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URBAN BUS OPTIMAL PASSIVE SUSPENSION STUDY

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by

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16. Abstract

Systematic analytical, laboratory and field studies were conducted to determine optimal suspension damping for urban buses to reduce the magnitudes of vibration transmitted to the driver, as well as the dynamic forces transmitted to the pavement and chassis for the preservation of urban roads and the chassis structure, respectively. It was recognized that urban buses encounter wide variations in their operating conditions, including passenger load, road roughness, speed and tire inflation pressure. Simplified and comprehensive computer models of Classic and Low Floor urban buses were formulated to study their dynamic performance under specified ranges of operating variables. A series of laboratory and road tests were performed to examine the validity of the proposed computer models and to study the role of varying operating conditions. Results suggested that the ride vibration as well as the dynamic tire and chassis load responses of urban buses are strongly influenced by variations in road roughness, operating load and suspension-damping properties. A multi-parameter, nonlinear optimization problem was formulated and solved to identify the optimal parameters for multi-stage hydraulic dampers for the candidate buses. A series of field tests and computer simulations were performed to demonstrate the potential benefits of the optimal dampers. The results of the study demonstrated superior performance of the optimal dampers for both types of vehicles in terms of driver- and road-friendliness measures, irrespective of the variations in road roughness, speed, tire inflation pressure and operating load.

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16. Résumé

Des études systématiques, soit des analyses, des essais en laboratoire et des essais sur route, ont été menées pour déterminer l'amortissement optimal de la suspension des autobus urbains, c'est-à-dire le coefficient d'amortissement nécessaire pour atténuer à la fois les vibrations transmises au conducteur et les forces dynamiques transmises à la chaussée et au châssis, aux fins de préserver les chaussées des villes et le châssis des véhicules. Il a été reconnu d'emblée que les conditions d'exploitation des autobus urbains varient grandement, qu'il s'agisse du nombre de passagers transportés, des inégalités de la route, de la vitesse du véhicule ou de la pression de gonflage des pneus. Des modèles informatiques simplifiés et détaillés des autobus Classic et à plancher surbaissé ont été développés puis utilisés pour l'étude du comportement dynamique de ces véhicules dans des gammes précisées de paramètres de fonctionnement. Des essais en laboratoire et des essais sur route ont ensuite servi à examiner la validité des modèles informatiques et à étudier l'impact de la variabilité des conditions de fonctionnement. Les résultats obtenus donnent à penser que la douceur de roulement des autobus ainsi que leur comportement dynamique sous la charge exercée sur les pneus et le châssis varient grandement en fonction des inégalités de la route, de la charge transportée et du coefficient d'amortissement de la suspension. Un problème d'optimisation non linéaire à plusieurs variables a été posé et résolu, ce qui a permis de définir les paramètres optimaux des amortisseurs hydrauliques à plusieurs positions destinés aux autobus candidats. Des essais sur le terrain et des simulations par ordinateur ont permis de démontrer les avantages potentiels des amortisseurs optimaux ainsi définis. Globalement, l'étude a révélé une performance supérieure des amortisseurs optimisés à celle des amortisseurs standard des deux autobus, tant du point de vue du conducteur que sur le plan de la préservation de la chaussée, peu importent les inégalités de la route, la vitesse du véhicule, la pression de gonflage des pneus et la charge transportée.

17. Mots clés
Autobus urbain, suspension passive, amortisseurs à plusieurs positions, mesures de performance, modèles informatiques, optimisation de la suspension, charge sur la chaussée, charge sur le châssis, vibration

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EXECUTIVE SUMMARY

Dynamic interactions of urban buses with relatively rough urban roads transmit high magnitudes of tire forces to the road, suspension forces to the chassis and whole-body type low frequency vibration to the driver. The high magnitudes of dynamic tire forces are known to cause premature road damage, while the suspension forces yield reduced service life of the chassis. Occupational exposure to whole-body vibration has been associated with fatigue, discomfort, and an array of musculoskeletal disorders among drivers.

The dynamic wheel loads and ride vibration environment of a heavy road vehicle are strongly related to vehicle weight and dimensions, axle loads, and suspension and tire properties. Considering that the provincial road laws and transportation economy govern the gross weight and axle loads of urