their six trailer pairs with ABS systems model Kappa. All system installations and subsequent adjustments/modifications were performed by or under the supervision of a Bosch technician.

- The ABS systems and their installation on all units were basically equivalent with only minor air brake piping variations. However, one of the Toronto tractors was equipped with the ABS/ASR option, where ASR stands for traction control.

- The Electronic Control Units (ECU) of the trailer ABS systems were replaced with a newer version between December 1991 and January 1992. The only difference between the original and replacement ECU was an improved casing which provided better protection of the enclosed electronic equipment.

The basic configuration of the ABS system, as installed on the Shell Canada vehicles, is illustrated in Figure 3. The main components of this system, illustrated in Figures 4, are the following:

- A speed measuring device installed on each of the wheels monitored by the ABS system and comprising:

    - A toothed pulse ring mounted on the hub of the wheel

    - A speed sensor fitted in a spring loaded pressure clamp supported in a mounting block carried on the axle or, on tractor steer axle wheels, in a pre-drilled hole in a non-rotating part of the brake assembly and an extension cable connecting the sensor to the corresponding ECU

    It will be noted that most but not all axle ends have one speed monitored wheel.

- Each unit component (tractor, lead trailer, and pup trailer) has an independent ECU which performs the following functions:

    - Monitoring of the wheel speed inputs and determination of actual or imminent wheel "lock-up" as perceived through calculation of the difference between the speed of any given wheel and the vehicle speed assumed to be the average speed of the other monitored wheels

    - Actuation, when actual or imminent wheel "lock-up" has been detected, of a Pressure Modulation Valve to limit or relieve braking system air pressure at the identified wheel or combination of wheels to eliminate or prevent the "lock-up" condition

    - Performance of continuous self-diagnostic testing of the ABS system to determine its operational status. If system or equipment failures are detected through this process, the ECU immediately goes to fail-safe mode and activates the "ABS warning light" in the tractor cabin and electronically registers, as a "blink code", the type, nature and location of the identified failure. There is a procedure to retrieve the "blink code" information from the ECU.

- Pressure Modulation Valves mounted in line with the brake actuator of each wheel or wheel pair. These valves, when actuated by electric impulses generated by the ECU, will either release the air pressure already in the actuator or prevent further braking system air pressure from entering the actuator thus eliminating or preventing actual or imminent wheel "lock-up". It will be noted that a parallel control configuration is used on the tractor and trailer tandem axles. This enables the control of both actuators on one side of a tandem axle using a single valve while assuring that all wheels are protected by the ABS system.

- An electrical power distribution network from the tractor electrical system to each ECU of the ABS system. Electrical power supply is provided directly from the ignition circuit in the case of the tractor ECU and through special connector cables, between the tractor and lead trailer, and between the lead and pup trailer, to supply each trailer ECU.

- An "ABS warning light" feature which is meant to provide information to the vehicle driver on the operating status of the ABS systems. It is materialised by two lights, one for the tractor system and one for both trailer systems, which should:

    - Come ON when the vehicle ignition is turned on.

    - Go OFF when the vehicle is first moved and remain OFF while the vehicle is in operation indicating that the system and all its components are functioning as intended.

  Any other light activation is an indication of an ECU-identified system or equipment failure which requires attention and correction.

- A "fail-safe" feature, incorporated in the electronic instructions of each ECU, by which the ECU will de-activate the ABS system it controls, reverting braking to that of the standard vehicle system, and activate the corresponding "ABS warning light" whenever and while it detects a system or equipment failure. Thus a functioning and reliable "ABS warning light" feature is important since it is the only warning given to the driver of the vehicle that part of or the whole ABS system has been de-activated and that the corresponding superior braking and stability characteristics are no longer available to the driver should an emergency stopping situation arise.

**Figure 3**
**CONFIGURATION OF BOSCH ABS SYSTEM**
**AS INSTALLED ON THE SHELL CANADA FLEET VEHICLES**

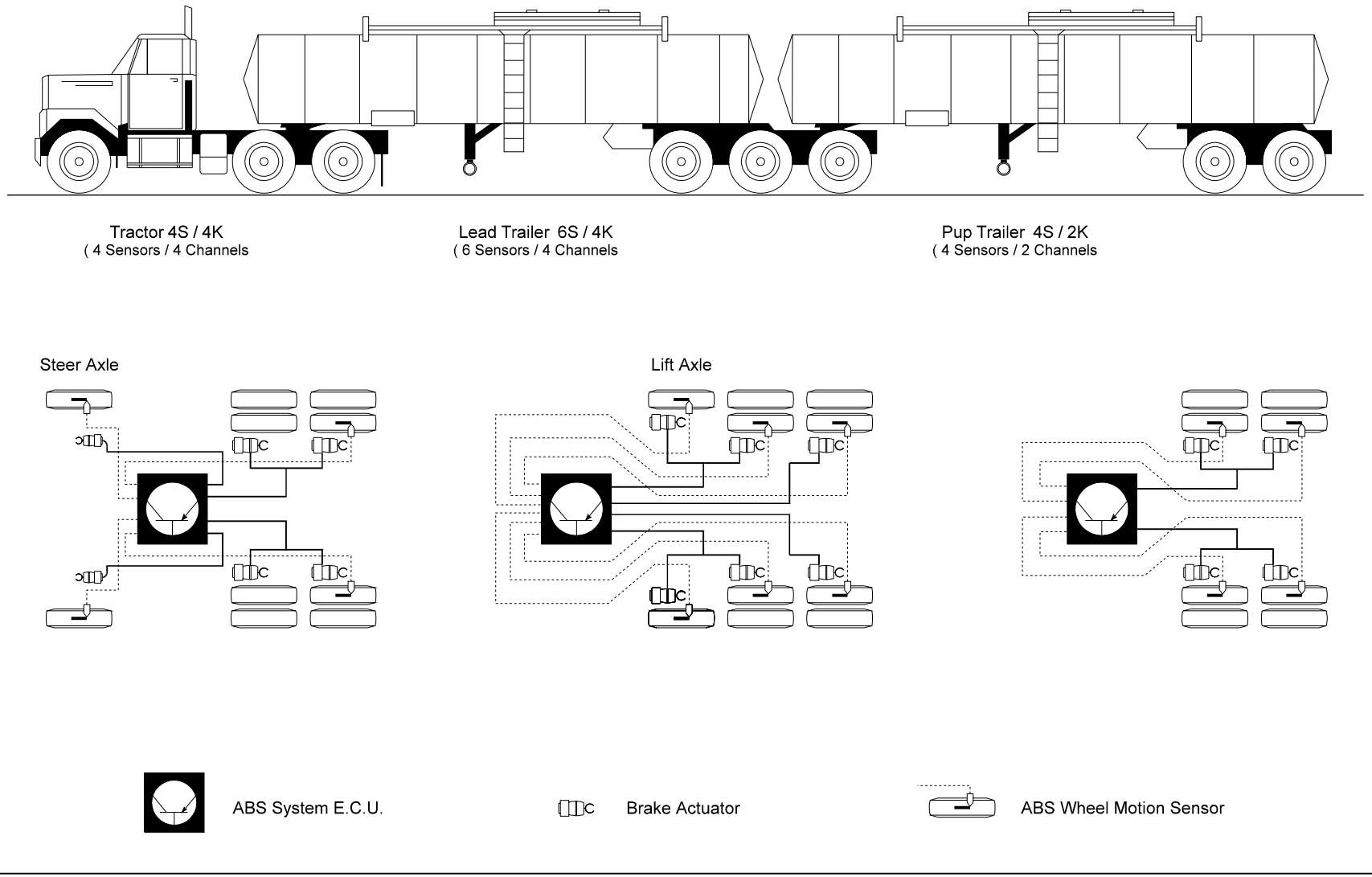
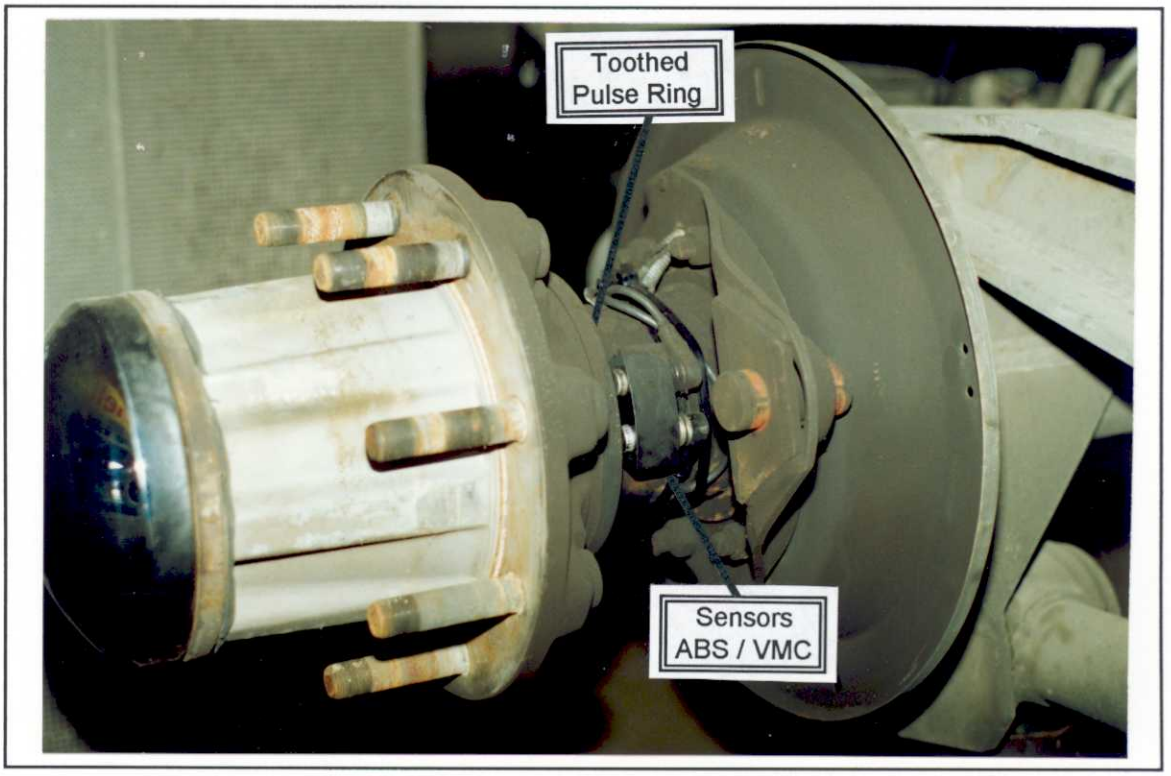
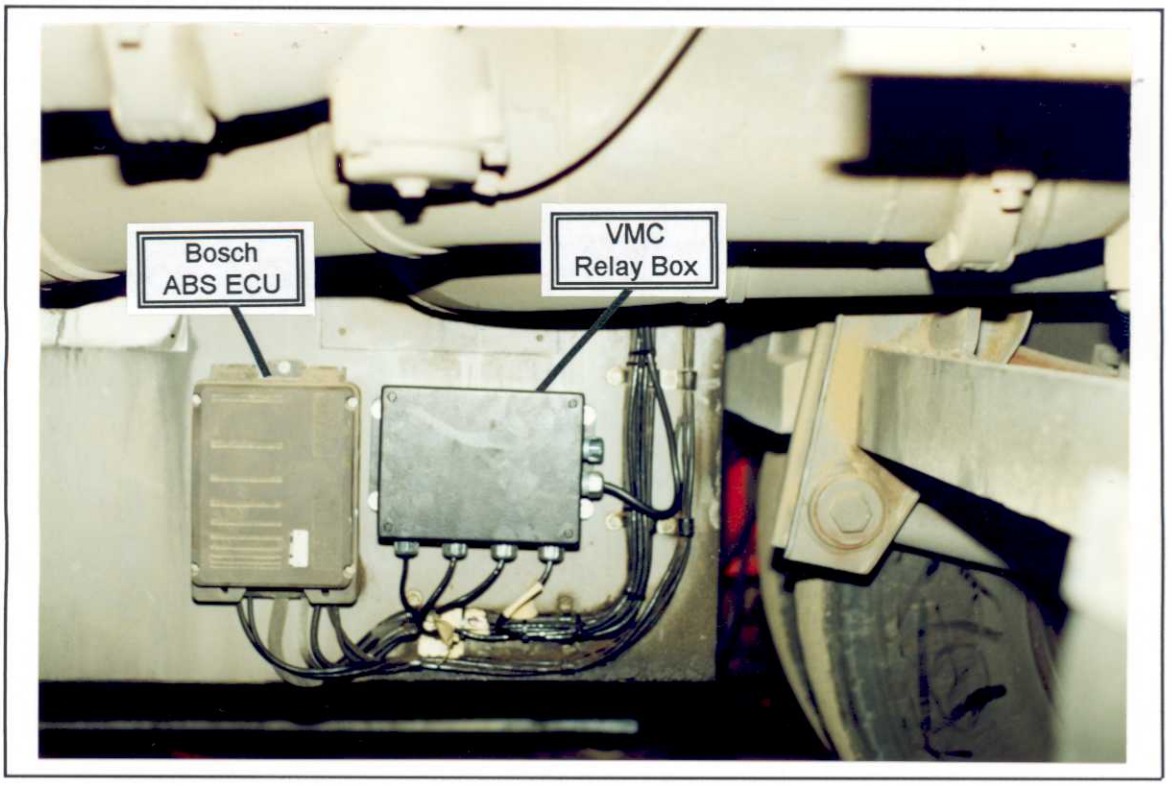


Figure 4

**BOSCH ABS SYSTEM - MAJOR COMPONENTS**




**a) Speed Measurement Device (Tractor Drive Axle Installation)**

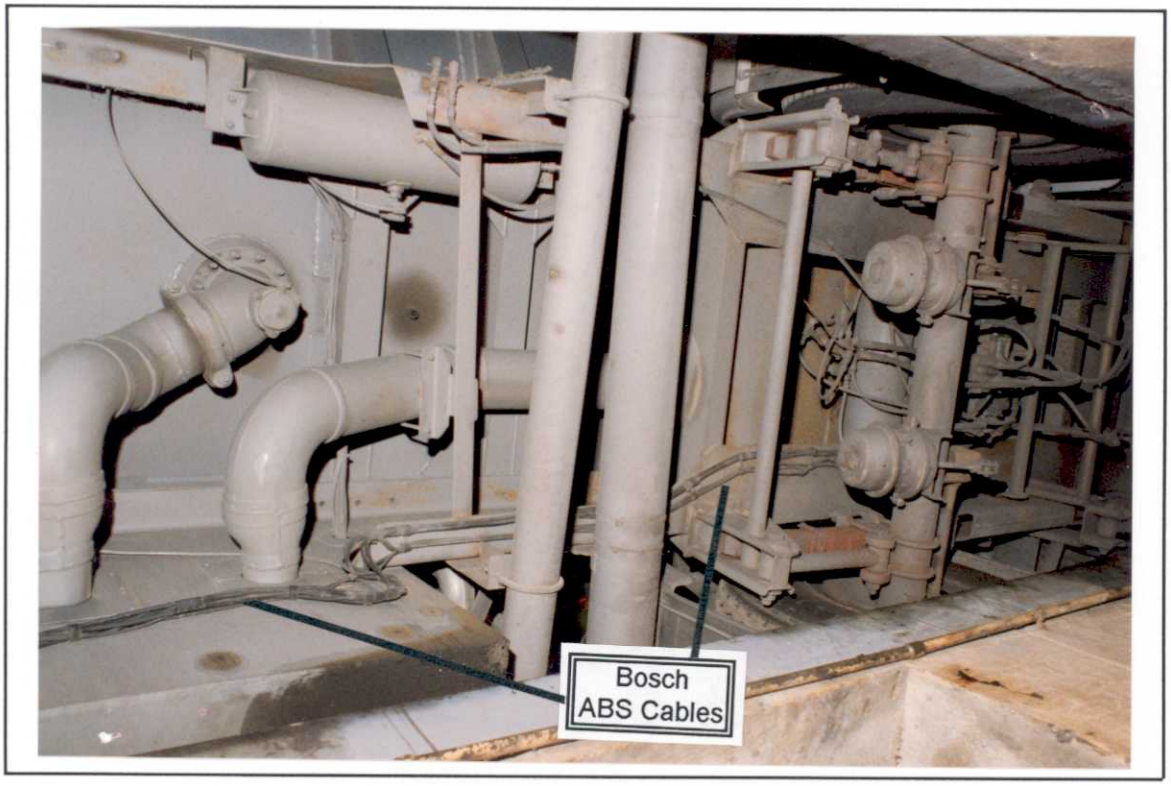



**b) Electronic Control Unit - ECU ( 4-Channel Pup Trailer Configuration)**

Figure 4 cont'd

**BOSCH ABS SYSTEM - MAJOR COMPONENTS**


**c) Pressure Modulating Valve - PMV (4-Channel Pup Trailer Configuration)**




**d) Typical Wiring (Underside of Pup Trailer)**

### 3.2.2 Rockwell-Wabco Automotive

Rockwell-Wabco Automotive was selected by Canadian Liquid Air Limited to supply ABS systems for installation on its double tanker B-Train vehicles. The main characteristics of this equipment and its installation are the following:

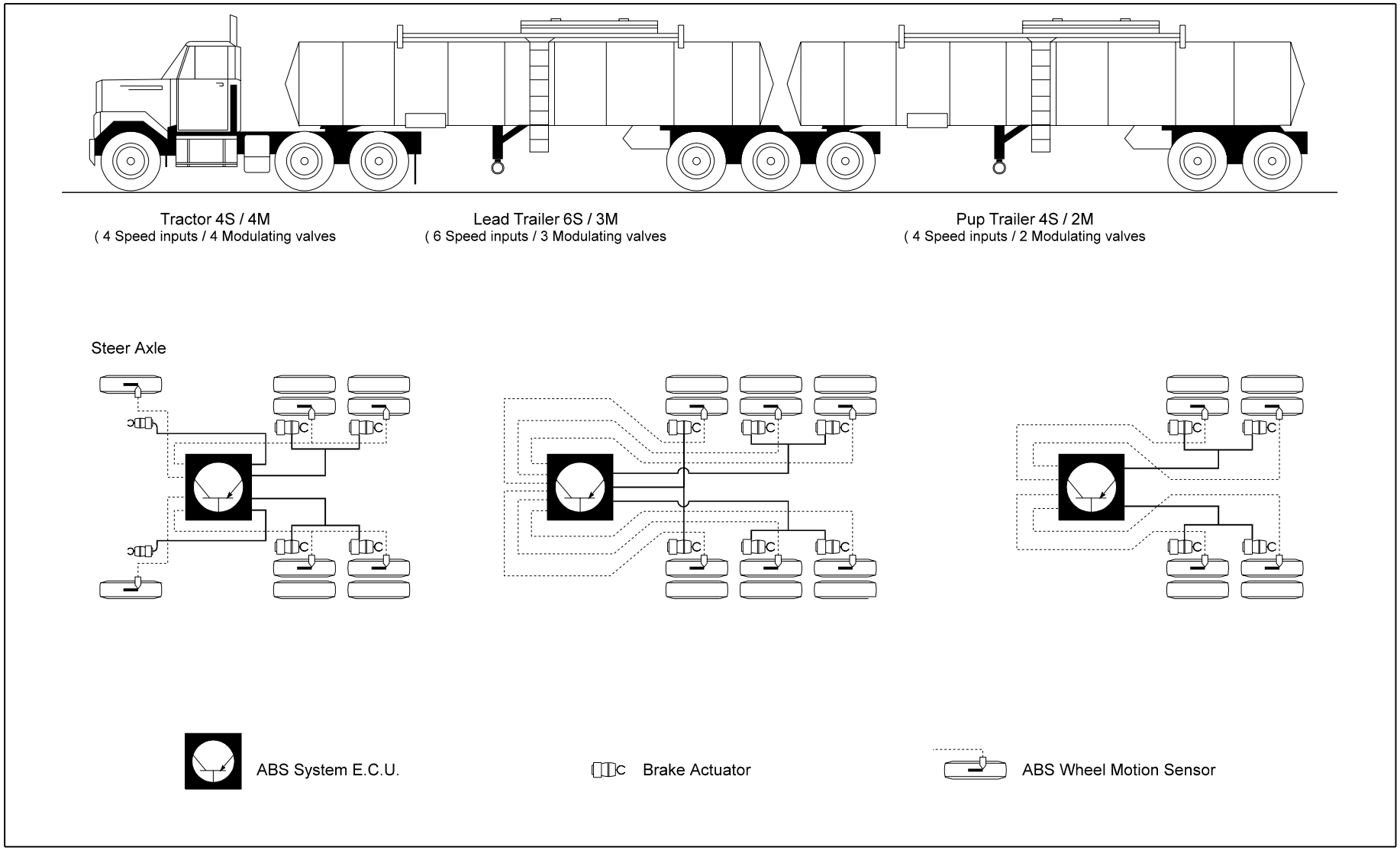
- The ABS-equipped tractors, built by Freightliner and placed in service between September 1991 and March 1992, were delivered with factory-installed Model ABS/ATC C2 ECU 6S/4M systems comprising 6 speed inputs and 4 modulating valves.

- The ABS-equipped lead trailers are equipped with Vario C2 ECU 6S/3M systems comprising 6 speed inputs and 3 modulating valves as well as the "blink code" feature.

- The ABS-equipped pup trailers are equipped with Vario C2 ECU 4S/2M systems comprising 4 speed inputs and 2 modulating valves as well as the "blink code" feature.

The general configuration of these installations, which incorporate an ECU fail-safe feature similar to the one found on the Bosch equipment, is illustrated on Figure 5.

**Figure 5**
**CONFIGURATION OF ROCKWELL-WABCO ABS SYSTEM**
**AS INSTALLED ON THE CANADIAN LIQUID AIR FLEET VEHICLES**



## 3.3 ABS MONITORING - VMC

The actual real-time operation of the ABS systems installed on the Shell Canada vehicles was electronically monitored and recorded by equipment supplied and installed by the Vehicle Monitor Corporation (VMC) of Redmond (WA) U.S.A. This equipment was essentially selected on the basis of availability and suitability to the task as well as for compatibility of data with the NHTSA program which had also chosen the VMC equipment in its monitoring of ABS systems mounted on heavy truck tractors. The VMC monitoring equipment, of which a detailed description is provided in a VMC document "ABS LOGGER - Installation and Operations Manual" reproduced in Appendix B, consisted of the following components:

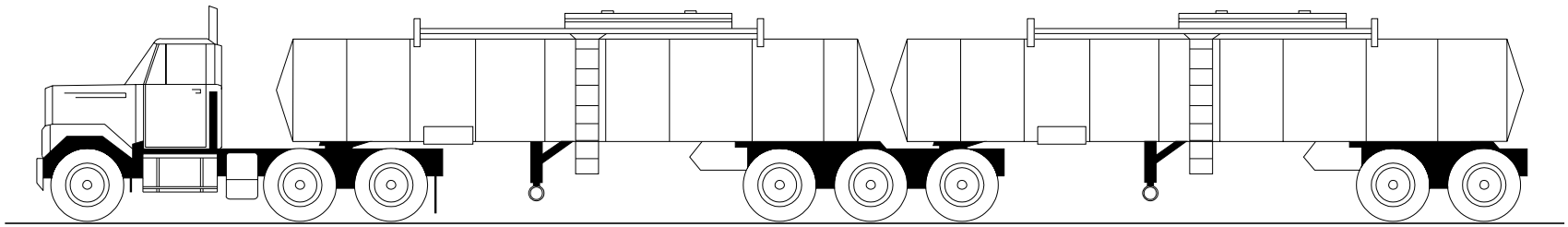
- On-board monitoring and data recording equipment installed on the monitored Shell Canada B-Trains
- Data retrieval equipment installed at the Shell Canada plants from which the monitored vehicles were operated
- Data analysis software to enable analysis both at the micro level of individual events and at the macro level involving generating summaries of recorded events.

### 3.3.1 On-board Monitoring and Data Recording Equipment

The on-board monitoring and data recording equipment, as shown in Figures 6 and 7, included the following components:

- One tractor logger and one logger monitoring both the lead and pup trailers.
- One speed sensor on each wheel controlled by the ABS system, with the exception of the lead trailer lift-axle and the pup trailer rear-axle, for a total of 4, 4 and 2 speed sensors on the tractor, lead trailer and pup trailer respectively. The tractor steer-axle configuration required the installation of a dedicated toothed ring while all other speed sensors made use of the ABS system's toothed ring.
- One pressure transducer installed in parallel with each pressure modulating valve of the ABS system to monitor air pressure at the wheel brake chamber, as controlled by the ABS system, for a total of 4, 4 and 2 pressure transducers on the tractor, the lead trailer and the pup trailer respectively.
- One electrical current detector for each of the ABS system solenoid activation circuits to monitor ABS activity in terms of activations of the solenoids controlling the pressure modulating valves. These detectors were wired to the ABS system through a Bosch interface box at each ECU and numbered 4 on the tractor logger and 6 on the trailers logger.

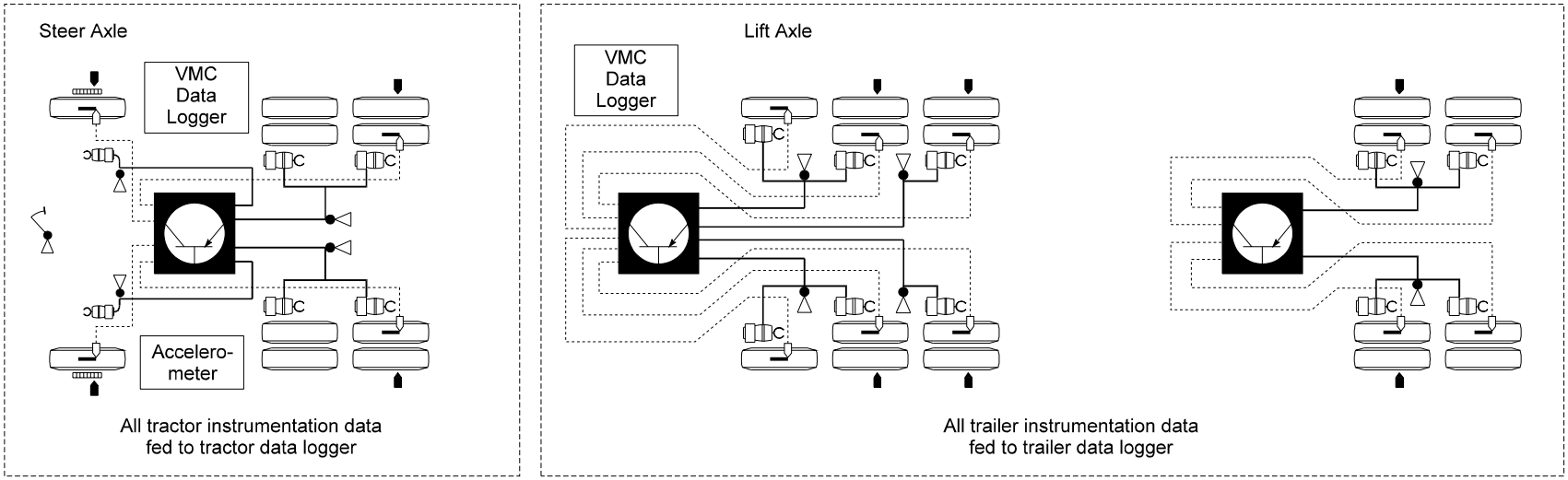
**Figure 6**
**CONFIGURATION OF VMC ON-BOARD MONITORING INSTRUMENTATION INSTALLED ON SHELL CANADA FLEET VEHICLES**



TRACTOR 4S / 4K
( 4 sensors / 4 channels )

LEAD TRAILER 6S / 4K
( 6 sensors / 4 channels )

PUP TRAILER 4S / 2K
( 4 sensors / 2 channels )



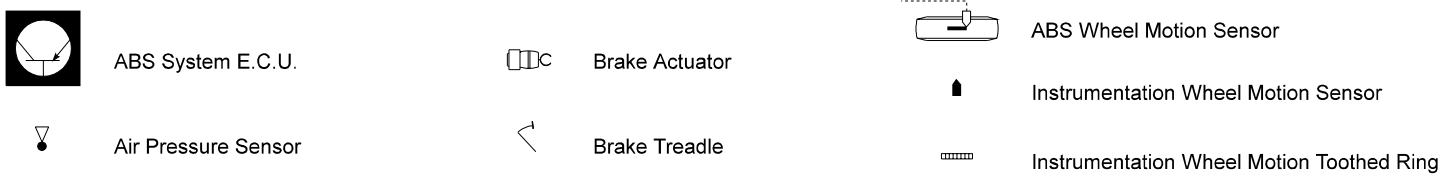
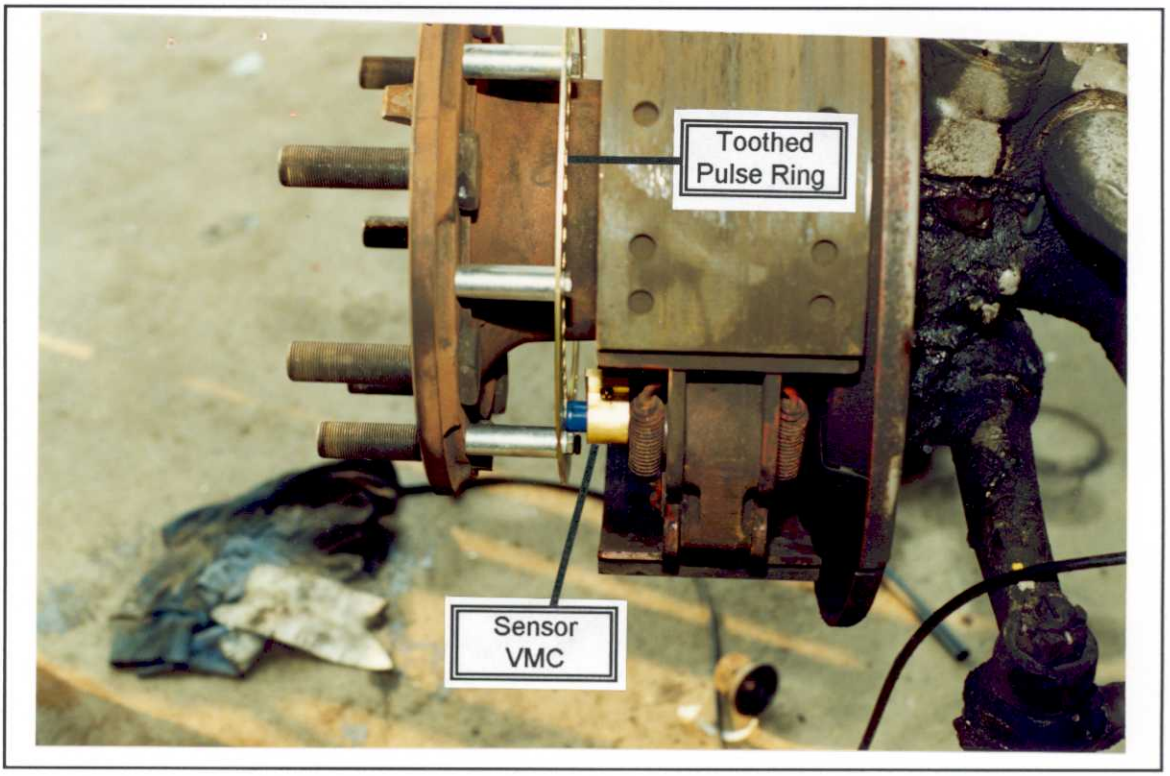
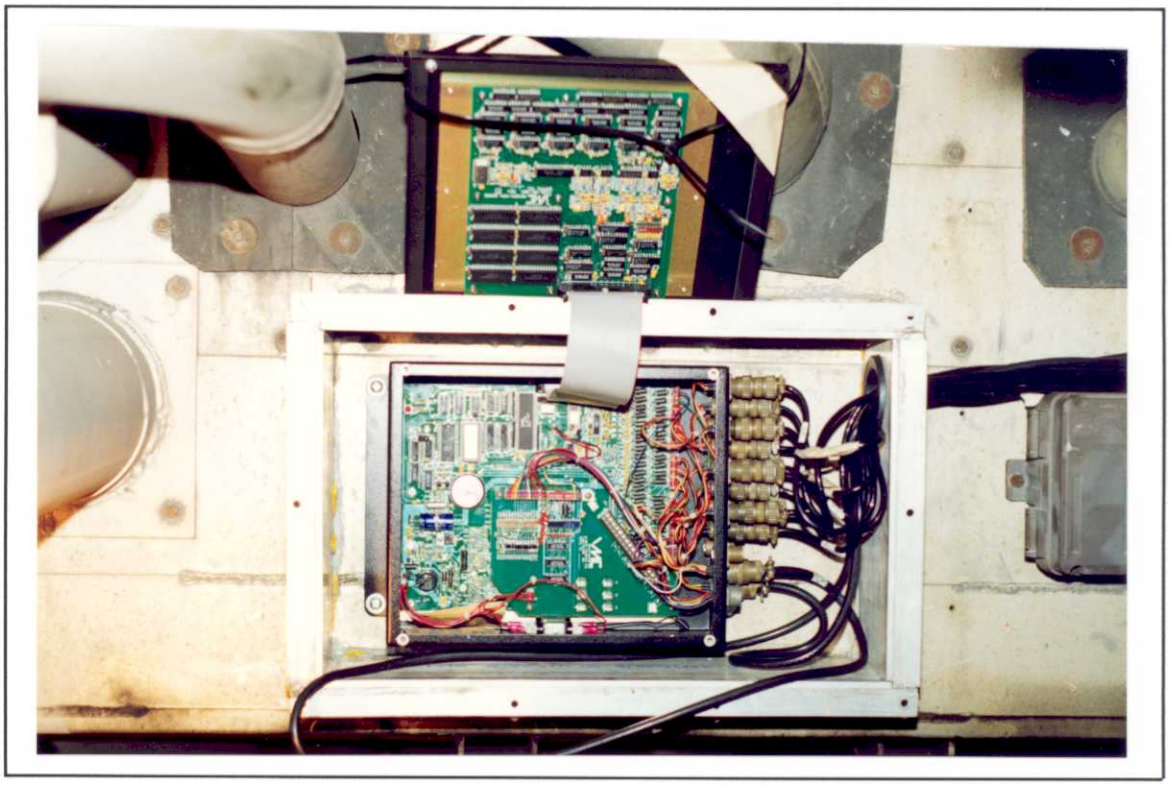



Figure 7

**VMC MONITORING EQUIPMENT - MAJOR COMPONENTS**



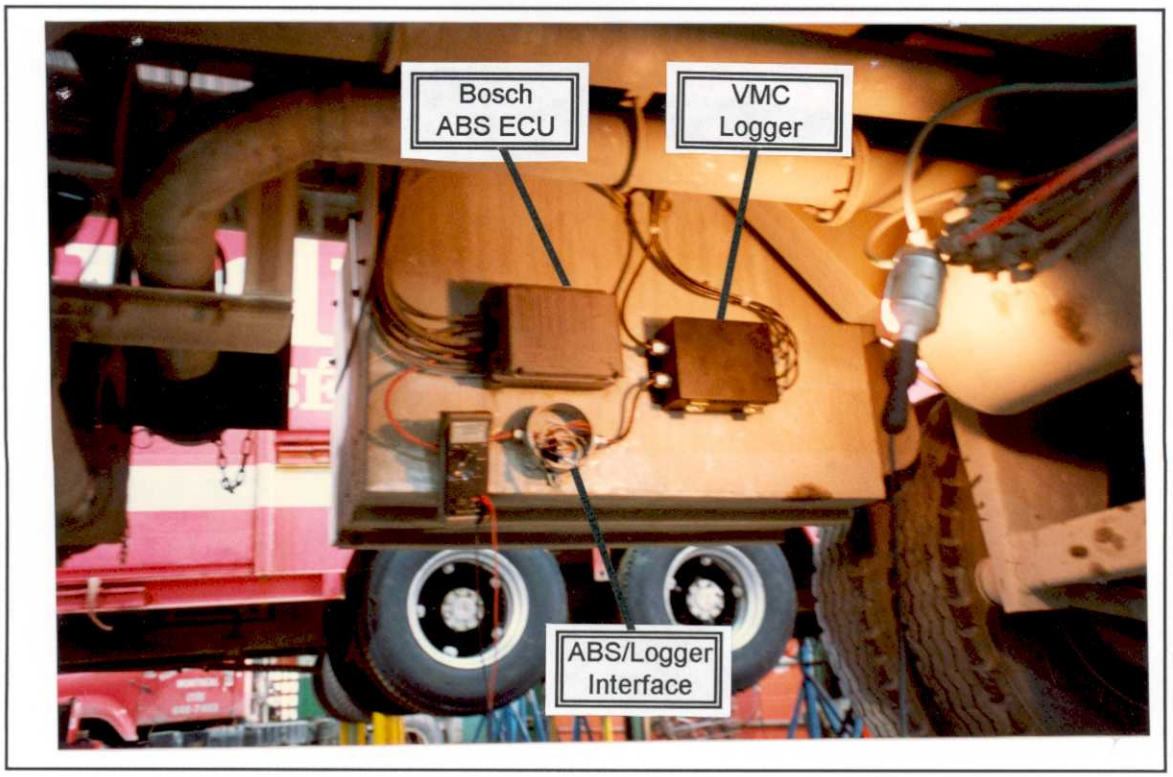

**a) Speed Measurement Device ( Tractor Steer Axle Installation)**



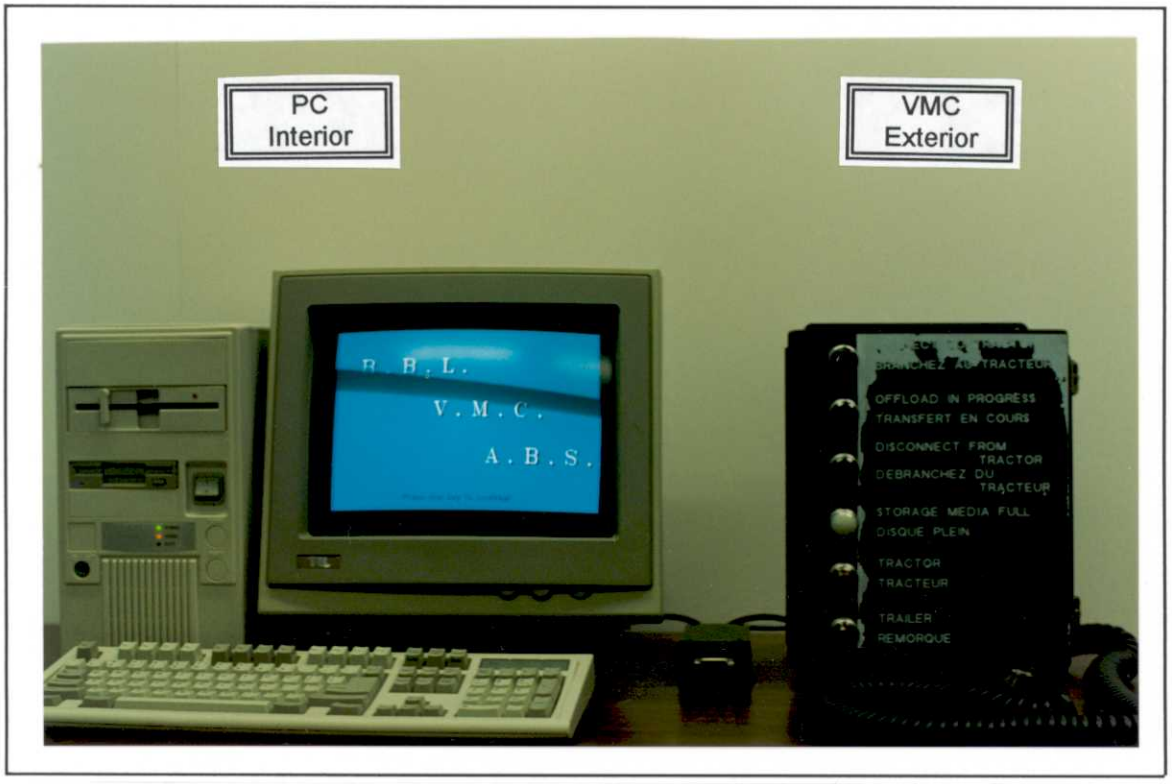
**b) Electronic Logger (6-Channel Trailers Configuration)**

Figure 7 cont'd

**VMC MONITORING EQUIPMENT - MAJOR COMPONENTS**




**c) Interface with ABS System (Lead Trailer Installation)**




**d) VMC Download Box and Site Computer**

- One pressure transducer which monitored the application and intensity of brake treadle valve pressure and transmitted this information for recording at both loggers

- One electrical current voltage meter monitoring the current supply to the ECU of the tractor and of the lead trailer

- One electrical current detector on each of the ABS system warning light circuits monitoring the incidence of detection by the ECU of system or equipment failures

- One accelerometer installed on the tractor to monitor rates of vehicle speed modification

- One data exchange interconnection between the two loggers to enable internal clock synchronisation, simultaneous recordings and access to the trailer logger data for downloading through the tractor logger

- One download port at the tractor logger giving access to both tractor and trailers data.

This on-board equipment continuously monitored all input signals (treadle valve and wheel chamber pressures, wheel speeds, solenoid activations, voltage, acceleration, warning lights).

Some of the signals were used to continuously update general records of operations between successive down-loads in terms of:

- Total time of operation

- Total distance travelled

- Brake pressure histogram for the total number of brake applications

- Deceleration histogram

- Total solenoid activations

- Total number and duration of ABS warning light activations

Other signals - wheel speeds, brake chamber pressures and solenoid activations - were continuously monitored and compared against a set of criteria, in terms of braking duration and severity as well as vehicle speed, to detect the occurrence of "ABS braking events". These criteria, based on earlier NHTSA testing experience, are fully detailed in Appendix B and enabled the loggers to identify "ABS braking events" from simple brake applications. Only those brake applications which met the "ABS braking event" criteria triggered the recording of all monitoring inputs at intervals of 20 milliseconds during the event and at intervals of 100 milliseconds during one second before and one second after the event.

### 3.3.2 Data Retrieval Equipment

The following data retrieval equipment was installed at each of the four Shell Canada plants from which the monitored B-Trains were operated:

- One download cable which could be connected to the tractor logger by the vehicle driver to enable the retrieval equipment to access the data stored in the 250 kilobytes of memory built into each logger and to reset all cumulative counters to the appropriate initial value

- One download box, installed adjacent to the B-train parking area, which served two purposes:

    - Acted as a junction box between the download cable and the cable link to the download computer

    - Provided, through a series of coloured lights, instructions to the driver performing a data downloading operation

- One download computer: 286 PC with a hard disk capacity of 40 megabytes, monitor and keyboard; which operated a data downloading software program and stored the retrieved data files on the hard disk

### 3.3.3 Data Analysis Software

VMC developed and supplied the following data analysis computer programs:

- A micro level analysis program which enabled detailed event-by-event analysis of the data files retrieved from the on-board loggers. This program gave access to every individual parcel of information, recorded during the occurrence of "ABS braking events", both in its hexadecimal format for the performance analysis of specific components of the ABS system and as graphical "Strip Charts" for the analysis of the response performance of the ABS system during an entire event. Examples of such "Strip Charts" are provided in Appendix C of this report.

- A macro level analysis program which compiled and printed a report of vehicle and ABS system operation statistics as well as the characteristics of every recorded "ABS braking event" for the entire period between successive downloads of data from the on-board loggers. An example of such a report is also provided in Appendix C.

# 4.0 DATA ANALYSIS AND PROJECT FINDINGS

This chapter provides the results of the analyses performed on the data collected during this evaluation project and the specific project findings associated with these analyses. The contents of the chapter are organised into three distinct sections:

- ABS systems performance: operation, reliability, maintenance and perception
- ABS systems impact on vehicle operation: tires, braking system and safety
- ABS systems cost impact: installation, system and vehicle maintenance.

## 4.1 ABS SYSTEMS PERFORMANCE

This section provides insight into the performance of ABS systems from the following points of view:

- System operation in terms of frequency of occurrence of ABS events and particularly major ABS events which correspond to potential accident producing conditions of severe braking and/or slippery pavement surface
- System reliability in terms of system integrity, response and operation
- System maintenance requirements and durability
- System perception by vehicle drivers, operators and maintainers.

### 4.1.1 System Operation

The ABS systems installed on the Shell Canada vehicles were, as previously described, the subject of a continuous real-time electronic monitoring performed through on-board equipment which produced data files for subsequent detailed macro and micro analysis as indicated in Appendix C.

The ABS systems installed on the Canadian Liquid Air vehicles were not monitored electronically on a real-time basis and, consequently, their operation cannot be analysed and evaluated in this section of the report. This subsection is thus solely based on data collected from Shell vehicles.

#### 4.1.1.1 Definitions

In order to characterise the collected data and enable meaningful analyses, the following definitions were established:

- Brake Application

  A brake application was deemed to have occurred whenever the on-board monitoring system detected a brake pressure at the treadle valve of the vehicle braking system. Each brake application was simply recorded as a unit increment to the corresponding monitoring data field.

- ABS Event

  Initially an ABS braking event was recorded whenever:

  - The vehicle speed, assumed to be equal to the speed of the fastest monitored wheel, was equal to or greater than 8 km/h. It will be noted that the ABS ECU assumes that the vehicle speed is the average of the speeds of the monitored wheels (page 3-8) while the VMC monitoring equipment assumes the vehicle speed to be that of the fastest monitored wheel. This difference is not significant under normal operating conditions but it may have resulted in occasional meaningless recordings whenever the speed of a wheel spinning on ice triggered the recording of a non-event.

  - An ABS solenoid activation pulse was detected or a wheel lock-up, defined as a 50% reduction of the wheel speed as compared to vehicle speed, occurred with a duration of at least 0.1 second.

  These criteria resulted in the recording of a great number of events that occurred in the absence of brake application, that were of minimal interest and significance, and which rapidly filled the available memory buffers, curtailing further monitoring. As best as could be determined, these events occurred primarily when lightly loaded or empty trailers bounced on uneven pavements, causing wheels to lose speed and the ABS system to react by activating the corresponding solenoids. Consequently an additional selection criterion was introduced to restrict recording to more meaningful events:

  - The occurrence of a brake application.

- Minor ABS Event

  ABS events were classified as minor ABS events when the ECU, having detected imminent wheel slip, activated the "hold" function of the pressure modulating valve preventing further pressure increase in the wheel brake chamber. If this action was sufficient to prevent actual wheel slip the event did not classify as a significant ABS event since wheel slip was not experienced nor reduced by an ABS system reaction.

- Significant ABS Event

  ABS events were classified as significant ABS events when the following two additional criteria were met:

  - At the beginning of the event one or more wheels had experienced at least 20% slip (i.e. their speed had to be inferior to 80% of the vehicle speed)

  - After the corresponding ABS solenoid activity, wheel slip had been reduced to less than 5%.

  Thus the recorded event corresponded to a true significant ABS event sequence: brake application, wheel slip, ABS braking pressure release, reduced wheel slip.

- Major ABS Event

  Major ABS events were defined as significant ABS events during which more than 4 solenoid activations were recorded either successively on one wheel or simultaneously on different wheels.

Furthermore, significant and major ABS events were classified under three initial vehicle speeds indicative of the severity of the situation. The speed intervals were: under 40 km/h, between 40 and 75 km/h and above 75 km/h.

It should be noted that the above definitions are identical or equivalent to those of the corresponding NHTSA program of ABS system evaluation projects. Therefore, direct comparisons of results can be made.

#### 4.1.1.2 Monitoring Data

The ABS system electronic monitoring data collected during this evaluation project and subsequently subjected to macro analysis are summarised in Tables 2 and 3 respectively for tractor and trailer components of the test vehicles.

These data call for the following comments and restrictions on its validity as a true representation of actual ABS system operation.

- The tractor ABS system data of Table 2 can be considered as relatively accurate since the monitoring files indicate that the availability of ABS, as shown by the recorded status of the Warning Light, was 97.3%. This means that the recorded ABS activity occurred in almost the same percentage of hours of operation and kilometres travelled. In order to be rigorous, ABS recorded activity should therefore be increased by 2.7%. However, other non-quantifiable variables affecting the data simply make such an attempt at precision unrealistic.

- The trailer ABS system data of Table 3 cannot be considered an accurate picture of ABS activity since full vehicle ABS availability was only 52.9%. Also, since the system only has one Warning Light to indicate the operating status of both trailer ECU's, there is no accurate way to determine from the recording files whether one or the other or even both of the ECU's had, at any given time, de-activated themselves because of detected faults in the ABS systems. The detailed analysis of individual events, from VMC recordings, shows that the ABS systems installed on the lead trailers were out of operation substantially more than those on the pup trailers. One possible explanation for this observed situation is that the lead trailer ABS ECU monitors six wheels while only four wheels are monitored on the pup trailer. There is thus 50% more opportunity for speed sensor failure and ECU de-activation on the lead trailer.

- Consequently, it may be reasonably estimated that the recorded ABS activity should be increased by factors of 35% and 15%, respectively for lead and pup trailers, in order to reflect expected ABS activity for the total mileage travelled by the lead and pup trailers. It should be noted that the majority of ABS unavailability was due to delays in effecting maintenance and adjustments by the operators for a variety of reasons. As such, availability figures presented here are not a good reflection of ABS reliability.

- The actual numbers of significant ABS events were not recorded as such by the on-board monitoring equipment and had to be estimated from the distribution tables assuming 1, 3 and 6 events respectively for the three categories identified.

**Table 2**

**SUMMARY OF RAW DATA FROM ON-BOARD ABS MONITORING SYSTEM - TRACTORS**

**Vehicle Operational Data**

| | | |
|---|---|---|
| Hours of Operation: | 10 677 | |
| Kilometres Travelled: | 328 959 | (30.8 km / hr) |
| Number of Brake Applications: | 358 013 | (1.1 brake application / km) |

**ABS System Operational Status**

| | | |
|---|---|---|
| Hours of Warning Light "ON" | 283 | |
| Hours of Warning Light "OFF" | 10 394 | (97.3% full ABS availability on tractor) |

**Recorded ABS Events**

| | | |
|---|---|---|
| Total ABS Events | 29 694 | |
| Significant ABS Events | 1 642 | (see note below) |
| Major ABS Events | 49 | |

**Significant ABS Events Distribution**

| Vehicle Speed | Number of Significant ABS Events by number of solenoid activations | | |
|---|---|---|---|
| | 1 | 2 - 4 | › 4 |
| ‹ 40 km/h | 394 | 200 | **28** |
| 40 - 75 km/h | 145 | 63 | **11** |
| › 75 km/h | 14 | 2 | **10** |

**Note:** Assuming 1, 3 and 6 as the average number of solenoid activations in the three distribution columns ( 1, 2-4, and ›4) indicated in the table above.

**Table 3**

**SUMMARY OF RAW DATA FROM ABS ON-BOARD MONITORING SYSTEM - TRAILERS**

**Vehicle Operational Data**

| | | | |
|---|---|---|---|
| Hours of Operation: | | 9 842 | |
| Kilometres Travelled: | | 282 042 | (28.6 km / hr) |
| Number of Brake Applications: | | 204 796 | (0.7 brake application / km) |

**ABS System Operational Status**

| | | | |
|---|---|---|---|
| Hours of Warning Light "ON" | | 4 631 | |
| Hours of Warning Light "OFF" | | 5 211 | (52.9% full ABS availability on both trailers: most unavailability is eplained by excessive delays in effecting maintenance) |

**Recorded ABS Events**

| | | | |
|---|---|---|---|
| Total ABS Events | | 24 095 | |
| Significant ABS Events | Lead Trailer | 497 | (see note below) |
| | Pup Trailer | 3 215 | (see note below) |
| Major ABS Events | Lead Trailer | 40 | |
| | Pup Trailer | 148 | |

**Significant ABS Events Distribution**

**Lead Trailer**

| Vehicle Speed | Number of Significant ABS Events by number of solenoid activations | | |
|---|---|---|---|
| | 1 | 2-4 | › 4 |
| ‹ 40 km/h | 69 | 42 | **23** |
| 40 - 75 km/h | 20 | 8 | **16** |
| › 75 km/h | 9 | 3 | **1** |

**Pup Trailer**

| Vehicle Speed | Number of Significant ABS Events by number of solenoid activations | | |
|---|---|---|---|
| | 1 | 2-4 | › 4 |
| ‹ 40 km/h | 303 | 229 | **37** |
| 40 - 75 km/h | 237 | 273 | **80** |
| › 75 km/h | 62 | 73 | **31** |

**Note:** Assuming 1, 3 and 6 as the average number of solenoid activations in the three distribution columns ( 1, 2-4, and ›4) indicated in the tables above.

#### 4.1.1.3 Data Analysis

The more significant ABS system operation statistics relate to the frequencies of ABS events, significant ABS events and major ABS events, which are summarised in Table 4. The values in this table are derived from Tables 2 and 3 but result from the application of the correction factors estimated above (+35% for lead trailer events and +15% for pup trailer events).

- The frequency of ABS events (vehicle speed > 8 km/h, brake application, solenoid activation or wheel lock-up) diminishes from the tractor (903 / 10 000 km) to the lead trailer (577 / 10 000 km) and to the pup trailer (491 / 10 000 km). This could be explained by the fact that, during very light braking, the pressure developed in the trailer brake chambers is insufficient to generate ABS system response.

- The frequency of significant ABS events (ABS event + reduction in wheel slip resulting from ABS triggered pressure release) increases from the tractor (55 / 1 000 ABS events) to the trailers (41 and 267 / 1 000 ABS events respectively for the lead and pup trailers). The lead trailer value may have been underestimated by the above correction factor.

- The difference in frequencies of ABS events and significant ABS events corresponds to minor ABS events.

- The frequency of major ABS events (sequence of 4 or more solenoid activations) increases from the tractor (1.5 / 10 000 km), to the lead trailer (1.9 / 10 000 km) and to the pup trailer (6.0 / 10 000 km). The lead trailer value may have been underestimated by the above correction factor.

The following conclusions can consequently be drawn from these ABS system operation parameters:

- ABS systems are relatively active since they generate, in response to detected conditions of actual or imminent wheel slip, for each 10 000 kilometres of vehicle operation:

    - 1 971 ABS Events

    - 1 766 Minor ABS Events

    - 205 Significant ABS Events

    - 9.4 Major ABS Events (a subset of Significant ABS Events)

**Table 4**

**SUMMARY OF ABS SYSTEM OPERATION STATISTICS ***

| OPERATION PARAMETERS | TRACTOR | LEAD TRAILER | PUP TRAILER | VEHICLE TOTAL |
|---|---|---|---|---|
| **Frequency of ABS Events** | | | | |
| • Number of events / 1 000 hours of operation | 2 775 | 1 660 | 1 414 | 5 849 |
| • Number of events / 10 000 kilometres | 903 | 577 | 491 | 1 971 |
| • Number of events / 10 000 brake applications | 829 | 793 | 676 | 2 298 |
| **Frequency of Significant ABS Events** | | | | |
| • Number of events / 1 000 hours of operation | 153 | 68 | 377 | 598 |
| • Number of events / 10 000 kilometres | 50 | 24 | 131 | 205 |
| • Number of events / 10 000 brake applications | 46 | 33 | 180 | 259 |
| • Number of events / 1 000 ABS events | 55 | 41 | 267 | 363 |
| **Frequency of Major ABS Events** | | | | |
| • Number of events / 1 000 hours of operation | 4.6 | 5.5 | 17.4 | 27.5 |
| • Number of events / 10 000 kilometres | 1.5 | 1.9 | 6.0 | 9.4 |
| • Number of events / 10 000 brake applications | 1.4 | 2.6 | 8.3 | 12.3 |

* Values in this table derived from Tables 2 (tractors) and 3 (trailers) after application of correction factors of 1.35 for lead trailer events and 1.15 for pup trailer events.

- It is estimated from the data reported in Tables 2, 3 and 4 that, under the vehicle operation characteristics observed during this evaluation project totalling approximately 100 000 kilometres per year, a functioning ABS system would generate, in reaction to severe braking and/or slippery road conditions, approximately 100 major ABS events of which 20 would occur at speeds above 75 km/h. The potential for ABS to reduce braking related accident frequency and severity and to contribute to traffic safety, through its test-track proven capacity to reduce stopping distances and to improve vehicle control during braking, is certainly very real and significant.

- The potential value of ABS is particularly obvious in the case of the pup trailer on which the frequencies of occurrence of significant and major ABS events are 3 to 4 times those on the tractor and lead trailer.

#### 4.1.1.4 Unresolved Issues

There remain two ABS system operation issues which this evaluation project has identified but which could not be independently resolved given the monitoring data available and the limitations of the on-board monitoring equipment.

- The first of these issues concerns the life expectancy of the solenoids and pressure modulating valves (PMV) components of the ABS systems. As noted above, there appears to be a very significant level of ABS system activity even in the absence of brake application. This activity was such that recording memory was very rapidly filled with data until the presence of treadle valve pressure was included as a screening parameter. Since solenoids and PMV have mechanical parts, such a level of non-braking activity raises a question as to their durability and life expectancy. The actual in-service numbers of activations of these mechanical components should be compared to their design parameters in order to verify their capacity to perform adequately for their total planned life expectancy. The limited memory capacity of the on-board monitoring equipment installed under this evaluation project had to be kept available for the recording of ABS activity during brake applications. Consequently, the magnitude of the non-braking ABS system activity remains undetermined.

  In a manufacturer's letter addressing this matter, it was stated that, in the laboratory, the pressure modulation valve has been endurance tested under similar operating conditions. During one of the tests the solenoid was cycled 13.8 million times. At the end of the tests the armature of the solenoid showed 0.1 mm wear. This wear did not have any effect on the function of the pressure modulation valve. The valve has been shown to be very reliable from their examination of field failure rates, with the overall rate being 0,21 % (1994), and most customer claims being the result of contaminated air supply.

- The second of these issues concerns the distinction between the "hold" and "release" activations of the PMV's. The electrical monitoring links between the ABS systems and the on-board monitoring equipment did not allow to distinguish between these two types of actuation. The availability of this information would allow determination of the capability of the ABS system to actually prevent wheel lockup by detecting slip and activating the "hold" function which simply prevents further build-up of pressure in the

brake chamber. The collection of these data would require increased memory capacity and modified monitoring links for the on-board equipment.

#### *4.1.1.5 Project Findings / ABS Systems Operation*

*The project findings with respect to ABS systems operation can be summarised as follows:*

- *ABS systems generate, for each 10 000 kilometres of vehicle operation, the following approximate numbers of ABS events for the type of operation monitored under this project:*
  - *1 971 ABS Events*
  - *1 766 Minor ABS Events*
  - *205 Significant ABS Events*
  - *9.4 Major ABS Events*

- *It is estimated that, under the vehicle operation characteristics observed during this evaluation project totalling approximately 100 000 kilometres per year, a functioning ABS system would generate, in reaction to severe braking and/or slippery road conditions, approximately 100 major ABS events of which 20 would occur at speeds above 75 km/h. The potential for ABS to reduce braking related accident frequency/ severity and to contribute to traffic safety, through its test-track proven capacity to reduce stopping distances and to improve vehicle control during braking, is certainly very real and significant.*

- *The potential value of ABS is particularly obvious in the case of the pup trailer on which the frequencies of occurrence of significant and major ABS events are 3 to 4 times those on the tractor and lead trailer.*

- *Two issues related to ABS systems operations have not been resolved given the limitations of the on-board monitoring equipment installed on the vehicles under this evaluation project. These are:*
  - *Durability and life expectancy of solenoids and pressure regulating valves given the very significant level of non-braking activity noted from early monitoring records (N.B.- Self-reported manufacturer testing and field history appear to show very reliable valve operation)*
  - *Capability to prevent actual wheel slip by detecting imminent slip and activating the "hold" function which simply prevents further build-up of pressure in the brake chamber*

  *The collection of the data necessary to study these aspects of ABS systems operation would require more sophisticated monitoring equipment with increased memory capacity and better monitoring links to the ABS systems.*

### 4.1.2 System Reliability

There are essentially three aspects to ABS system reliability:

- System integrity which can be defined as the availability of the ABS function determined by the absence of failure of the system or of any individual system component.

- System response which relates to the consistency with which the system detects and recognises imminent wheel lock-up during brake application, and triggers the ABS function.

- System operation as determined by the consistent adequacy of the ABS response whenever the pre-set triggering conditions have been detected.

ABS system reliability could only be analysed for the Bosch systems installed on the Shell Canada vehicles which were monitored electronically and for which detailed recorded operational data were available.

#### 4.1.2.1 System Integrity

ABS system integrity can be measured by its maintenance requirements and its operational status as determined by its own internal self-test which indicates system and/or component failures by an activation of a "warning light". This aspect of ABS system reliability is analysed in detail in the following section of the report: 4.1.3 System Maintenance requirements.

The ABS system, with the notable exception of its wheel speed measuring component, has demonstrated a high level of reliability in terms of system integrity and practically maintenance-free operation.

#### 4.1.2.2 System Response

The electronic monitoring equipment installed on the Shell Canada vehicles, because of memory limitations, was configured to record only data triggered by ABS events. Consequently, there is no possibility of determining whether or not the system detected and recognised all situations of imminent wheel lock-up and if it responded appropriately in all cases.

The collection of detailed continuous data enabling the determination of ABS system reliability, in terms of its capability to detect and respond to all situations corresponding to ABS function pre-set triggering conditions, would require:

- Monitoring equipment with greatly increased memory capacity and/or automatic data analysis capability to detect and record, independently from the ABS system ECU, all situations calling for the ABS function and the corresponding ABS system response

- Data analysis software which would enable the efficient handling of a greatly increased mass of data.

However, based on consistent results from previous track tests and discussions with drivers, there is no reason to believe that pre-set triggering conditions are not consistently handled by the ABS system.

#### 4.1.2.3 System Operation

The micro analysis, through the production and analysis of "strip charts" as described in Appendix C, of a sizeable sample of the ABS events recorded by the monitoring equipment, has not revealed a single instance of ABS system malfunction which involved an inappropriate response. In all analysed events the ABS function operated as expected and in accordance with system specifications.

#### *4.1.2.4 Project Findings / ABS Systems Reliability*

*The project findings with respect to ABS systems reliability can be summarised as follows:*

- *The ABS system, with the notable exception of its wheel speed measuring component, has demonstrated a high level of reliability in terms of system integrity and practically maintenance-free operation*

- *The ABS system has demonstrated a high level of consistency and reliability in its operation by providing in all cases analysed the adequate ABS response as expected and in conformity with the system specifications.*

- *The monitoring data available have not enabled the determination of the reliability of the ABS system in terms of its consistency in detecting, recognising and responding to all situations corresponding to the pre-set conditions of ABS function triggering. The collection of the data necessary for such an analysis would require, given the vastly increased mass of data, more sophisticated monitoring equipment and analysis software. However, based on consistent results from previous track tests and discussions with drivers, there is no reason to believe that pre-set triggering conditions are not consistently handled by the ABS system.*

### 4.1.3 System Maintenance Requirements

The determination of ABS durability and maintenance requirements constituted one of the main objectives of this project. Consequently, particular care was taken to obtain as complete as possible information on ABS equipment failures and associated repair and/or maintenance requirements.

#### 4.1.3.1 Shell Canada Vehicles

The available ABS systems failure/repair/maintenance data for the Shell Canada monitored vehicles were obtained from the following sources:

- The on-board monitoring equipment which detected "warning-light" activity and recorded ABS system and/or component malfunctions.
- The records of the Robert Bosch Corporation of repairs or services carried out on their equipment during the warranty period, which covered most of the duration of this project.
- Reports of maintenance and repair requirements made by the vehicle operators and maintainers.
- A complete and detailed inspection of the ABS systems, performed by a Bosch engineer, at the end of the project.

The collection of maintenance data was hindered by the following facts which also affected the validity of part of the data:

- The vehicle maintenance contractors' lack of familiarity with the ABS systems and inability to perform routine diagnostic/maintenance operations. All repairs had to be referred to specialised shops resulting in substantial maintenance costs and delays.
- The vehicle operators' attitude not to consider ABS systems failures as a safety issue, since the systems are "fail-safe" and revert to normal braking in case of failure.

As a consequence of the above, ABS failures and/or maintenance requirements, though in most cases minor, were neglected for substantial periods of time.

The ABS systems were proven to be remarkably durable and, with one major exception, to be virtually maintenance free. The one weak component of the system is the wheel speed measuring device which readily and frequently gets out of adjustment resulting in an automatic shut-down of the system by the ECU as part of its fail-safe routine.

The actual durability and maintenance data collected indicate the following:

- **On-board Electronic Monitoring Records**

  The macro analysis of these records indicates that the ABS systems were operational, as indicated by the warning light not being "on", 97% of the time on tractors and 53% of the time on the trailers. In almost all instances, except as noted below, the system failures were associated with wheel speed sensor failures and the duration of these failures were for extended periods through the neglect of vehicle operators to provide maintenance because of their attitude of not considering these failures as a safety issue.

  The difference in operational availability of ABS systems between tractors and trailers is considered to be the result of the greater number of speed sensors on the trailers (10) by comparison with the tractor (4), with the resulting greater probability of failure and out-of-adjustment problems, and the much higher level of maintenance and frequency of inspection afforded to tractors.

- **Repair/Service Records of Bosch**

  The Robert Bosch Corporation prepared, at the request of Beauchemin-Beaton-Lapointe Inc., a report (Appendix D) which lists in table form (Attachment #1) all ABS system failures and required maintenance prior to and during this evaluation project.

  It will be noted that not a single failure of a major ABS system component is reported and that most repairs were related to:

  - Limited experience with ABS on the part of the field systems maintainers resulting in inadequate cable routing or protection and damage due to unrelated maintenance work.

  - Vehicle accident or malfunction (wobbly wheels, seized bearings, etc.) resulting in damage to ABS system components.

- **Vehicle Maintenance and Repair Reports**

  The available maintenance and repair reports for each monitored vehicle were scrutinised in order to identify all maintenance and repairs performed on the ABS systems and it was found that, other than wheel speed sensor adjustments and warning light bulb replacements, the systems had been completely maintenance and repair free.

- **Final Inspection Report**

  The same report (Appendix D) provides in table form (Attachment #2) the results of a detailed inspection of the ABS systems performed at the conclusion of this evaluation project. At that time the tractor systems had been in service for almost three years while the trailer systems had been in service for two years.

  This inspection, performed on the four available vehicles, revealed that, other than wheel speed sensor misadjustments and cable damages, the only ABS system failures were the following:

  - One pressure modulating valve (PMV) was found to be defective and had to be replaced.

  - Available electrical voltage was found to be or to have been insufficient on all four units and had resulted in ABS system shut-down. This condition originated from reduced voltage output from older vehicle batteries.

#### 4.1.3.2 Canadian Liquid Air Vehicles

The maintenance director for the Canadian Liquid Air fleet in Midale has indicated that, after slightly more than a year and approximately 400 000 kilometres, the ABS systems have not required any maintenance. However, he did report:

- All original ECU's were replaced by the supplier for an unspecified reason.

- A faulty installation on a tractor, where wires had been crossed and ABS had to be corrected immediately after the vehicle was put into service: brake pressure release was being directed to non-slipping wheels instead of to the slipping wheels.

#### *4.1.3.3 Project Findings / ABS Systems Maintenance Requirements*

*The project findings with respect to ABS systems durability and maintenance requirements can be summarised as follows:*

- *ABS systems, with the exception of their wheel speed measuring component, are remarkably durable and virtually maintenance free.*

- *The wheel speed sensor assembly provided with the ABS system requires frequent and difficult adjustments. This problem appears to be more severe in the case of a retro-fit system installation. This aspect of the system obviously requires further engineering consideration.*

- *Many of the problems associated with ABS systems and required repairs appear to result from the lack of familiarity of field maintainers with the systems.*

- *The ABS system appears to have electrical power supply voltage requirements which are often not satisfied by the vehicle electrical system. Consideration should be given to lowering this voltage requirement since even a very modest reduction would eliminate a significant number of system shut-downs.*

### 4.1.4 System Perception by Drivers / Operators / Maintainers

The perception and acceptance of ABS systems by vehicle drivers, operators and maintainers was considered an integral and essential aspect of the in-service evaluation conducted under this project. In order to obtain as much information as possible from these sources the following steps were taken:

- At the beginning of the data collection phase of the project, each driver, operator and maintainer of the monitored (Shell Canada Fleet) ABS-equipped units were informed, individually or in group sessions, of the nature and objectives of the project as well as of the type of information required from them.

- Voice recorders were installed in the cabs of all monitored (Shell Canada Fleet) ABS-equipped units and drivers were requested to provide a spoken description of the circumstances surrounding any major braking event to enable a more complete analysis of the electronic data recorded of the event. This followed the unsuccessful attempt during the NHTSA test program to obtain from drivers similar written descriptions of such major braking events.

- At the end of the data collection phase of the project, as many interviews as possible were conducted, either in person or by telephone, with the drivers, operators and maintainers of the monitored (Shell Canada Fleet) ABS-equipped units. Information was also obtained from the Canadian Liquid Air fleet manager on his experience with ABS systems installed on B-Trains.

The success of these information collection efforts, which produced the results reported hereafter, was somewhat limited due to the following:

- At the time interviews were conducted, Shell Canada had sold its fleet of ABS-equipped B-Trains to various independent operators. This resulted in many of the drivers, operators and maintainers, initially briefed on the project, having had their involvement with the test units curtailed approximately six to eight months into the data collection year. Furthermore, many individuals could not be located or were not interested in participating in an interview.

- Drivers were most reluctant to make use of the voice recording equipment installed in the tractor cabs and, as a result, not a single significant event description was obtained from this equipment which was eventually removed from the units approximately halfway through the data collection year.

#### 4.1.4.1 Shell Canada Vehicles

Information on the perception of the ABS systems installed on the Shell Canada B-Trains was obtained through the following interviews:

- A group of nine drivers, all from the Hamilton and Toronto operations and none from either Montreal or Ottawa, having the following general experience profile:
    - Drivers were assigned to one particular vehicle and always operated out of the same facility.
    - Drivers had a lengthy career with Shell Canada, ranging from 12 years to 34 years with a minimum of 12 years of experience operating B-Trains.
    - All drivers had participated in the prototype ABS testing in Centralia (Ontario)[3] and had been very favourably impressed by the performance of the ABS system under those difficult test conditions.
- The fleet managers at all four Shell Plants were interviewed and provided, given their minimum of 15 years of experience with the operation of specialised liquid fuel and chemical heavy haul vehicles, very significant insight into the overall performance of ABS systems from an operator's perspective.
- The vehicle maintainers, given the number of specialised maintenance contractors and subcontractors as well as the changes which occurred during the data collection year, did not contribute significantly to the information already provided by the fleet managers.

**DRIVERS**

The perception of the ABS system by each interviewed driver and the comments that they individually formulated were surprisingly similar and generalised. These can be summarised as follows:

- Drivers have acquired and maintained a high degree of confidence in the performance and reliability of the ABS systems.

- Drivers either believe or have noticed that ABS provides improved control under conditions of hard braking, slippery roads and light trailer (pup) loads.

- Drivers do not believe that ABS is necessary for them to control the B-Train in most circumstances. However, they agree that controlling an empty pup trailer is less of a concern with ABS even under regular braking.

- Drivers are satisfied with the location and brightness of the warning light. However the operation of the ABS warning lights did create some initial confusion for some of the drivers.

- Drivers believe that the ABS system would help them in panic situations.

- Drivers could recall very few events that required panic stops or severe braking under adverse pavement conditions. Of those few events, none of the drivers positively considered that the ABS system was the determining factor in preventing an accident.

- Drivers felt that, even during regular stops, braking appeared to be improved, resulting in less frequent corrections during braking and less concern that a lightly loaded pup trailer would swing out of line on a slippery pavement surface.

- Drivers emphatically stated that ABS systems had not changed their driving habits or reduced their vigilance in monitoring the reactions of the trailers during brake applications.

#### OPERATORS

The most significant comments on ABS systems from fleet operators can be summarised as follows

- It was generally stated that the successful introduction of ABS requires an appropriate training program to assure understanding of and familiarity with this technology by operators, drivers and maintainers. A test track practice session for drivers would be considered as a most valuable feature of such a program.

- Local and readily available specialised support service from the suppliers of ABS systems is considered of primary importance. The lack of such support is likely to result in frustration with recurring specific problems and eventual failure to maintain the ABS systems since there is reliance on their fail-safe feature which enables the vehicle to be operated with the standard braking system.

- It is believed that introduction of ABS systems could allow other braking system components such as pressure limiting or proportioning valves to be eliminated.

- ABS systems may significantly reduce tire flat-spotting, though available data are not sufficient to be conclusive. If this was the case, higher performance tires with softer, more adherent tread compound could be used without resulting in increased costs per distance travelled. Conversely, less expensive tires could be used resulting in decreased costs per distance travelled.

- ABS systems are a major contribution to safety by providing improved vehicle control during braking particularly when trailers are empty, weather conditions are poor and pavement conditions cause "wheel bounce". The operators stated that their drivers have expressed an improved "level of comfort and confidence" during regular braking and a significant increase in "protection" in panic situations.

- ABS systems reliability was rated "high" and performance was rated "excellent" thus resulting in a high level of acceptance and a positive attitude from their personnel.

- One operator commented that a policy should be formalised on the colour of the warning lights, suggesting that it should be yellow for "caution" and not red for "failure", since it does not indicate brake system failure and operation of the vehicle remains safe.

- The operators believed that the additional costs associated with ABS systems were such that they would be offset by associated benefits provided that the systems were factory installed and that specialised service support was readily available.

- All operators were extremely satisfied with the ABS systems and would recommend their purchase as a standard equipment option on any new vehicle. As a matter of note, one motor carrier who purchased an ABS-equipped unit from Shell, did not believe ABS to be a useful feature and proceeded to remove the system without ever attempting to operate with it.

#### 4.1.4.2 Canadian Liquid Air Vehicles

Information on the perception of the ABS systems installed on the Canadian Liquid Air B-Trains was essentially obtained from the Corporate Fleet Manager at the company headquarters in Montreal. It will be remembered that these vehicles were not monitored under this evaluation project and, consequently, contact was never established with the drivers, maintainers and operators of these units.

This source of information generally confirmed the positive perception of ABS systems obtained from the Shell Canada drivers and operators and also emphasised the benefits associated with this technology. Consequently, it appears that the company's policy, at least at an informal level, is to equip all new units with ABS systems.

#### *4.1.4.3 Project Findings / ABS Systems Perception*

*The perception by vehicle drivers and operators of ABS systems appears, from the information and comments collected, to be the following:*

- *ABS systems are reliable and their performance have generated acceptance and confidence particularly from the drivers.*

- *ABS systems contribute significantly to safety by improving vehicle control during severe braking, particularly under adverse trailer loading characteristics and weather/pavement conditions.*

- *The successful introduction of any new technology, such as ABS systems, requires an adequate training and familiarisation program for drivers, maintainers and operators. A test track practice session for drivers would be a most valuable feature of such a program.*

- *Local and readily available specialised support service from the suppliers is essential to assure ABS systems acceptance and continued maintenance.*

- *The benefits associated with ABS systems outweigh their costs provided they are factory installed and that specialised service support is readily available.*

- *ABS systems warning lights create some confusion and should be standardised to better inform the driver of the status and availability of ABS on the vehicle.*

- *Operators unanimously recommend that all new vehicles be equipped with factory installed ABS systems and, similarly, drivers would rather drive ABS-equipped vehicles.*

## 4.2 ABS SYSTEMS IMPACT ON VEHICLE OPERATION

This section analyses the impact of ABS systems on vehicle operation with respect to the following aspects which are most likely affected by these systems:

- Tire tread wear and replacement on which ABS would be expected to have a positive impact by preventing "flat spotting"
- Braking system maintenance on which ABS may have both a positive impact, by more evenly distributing braking efforts and stresses, and a negative impact, by increasing the effective number of brake applications due to system pulsing.
- Safety record on which ABS certainly has a positive impact by reducing stopping distances and improving vehicle control and stability.

### 4.2.1 Tire Wear and Replacement

The objective of collecting data on tire wear and replacement, was to verify the plausible hypothesis that ABS can prevent irregular tire wear. This hypothesis is based on the rationale that, by preventing wheel lock-up, ABS prevents tire "flat-spotting" which is considered to be the leading cause of premature tire wear.

#### 4.2.1.1 Shell Canada Vehicles

The only consistent source of Tire Wear and Replacement data from the Shell units was tire tread depth measurements recorded as part of the periodic maintenance inspections performed on each vehicle. Other potential sources of information such as:

- Monthly Summary Reports of Vehicle Operations Data produced monthly by Shell
- Invoices received by Shell for tire purchases, repairs and maintenance
- Records of work performed kept by tire maintenance subcontractors

were also culled but the resulting data lacked the levels of detail, continuity and consistency required to enable meaningful analysis.

The periodic maintenance inspection records provide tire tread depth measurements, to the nearest 1/32 inch, for each wheel of the vehicle as well as date of inspection and vehicle odometer reading. The frequency of inspections varies:

- Tractors, approximately every 12,000 kilometres, or intervals of about 1.5 months
- Trailers, approximately four inspections per year.

The data collected from Shell vehicle maintenance contractor records, for each component (tractor, lead trailer and pup-trailer) of each ABS-equipped and non-ABS reference unit, revealed numerous inconsistencies and shortcomings:

- Unexplained inconsistencies in the tire tread depth measurements. These are deemed to result from multiple unrecorded tire replacements or, more likely, from lack of measurements precision.

- Maintenance records were frequently lost at the maintenance facility which further reduced the amount of statistically valid data.

- The distance measuring devices on the units, particularly the hub odometers on the trailers, are often faulty and remain unrepaired for substantial periods of time thus preventing meaningful calculation of tire wear rates and comparison with other units.

- Tire tread depth measurements are generally not made on tires as they are removed from the units. Consequently, a significant portion of tread wear never appears in the reported data.

- Since tire tread wear rates vary substantially during the life of a tire, particularly very high wear rates for the first quarter of the initial tread depth, the number of new sets of tires installed on a given unit will significantly affect its overall tire wear rate for the period for which data are available.

The analysis of the available tire tread wear data, for each of the components of the monitored Shell B-Trains revealed that:

- Apparently valid data were available for only one complete vehicle combination, the ABS-equipped B-Train operating out of Hamilton. In all other cases, data are either not available or obviously not statistically significant for one or more of each unit components.

- Apparently valid data are available for all twelve monitored tractors. This may be explained by the fact that tractors are subjected to more frequent and careful maintenance.

Consequently, a meaningful comparison of tire tread wear rates could only be attempted between the tractor components of the ABS-equipped and non-ABS reference units. This comparison is summarised in Table 5.

**Table 5**

**SHELL FLEET - TRACTOR TIRE TREAD WEAR RATES**

| UNIT IDENTIFICATION | TIRE TREAD WEAR RATE - 1/32" (0.8 mm) per 10 000 KM | | | |
|---|---|---|---|---|
| | STEER AXLE 2 Wheels | FRONT DRIVE AXLE 4 Wheels | REAR DRIVE AXLE 4 Wheels | TOTAL 10 Wheels |
| **ABS Units** | | | | |
| ABS - 1 | 2.045 | 5.094 | 5.789 | 12.928 |
| ABS - 2 | 2.083 | 8.143 | 7.101 | 17.327 |
| ABS - 3 | 2.184 | 6.396 | 6.292 | 14.872 |
| ABS - 4 | 1.685 | 3.752 | 5.897 | 11.334 |
| ABS - 5 | 1.211 | 4.170 | 8.072 | 13.453 |
| ABS - 6 | 1.260 | 7.980 | 6.720 | 15.960 |
| **AVERAGE** | **1.745** | **5.923** | **6.645** | **14.312** |
| **Reference Units** | | | | |
| REF - 1 | 2.202 | 5.610 | 5.942 | 13.754 |
| REF - 2 | 1.973 | 4.056 | 4.824 | 10.853 |
| REF - 3 | 1.902 | 5.762 | 5.979 | 13.643 |
| REF - 4 | 1.699 | 5.882 | 9.411 | 16.992 |
| REF - 5 | 1.932 | 6.281 | 7.005 | 15.218 |
| REF - 6 | 1.377 | 2.984 | 6.082 | 10.443 |
| **AVERAGE** | **1.848** | **5.096** | **6.541** | **13.484** |

The total tire tread wear rates, in 1/32 inch (0.8 mm) per 10 000 kilometres, show substantial variation and dispersion within both the ABS Units sample and Reference Units sample which are each limited to six (6) values. A standard Wilcoxan 2 Sample Variance Test indicates that, given the number and dispersion of the sample values, there is not a statistically significant difference between the ABS and Reference tire tread wear rates.

#### 4.2.1.2 Canadian Liquid Air Vehicles

The maintenance contractor for the CLA B-Trains at the Midale operation reported that there was no noticeable tire tread wear rate difference between ABS-equipped and non-ABS units. This observation was based on 13 months of operation during which four ABS-equipped units and two non-ABS units each travelled approximately 400 000 kilometres.

However, "flat-spotting", presumably resulting from locked wheels during hard braking events, led to the replacement of two tires on the non-ABS units while no "flat spotting" was observed during the period on the ABS-equipped units. Consequently, ABS may marginally reduce the tire component of unit operating cost by preventing or reducing "flat spotting". However, it should be remembered that these vehicles were essentially operated on highways, as opposed to the varied operational environment of the Shell vehicles, and that this observation may not be fully meaningful.

#### *4.2.1.3 Project Findings / Tire Wear and Replacement*

*The analysis and evaluation of the available tire tread wear and replacement data indicate that:*

- *Numerous uncontrolled factors can significantly affect the reliability and consistency of the collected data*
- *The collected data do not reveal a statistically significant tire tread wear rate difference between ABS and Reference units*
- *ABS may, by preventing or reducing tire "flat spotting", marginally reduce the tire component of unit operating cost*
- *Tire tread wear and replacement, given the low accuracy and poor reliability of reported monitoring measurements, do not appear to constitute a major concern of vehicle operators since they are apparently satisfied with very approximate and incomplete data.*

*A specific and meaningful study of ABS impact on tire wear and replacement as well as associated vehicle operating cost would require:*

- *A reduction of the number of variables by standardising the brand, type and quality of tires installed on the monitored vehicles*
- *A detailed monitoring of tire tread wear, rotation and replacement in order to assure representative and reliable data*
- *Significantly more frequent and accurate tire tread depth measurements to constitute a more complete and valid data base.*
- *A number of monitored vehicles and a duration of study generating sufficient data to enable a statistically valid analysis of what appears to be a relatively complex phenomenon on which ABS may only have a marginal impact.*

### 4.2.2 Braking System Maintenance

The objective of collecting relevant data on braking systems maintenance was to determine the impact, if any, of ABS on the wear of braking system components.

#### 4.2.2.1 Shell Canada Vehicles

The only sources of detailed information on the actual nature of braking systems repairs and maintenance were determined to be the shop records kept by the maintenance contractors and the repair invoices sent to Shell Canada. The collection and analysis of these data proved to be very difficult and time consuming since:

- Braking system repairs are often grouped with other maintenance operations on the same records or invoices and are difficult, if not impossible, to isolate.
- Shop records were not readily made available by maintenance contractors and, in the best of cases, had to be consulted at each location to extract braking system related items manually.
- Shop records were found to be incomplete and/or inconsistent in many instances due generally to a lack of accuracy in work description and to the absence of an efficient filing system which prevented the tracking of maintenance performed on any given vehicle.

The validity, reliability and significance of the available data were further reduced by the following characteristics identified during analysis:

- Most of the tractors on the program were delivered new with and without ABS at approximately the same time and could thus be considered to constitute a statistically

valid sample. However, the data obtained for the trailers could not be significantly analysed since the detailed status of all the braking systems and associated equipment at the start of the testing period could not be ascertained

- At the end of the data collection phase of the present study, most of the tractors had logged approximately 250 000 kilometres and none, whether ABS-equipped or non-ABS reference vehicles, had required major braking system maintenance or replacement of parts

- Various trailer components of the monitored vehicles had required one instance of major braking system maintenance or replacement of parts but, since the initial condition of the system could not be determined, this information could not justify any conclusions

- The intermediate measurements of remaining brake lining thickness, made by mechanics as part of periodic maintenance inspections, are not actual measurements but visual estimates which are, therefore, neither exact nor reliable.

- The validity of the available data was further reduced by the lack of control on the type and quality of replacement brake linings which have a major impact on the frequency of required maintenance, and the lack of consistency in maintenance standards and replacement parts.

Consequently, given the quality of the available data, the impact of uncontrolled variables and the insufficient duration of the monitoring period, it has been impossible to produce a detailed statistically significant analysis of the impact of ABS on the general maintenance of braking systems. However, it can at least be stated that there do not appear to be any significant differences in the maintenance of braking system components, both in terms of extent and of frequency, between ABS-equipped and non-ABS vehicles.

#### 4.2.2.2 Canadian Liquid Air Vehicles

The Canadian Liquid Air maintenance contractor in Midale also reports that during the accumulated 13 months of operation and approximately 400 000 kilometres/vehicle:

- Brake lining wear rates appear to be similar on ABS-equipped and non-ABS units

- Major braking system maintenance or parts replacement have thus far not been required on any of the vehicles.

*4.2.2.3 Project Findings / Braking System Maintenance*

*The analysis and evaluation of the available braking system maintenance data indicate that:*

- *The collected data were not of sufficient duration to reveal a statistically significant difference in braking system maintenance between ABS-equipped and Reference units*

- *Braking system maintenance, given the accuracy and reliability of reported monitoring measurements, does not appear to constitute a major concern of vehicle operators since they are apparently satisfied with very approximate and incomplete data.*

*A specific and meaningful study of ABS impact on braking system maintenance as well as associated vehicle operating cost would require:*

- *A reduction of the number of variables by standardising the brand, type and quality of brake linings installed on the monitored vehicles*

- *Significantly more frequent and accurate brake lining thickness measurements to constitute a more complete and valid data base.*

- *A number of monitored vehicles and a duration of study generating sufficient data to enable a statistically valid analysis of a phenomenon on which ABS may only have a marginal impact.*

### 4.2.3 Safety Record

ABS systems, by reducing stopping distances and improving vehicle control during braking as convincingly demonstrated by track tests[4,5], can potentially contribute significantly to increased safety. The objective of collecting data on the safety record of monitored vehicles was to attempt to demonstrate and verify the importance of this contribution under actual conditions of fleet operation.

4.2.3.1 Shell Canada Vehicles

The twelve monitored B-Trains, during the data collection year of this study, travelled approximately 100 000 kilometres each and were involved in the following two reported accidents:

- ABS-1, an ABS-equipped unit operated out of Hamilton, was destroyed by fire in August 1992 after its driver lost control while avoiding a frontal collision with an automobile entering an expressway from an exit ramp. The accident report, based on the driver's account, indicated that braking was not attempted and was thus not a factor in the loss of control. The fire occurred after the vehicle overturned in the ditch. The driver succeeded in escaping safely before the fire.

- ABS-5, an ABS-equipped unit operated out of Montreal and sold in August 1992 to a Quebec City transporter, suffered minor damage in December 1992 in a loss of control accident which resulted in the vehicle going into a ditch. The accident report, based on the driver's account, indicated that the pavement was extremely slippery, and that a particularly strong gust of cross wind simply pushed the unit off the road. Braking was not attempted and was thus not a factor in the loss of control.

The drivers of the twelve vehicles also reported a few near misses, as indicated above in the section of this report devoted to driver interviews. However, these were not of a sufficient number to constitute a meaningful source of statistically significant data.

#### 4.2.3.2 Canadian Liquid Air Vehicles

The Canadian Liquid Air fleet manager in Midale reports that in the first thirteen months of operation not a single accident occurred and drivers did not report any near misses. During this time the four units completely equipped with ABS systems and the two units with ABS on the tractors only each travelled an average of 400 000 kilometres.

#### *4.2.3.3 Project Findings / Safety Record*

*The analysis and evaluation of the available safety record related data indicate that they do not constitute a statistically significant sample of events enabling the determination of a difference between the safety records of ABS and of Reference units.*

*A specific and meaningful study of ABS impact on safety record as well as associated accident costs to the operator would require:*

- *A larger number of monitored vehicles and a duration of study generating sufficient data to enable a statistically valid analysis of accidents which are relatively rare occurrences and which generally involve multiple causal factors.*

- *A detailed analysis of accident related costs, both in terms of damages and of loss of hauling capacity, as well as the potential reduction in vehicle insurance costs resulting from reduced frequency and severity of accidents.*

## 4.3 ABS SYSTEMS COST IMPACT

The cost impact argument is often used by vehicle operators to justify their resistance to ABS systems. This section of the report presents a detailed analysis of this impact on the basis of average hourly B-train operating costs extracted from the Shell Canada unit statistics and observed performance characteristics of the vehicles monitored under this project.

This analysis considers such cost items as:

- Capital cost.
- ABS system maintenance cost
- General vehicle maintenance costs related to tires and brakes

The analysis demonstrates that the overall impact of ABS systems is marginal and substantially less than 1% of total vehicle operating costs. These results do not take into account potential reduction in cost items: tire wear, brake wear, preventable accidents and vehicle insurance; which the data available did not allow to quantify reliably.

### 4.3.1 Initial Installation Cost

In 1992, the initial installation cost of the ABS system on each of the Shell Canada B-Trains were reported to be the following:

- For the tractors, the systems were Original Equipment Manufacturer (OEM) installed at a reported cost of approximately $2 000 per unit
- For the trailers the systems were retrofitted at a reported cost of approximately $10 000 per trailer pair ($6 000 for parts and $4 000 for labour). It is estimated that the cost of OEM installed systems would have been substantially less and would likely have been in the range of $7 000 to $8 000.

The reported 1992 purchase price of a new B-Train equipped with a conventional braking system was approximately $235 000. The OEM-installed ABS option would have added approximately $10 000 or 4% to this purchase price.

### 4.3.2 System Maintenance Cost

There are inevitable maintenance costs associated with an ABS system as with any other vehicle component or system. One such cost is obviously a periodic maintenance inspection of the system to determine its operating condition. This inspection, since the system has a continuous self-diagnostic function, requires minimal specific effort and can be limited to a visual inspection of the apparent condition of the system components to detect any physical damage. It can readily be included at minimal additional cost with the regular maintenance and safety inspection performed on the vehicle.

Actual maintenance and repair costs of the ABS system, based on the experience and findings of this project must be separated into three distinct categories:

- Maintenance and repair costs resulting from a failure of the ABS system, with the exception of its speed sensing component, are minimal and represent a marginal cost increase, estimated at certainly less than 10% of the braking system maintenance costs.

- A substantial number of repair costs appear to result from damages to the system such as:

    - Cut wires during other vehicle maintenance on braking and suspension systems,

    - Tractor-to-trailer or trailer-to-trailer connecting cables damaged by improper handling,

    - Damage to ABS system components resulting from failures of other vehicle components.

    The occurrence of this damage to the system and their associated repair costs will certainly diminish as ABS systems become more common and as the vehicle drivers and maintainers become more familiar with their operation and maintenance.

- The more significant system maintenance cost item during this project was related to the wheel speed sensors which, as noted above in Section 4.1.3.1, required frequent position adjustment. This cost item will be largely eliminated when, as suggested, a more permanent and secure method of speed sensor installation has been developed.

### 4.3.3 Vehicle Maintenance Cost

The impact of an ABS system on vehicle maintenance cost can be established on the basis of its impact on maintenance requirements as described above in Section 4.2 of this report.

- The impact on tire related maintenance cost is marginal and likely to result in savings though the data available did not enable a statistically valid analysis to produce a meaningful quantification of this impact.

- The impact on braking system related maintenance costs is marginal and probably insignificant. Again the available data did not enable a statistically valid analysis to produce a meaningful quantification of this impact.

- The impact on safety record-related operating costs is probably significant and certain to result in savings. The available data did not enable a statistically valid analysis to produce a meaningful quantification of this impact. However, the reduced stopping distances and increased vehicle control would certainly result in fewer and less severe accidents and would translate into vehicle operation savings in terms of reduced damages, vehicle downtime and insurance premiums.

### 4.3.4 Overall Cost Impact

Shell Canada Limited provided, as part of its contribution to the data collection effort under this project, their monthly reports on operations statistics for each of the monitored B-Trains, both ABS-equipped and non-ABS reference units. These reports contain general data such as hours of operation and distance travelled, as well as detailed operating costs, including maintenance of various vehicle systems and components, running costs, driver wages and capital costs.

However, due to the accounting practices of Shell Canada, such as lumping costs over certain periods of time and the relatively short period of time for which data were available for ABS-equipped units, it is not possible to extract meaningful and reliable operating cost statistics on a per unit and/or per month basis. Furthermore, Shell Canada indicated the semi-confidential nature of this information and its preference that only essential average values be published.

Consequently, all operating costs were averaged and expressed on an average common basis of dollars per hour of vehicle operation ($/Hour). These Shell Canada fleet B-Train operating costs are shown on Table 6 for five main cost categories: maintenance, running, driver, other and capital; as well as two sub-categories: tires and brakes; most likely to be impacted by ABS systems. This Table also shows the cost impact, in both percentages and dollars, of ABS systems on the affected components of vehicle operating costs.

**Table 6**

**IMPACT OF ABS SYSTEM ON VEHICLE OPERATING COSTS**

| COST ELEMENTS | B-TRAIN OPERATING COSTS - $/Hour | | | | NOTES |
|---|---|---|---|---|---|
| | Shell Canada Fleet | Impact of ABS System | | ABS-Equipped Vehicle | |
| | Average Costs | % | $ | Resulting Costs | |
| **Maintenance Costs** | **7.63$** | | | **7.69$** | **Increase of approximately 1 % due to ABS System** |
| Engine | | | | | |
| Power Train | | | | | |
| Electrical | | | | | |
| Tires | 1.11$ | * | * | | Probable marginal reduction in Tire Tread Wear and Replacement Costs |
| Brakes | 0.63$ | 10% | 0.06$ | | 10 % increase in cost generated by Maintenance of ABS System |
| Cab/Tanks | | | | | |
| Delivery Equipment | | | | | |
| Suspensions | | | | | |
| Maintenance Schedules | | | | | |
| Other Miscellaneous | | | | | |
| Spill Protection | | | | | |
| Labour | | | | | |
| **Running Costs** | **9.80$** | | | **9.80$** | **Not affected by ABS System** |
| Fuel | | | | | |
| Misc Truck Expenses | | | | | |
| Replacement Rental | | | | | |
| **Driver Costs** | **34.39$** | | | **34.39$** | **Not affected by ABS System** |
| **Other Costs** | **0.83$** | | | **0.83$** | **Probable marginal reduction due to ABS System** |
| Licenses | | | | | |
| Insurance | | * | * | | Probable marginal reduction of Insurance Cost due to improved safety record |
| **Capital Costs** | **10.15$** | **4%** | **0.40$** | **10.55$** | **4 % increease corresponding to the increase in Vehicle Purchase Price** |
| **TOTAL OPERATING COSTS** | **62.80$** | **0.73%** | **0.46$** | **63.26$** | **0.73% increase in Total Vehicle Operating Cost** |

* Refers to operating cost elements which could not be quantified given the data available.

### *4.3.5 Project Findings / ABS Systems Cost Impact*

*The analysis of the potential impact of ABS systems on the vehicle operating costs, based on actual average Shell Canada fleet operating costs of B-Trains and observed performance characteristics of vehicles under this project, leads to the formulation of the following supported project findings. (Note that number of decimal places of dollars and cents as well as percentage figures quoted here are not meant to convey level of precision of results)*

- *The impact of ABS systems on the following operating cost items:*
    - *Tire tread wear and replacement (probable marginal reduction)*
    - *Braking system (including ABS system) maintenance*
    - *Vehicle insurance cost (probable marginal reduction related to improved safety record)*
    - *Capital cost*

  *is marginal in all cases and results in a total increase of approximately $0.46 per hour of vehicle operation or 0.73% of the total operating cost for a B-train at $62.80 per hour.*

- *The relatively low importance of the following maintenance items:*
    - *Tire tread wear and replacement: $1.11/Hour or 1.7% of the total hourly operating cost for a B-Train which is $62.80*
    - *Braking system parts and repairs: $0.63/Hour or 1.0% of the total hourly vehicle operating cost*

  *may account for the poor quality of data available on these aspects of vehicle operation since operators neither perceive the need for accurate information on, nor devote much attention to, such low impact cost items.*

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## 5.0 ASSESSMENT OF PROJECT FINDINGS

This chapter, in order to assess the representativity and validity of the results of this evaluation project, attempts to compare these results with the reported findings of other similar or related projects and studies on the performance characteristics of antilock braking systems installed on heavy commercial vehicles.

The sources identified of pertinent and comparable ABS system evaluation results and findings consist of two project reports [1, 8] published by the National Highway Traffic Safety Administration (NHTSA) of the U.S. Department of Transportation and of two technical papers published by the Society of Automotive Engineers (SAE)[9, 10].

The comparison of actual quantified performance indicators has been attempted to the extent possible while more subjective performance indications are also considered in the absence of sounder bases of comparison. The resulting assessment of the findings of this project, though not entirely satisfactory because of the scarcity of published comparable data, does provide a measure of confirmation of their representativeness and validity.

### 5.1 NHTSA STUDY FINDINGS

The National Highway Traffic Safety Administration has been testing and evaluating various generations, types, configurations and makes of ABS systems since the mid-1970's. Consequently it has acquired considerable knowledge of the performance characteristics of the ABS technology and expertise in techniques applicable to their evaluation.

In 1988, NHTSA began an ABS in-service evaluation program based on the monitored performance of five makes of ABS systems each installed on forty truck tractors. The monitoring of these 200 vehicles covered a period of two years and approximately 40 million miles (64 million kilometres) of accumulated travel distance. The monitoring techniques and the types of data collected in the NHTSA program are similar, though not identical, to those of the present evaluation project. In fact, this project was designed to assure data and result compatibility and comparability with the NHTSA program. The major difference was that this project monitored ABS systems installed on all three components of B-Train vehicles while the NHTSA monitoring was limited to the tractor component of the test vehicles. It should be noted that a subsequent NHTSA monitoring project included semitrailers.

The NHTSA program produced two reports which provide test results and ABS system performance parameters enabling comparison with and validation of the findings of the present evaluation project. The earlier (1991) publication [8] contains background information on ABS technology and previous performance studies as well as initial results of the Fleet Evaluation Program. The later (1992) publication [1] constitutes the final program report and contains a full

description of the evaluation methodology and complete test results as well as program conclusions and recommendations.

- **Frequency of Major ABS Events**

  The reported frequencies of Major ABS Events, occurring on tractors which were the only vehicle component monitored under the NHTSA initial program are the following:

  - NHTSA Program (Reference 1, Table 4.2, page 4-8)

    | | |
    |---|---|
    | Number of major events / 10 000 brake applications: | 1.4 |
    | Number of major events / 10 000 miles of travel: | 1.1 |
    | Number of major events / 10 000 kilometres of travel: | 0.7 |

  - This evaluation project (Table 4, page 4-7)

    | | |
    |---|---|
    | Number of major events / 10 000 brake applications: | 1.4 |
    | Number of major events / 10 000 kilometres of travel: | 1.5 |

  The consistency in the reported number of major ABS events per 10 000 brake applications indicates that both evaluation projects were equally successful in their attempt to monitor ABS system activity under actual in-service vehicle operating conditions.

  The difference in the reported number of major ABS events per 10 000 kilometres of travel, double for this project, is not inconsistent with the NHTSA program finding that this frequency-distance ratio varied by a factor of up to 9 between the participating fleets reflecting driving techniques and/or operating conditions. The noted difference may be explained by the fact that the Shell Canada vehicles, monitored under this project, operated substantially in urban and suburban environments where vehicle operation is likely to generate more brake applications, consequently more ABS events, per kilometre than highway operation. Climatic conditions may also account for part of the difference but this cannot be verified from the available data.

- **Reliability and Maintainability of ABS Systems**

  Both evaluation projects found that, discounting initial installation/pre-production associated problems, the monitored ABS systems were remarkably reliable and maintenance free. The types of initial problems, that mostly required adjustments and corrections, would likely be eliminated as ABS systems become more common and routinely installed as original equipment.

The most common source of maintenance requirements on ABS systems, monitored under both projects, was found to be the speed sensing device installed at each of the wheels monitored by the ABS system ECU. This project found this problem to be particularly acute in the case of trailers where it accounted for nearly 50% of the system failures. As noted earlier, this high unavailability was the result of operator delays in attending to ABS speed sensor adjustments due to the perceived fail-safe nature of ABS operation which reverts to standard brake operation when failures are detected. The fact that minimal problems and/or maintenance requirements related to cables and connectors where noted during this study may result from the "married pair" operation of tractors and trailers.

- **Impact of ABS Systems on Vehicle Maintenance Costs**

  Both the NHTSA study and this project found that ABS is not a zero maintenance item but that associated costs can be considered as marginal when compared to overall vehicle maintenance costs. NHTSA reported that ABS generated an increase of 0.59% of total vehicle maintenance cost while the corresponding value for this project is approximately 1%. This difference stems from the fact that:

  - The NHTSA program compared the maintenance cost of a single ABS system to the overall relatively high maintenance cost of a tractor.

  - This project compared the maintenance cost of 3 ABS systems with the overall maintenance cost of a B-Train including the relatively lower costs associated with trailer maintenance.

- **ABS System Perception and Acceptance**

  The comments collected from participants (drivers, vehicle maintainers and fleet operators) of both evaluation projects indicate that ABS technology is generally well perceived and accepted by most if not all persons who have had the opportunity to become familiar with its performance characteristics and are considered as contributing significantly to road safety. The following two concerns with ABS have however been identified from those responses:

  - The warning light arrangement that indicates to the driver an ABS system failure characteristics appears to be confusing. The resulting constant bright light is reported as annoying and distracting particularly since the ABS is fail-safe and standard brakes are available. Further design consideration, standardisation and instruction seems to be required with respect to this system component.

- The availability of specialised support service from the ABS system suppliers and of adequate training for maintenance personnel is a prime concern of fleet operators. The failure to provide such support and training would likely lead to a reduced acceptance level for the ABS technology and neglect of equipment maintenance given the fail-safe feature of ABS systems.

## 5.2 SAE REPORTS

The authors of the SAE document [9], prepared as a lecture presentation and which predates (1989) the NHTSA ABS Fleet Evaluation Program, present very detailed and comprehensive descriptions of the mechanics of braking, historical background information on ABS technology and analysis of current systems in terms of their components, their performance and reliability and procedures for the further quantification of braking performance enhancement by antilock. The performance parameters reported in this publication and which can be compared with the findings of the present evaluation project, were derived from data collected in Europe and in Australia where the application of present generation ABS technology is more advanced than in North America.

The more readily comparable findings reported in this publication are the following:

- "The lack of standardisation regarding the operation of the warning lights can be confusing to the drivers."

- "...it was common for drivers to remove the warning light bulb or tape over the light to keep it from shining continuously, especially at night."

- "...to give an overall reliability numeric, the average service call rate is estimated to be 0.0015 service visits per month per vehicle in use."

- "The European and Australian motor carrier experience with current antilock systems of European design indicates that when antilock is introduced into a fleet a variety of initial "teething" problems can be expected before the systems settle down to more trouble-free operation."

- "Information on the field experience of the newer digital systems was obtained from surveys conducted by Daimler-Benz. This information is based on approximately 40 000 heavy vehicles sold with antilock installed since 1982. The causes of failures are divided among components as follows: sensors, 25 percent; cables and connectors, 50 percent; ECU's, 21 percent; and solenoid valves, 4 percent."

These findings support those of this evaluation project related to required improvement to the warning light component, the reliability of ABS systems and the necessity for system suppliers to provide specialised support and training coincidental with the introduction of ABS technology. The reported distribution of failures by components does not concur with the findings of this project which identified the speed sensor component as the prevailing source of failures followed by accidental damage particularly to cables and connectors.

The second SAE reference document [10] presents descriptions of the hardware, software and performance of the on-board electronic real-time monitoring equipment developed for the NHTSA program and modified to enable multi-component monitoring for this evaluation project. The experience gained with this equipment in the present project essentially supports the contents of this reference document, written by the equipment developers, with two notable additions:

- As noted in the NHTSA report [1] configuration of the equipment to adequately monitor and record ABS activity required various Programmable Read Only Memory (PROM) changes. A number of failures related to improper equipment installation also had to be repaired before satisfactory and reliable data were obtained.

- Equipment and software modifications were required to assure the simultaneous and synchronised operation of the two recorders (tractor and trailers) essential to meaningful analysis of events involving all three B-Train vehicle components.

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# 6.0 CONCLUSIONS AND RECOMMENDATIONS

This last chapter contains the conclusions derived from, and the recommendations supported by, the results of this evaluation of Antilock Braking Systems installed on B-Train heavy tanker vehicles.

## 6.1 CONCLUSIONS

The results of this evaluation project, as formulated in the Project Findings sections of 4.0 - DATA ANALYSIS AND PROJECT FINDINGS, support the following conclusions with respect to the performance of ABS systems and their impact on the operation of B-Train vehicles.

- **Frequency of ABS System Activations**

  The electronic monitoring data have revealed that, for each 10 000 kilometres of vehicle operation, approximately 2 000 actual ABS Events are generated including 10 that are classified as Major ABS Events resulting in four or more system activations. These event frequencies are comparable to those reported by the NHTSA Evaluation Program.

  The same monitoring records have also revealed a high incidence of spurious ECU activations that occur in the absence of braking system treadle valve pressure. The frequency of these non-braking activations encountered in the early stages of this project was such that the data loggers had to be equipped with electronic filters to eliminate them and prevent saturation of the memory buffers with non-significant information. These high numbers of ECU activations, if they actually trigger solenoids and pressure modulating valves, raise questions as to the durability and life expectancy of the ABS systems and, in particular of their mechanical components such as solenoids and PMVs. However, since electronic memory availability limited monitoring recordings to actual ABS events, such spurious activations of mechanical components could not be verified or confirmed during this study.

- **Potential Impact on Traffic Safety**

  The safety record data collected under this project do not constitute a statistically significant sample of events given the facts that accidents are relatively rare occurrences and that they generally involve multiple causal factors.

  Since it is estimated that, under the vehicle operation characteristics observed during this evaluation project totalling approximately 100 000 kilometres per year, a functioning ABS system would generate, in reaction to severe braking and/or slippery road conditions, approximately 100 major ABS events out of which 20 would occur at speeds above 75 km/h. ABS certainly has a very real and significant potential to reduce accident frequency/severity and to contribute to traffic safety through its test-

track proven capacity to reduce stopping distances and to improve vehicle control during braking.

The potential value of ABS is particularly obvious in the case of the pup trailer on which the frequencies of occurrence of significant and major ABS events are 3 to 4 times those on the tractor and lead trailer.

- **System Reliability**

  The monitored ABS system demonstrated a high level of integrity, consistency and reliability in its operation by providing in all cases analysed the adequate anti-lock response as expected and in conformity with the system specifications.

  However, the monitoring data available have not enabled the determination of the reliability of the ABS system in terms of its consistency in detecting, recognising and responding to all situations corresponding to the pre-set conditions of ABS function triggering. The collection of the data necessary for such an analysis would require, given the vastly increased mass of data, more sophisticated monitoring equipment and analysis software. However, based on consistent results from previous track tests and discussions with drivers, there is no reason to believe that pre-set triggering conditions are not consistently handled by the ABS system.

- **Durability and Maintenance Requirements**

  ABS systems, with the exceptions noted below, are remarkably durable and virtually maintenance free. Many of the problems associated with ABS systems and required repairs appear to result from the lack of familiarity of installers/maintainers with the systems. These conclusions were also reported in NHTSA [1] and SAE [9] publications.

  The following two weaknesses were detected on the monitored ABS system:

  - The wheel speed sensor assembly provided with the monitored ABS system requires much too frequent and difficult adjustments. Further engineering development is necessary to minimise the requirement of frequent adjustment.

  - The monitored ABS system appears to have electrical power supply voltage requirements which are often not satisfied by the vehicle electrical system. Consideration should be given to lowering this voltage requirement since even a very modest reduction would eliminate a significant number of system shut-downs. [More recent ABS systems are apparently more tolerant and the frequency of this problem seems to have been significantly reduced]

- **Impact on Vehicle Operation**

  ABS would be expected to have a positive impact on tire tread wear and replacement by preventing "flat spotting" caused by wheel lock-up. In relation to braking system maintenance it may have a positive effect, by more evenly distributing braking efforts and stresses, and a negative effect, by increasing the effective number of brake applications due to system pulsing.

  In both cases the collected data did not reveal a statistically significant difference between the ABS and the Reference vehicles. This may partially be attributable to the limited sample size, one year of operation and six vehicles, and to the complexity of factors involved of which ABS effects may be only marginal.

  It was also found that corresponding maintenance records, as kept by vehicle maintainers and operators, are very incomplete and of limited reliability for the purposes of this project. This lack of concern for valid maintenance data on these vehicle components (tires and brakes) may be explained by their relatively low contributions, approximately 1.0%, of the total operating cost of a B-Train.

- **Impact on Vehicle Operating Cost**

  The analysis of vehicle operating costs, based on actual average Shell Canada fleet operating costs of B-Trains, indicates that, taking into consideration the following operating cost items:

  - Tire tread wear and replacement (probable marginal reduction)
  - Braking system (including ABS system) maintenance
  - Vehicle insurance cost (probable marginal reduction related to improved safety record)
  - Capital cost;

  the impact of ABS systems is marginal in all cases and results in a total increase of approximately $0.46 per hour of vehicle operation or 0.73% of total operating cost of a typical non-ABS B-train of $62.80 per hour.

- **Perception and Acceptance**

  The perception of drivers and operators on ABS systems can be summarised as follows:

  - ABS systems are reliable and their performance has generated acceptance and confidence particularly from the drivers.

- ABS systems contribute significantly to safety by improving vehicle control during severe braking particularly under adverse trailer loading and/or weather/pavement conditions.

- The successful introduction of any new technology, such as ABS systems, requires an adequate training and familiarisation program for drivers, maintainers and operators. A test track practice session for drivers would be a most valuable feature of such a program.

- Easy access to parts and technical support is essential to assure acceptance and proper maintenance of ABS systems.

- The benefits associated with ABS systems outweigh their costs provided they are factory installed and that specialised service support is readily available.

- ABS systems warning lights should be standardised to better inform the driver of the status and availability of ABS on the vehicle.

- Operators unanimously recommended that all new vehicles should be equipped with factory installed ABS systems and drivers prefer ABS-equipped vehicles.

## 6.2 RECOMMENDATIONS

The project findings and the above conclusions, supported by the reported findings of other evaluation projects, justify the following recommendations with respect to the application of ABS technology on heavy vehicles and particularly B-Trains.

- **Application of ABS Technology**

  The ABS technology and the available ABS systems should be promoted in the highway freight transportation industry and its application to all heavy vehicles should be supported and facilitated as much as possible.

  This recommendation particularly applies to double trailer combinations, such as the B-Train, on which ABS has been found to be more active on the pup trailer which tends to be more difficult to control when lightly loaded or empty.

- **Introduction of ABS Technology**

The successful introduction of ABS technology in the highway freight transportation industry will require from the ABS manufacturers:

- An adequate training and familiarisation program for drivers, maintainers and operators to demonstrate ABS capabilities, reliability and limited maintenance requirements. This will assure initial acceptance of a new technology which otherwise may only be considered as an accessory of limited practical value and a source of additional maintenance requirements and operating costs.

- The local availability of specialised support service from ABS systems suppliers. This will assure continued acceptance and maintenance of ABS which otherwise may be neglected and, given the system's fail-safe feature of reverting to standard braking mode, eventually be considered as a useless source of problems.

The suppliers of ABS systems must be made aware of the importance of adequate introduction programs and service networks as well as be convinced that their contribution to these aspects is essential to the successful introduction of ABS technology in the transportation industry.

- **ABS Systems Engineering Development**

ABS systems have demonstrated their general reliability, durability and low maintenance requirements, however the following aspects of these systems require further engineering development consideration.

- The Warning Light feature of all ABS systems, provided to inform the vehicle driver on the operating status of ABS, is reported to create confusion by only providing partial information and by the lack of standardisation in its operation between systems of different suppliers. This confusion and/or the annoyance created by this system component has led drivers to ignore this important safety feature and to frequently disable it by removing or taping over the light bulbs. There are obvious needs for further development, both technical and in terms of ergonomics, of this system component and for operational standards to be developed and adopted by all ABS systems suppliers.

- The wheel speed sensor assembly provided with the monitored ABS system requires much too frequent and difficult adjustments. This component of the system definitely requires further engineering development.

- The monitored ABS system appears to have electrical power supply voltage requirements which are often not satisfied by the vehicle electrical system. Consideration should be given to lowering this voltage requirement since even a very modest reduction would eliminate a significant number of system shut-

downs. [More recent ABS systems are apparently more tolerant and the frequency of this problem seems to have been significantly reduced]

- **Further ABS Systems Evaluation Projects**

This evaluation project has raised a number of questions relative to the operation of the monitored ABS system while the data available were insufficient to formulate adequate answers to the following questions:

- There appears to be a very significant level of ABS ECU activity even in the absence of brake application as detected through the monitoring of treadle valve pressure. This activity seems to be triggered by a reduction in wheel speed occurring when the vehicle travels over bumps and wheels are bounced off the roadway surface and to be most frequent when the vehicle is lightly loaded or empty. This, if corresponding activity is triggered at the wheels, raises the question of durability and life expectancy of mechanical system components, such as solenoids and pressure modulating valves, which may not have been designed to tolerate these levels of frequency of spurious non-braking system activity.

  In a manufacturer's letter addressing this matter, it was stated that, in the laboratory, the pressure modulation valve has been endurance tested under similar operating conditions. During one of the tests the solenoid was cycled 13.8 million times. At the end of the tests the armature of the solenoid showed 0.1 mm wear. This wear did not have any effect on the function of the pressure modulation valve. The valve has been shown to be very reliable from their examination of field failure rates, with the overall rate being 0,21 % (1994), and most customer claim being the result of contaminated air supply.

- The ABS system suppliers claim that their equipment has the capability to detect imminent wheel lockup and to prevent actual lockup by activating the "hold" function of the system which simply prevents further build-up of pressure in the corresponding wheel brake chamber. It would certainly be interesting to determine the efficiency of this system feature and its real benefits. There is a possibility that this feature requires very low system triggering thresholds and accounts for the high levels of spurious non-braking activity noted previously.

- The monitored ABS systems demonstrated very high levels of consistency and reliability in responding as expected and in conformity with system specifications. However, it should be remembered that the recording of electronic monitoring data were itself triggered by ABS activity and that, consequently, these data do not provide any indication of the system consistency and reliability in detecting, recognising and responding to all situations requiring ABS activity.

These questions could only be answered satisfactorily through an evaluation project which would provide continuous and simultaneous real-time electronic monitoring and recording of ABS system activity and wheel speed characteristics. Such an evaluation would require:

- Monitoring equipment similar to but more powerful, in terms of both number of recording channels and memory capacity, than the equipment used in this project.

- Participation by the ABS system supplier(s) which would have to provide monitoring access to all system components.

- Frequent access to the monitored vehicles to assure timely data retrieval and adjustments on both the ABS and monitoring equipment.

The acquisition of valid and representative data would likely require a three to six month period of monitoring at least one vehicle for each of the makes of ABS systems evaluated.

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# APPENDIX A

## LIST OF REFERENCES

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1 **An In-Service Evaluation of the Reliability, Maintainability and Durability of Antilock Braking Systems (ABS) for Heavy Truck Tractors**
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2 **B-Train ABS Evaluation; a Project Concerning the Evaluation of Antilock Braking System Performance and Durability on B-Train Double Tanker Vehicles**
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3 **The Braking Performance of Large Trucks and the Contribution of Antilock Systems**
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4 **Test Report - Antilock Braking System for B-Train Double Tanker Trailer Vehicles**
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7 **Impact of an Antilock Brake System on Braking Efficiency of Heavy Commercial Vehicles (Draft Report)**
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# APPENDIX B

## ABS MONITORING EQUIPMENT - VMC DOCUMENTATION
## ABS LOGGER - INSTALLATION AND OPERATIONS MANUAL

## APPENDIX B ABS MONITORING EQUIPMENT - VMC DOCUMENTATION
## ABS LOGGER - INSTALLATION AND OPERATIONS MANUAL

This appendix contains a 27-page document produced by Vehicle Monitor Corporation (VMC) which manufactured, installed and provided technical assistance for the operation of the on-board electronic equipment used to monitor the performance of ABS systems during this evaluation project.

This document “ABS LOGGER - Installation and Operations Manual” is intended to provide technical information on this specialized equipment, its monitoring functions and the resulting availability of data.

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***FOLLOWS A 27-PAGE MANUAL PREPARED BY VMC***

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***Non disponible en format électronique)***

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# APPENDIX C

## ABS SYSTEM MONITORING DATA ANALYSIS SAMPLE REPORT AND STRIP CHARTS

**(Not available in electronic format/Non disponible en format électronique)**

## APPENDIX D

# ROBERT BOSCH CORPORATION - REPORT
# BOSCH ABS EVALUATION ON B-TRAINS OVERVIEW

## APPENDIX D ROBERT BOSCH CORPORATION - REPORT BOSCH ABS EVALUATION ON B-TRAINS OVERVIEW

This appendix contains a 6-page document produced by Robert Bosch Corporation which manufactured, supervised the installation and provided technical assistance for the operation of the of ABS systems monitored on the Shell Canada vehicles during this evaluation project.

This document “Bosch ABS Evaluation on B-Trains Overview” provides a complete record of all maintenance and/or repair activities performed by Bosch on these ABS systems during the project. It also contains the results of a detailled inspection of the ABS systems on the four remaining B-trains at the end of the data collection phase of the project.

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***FOLLOWS A 6-PAGE REPORT PREPARED BY BOSCH***

***(Not available in electronic format/***
***Non disponible en format électronique)***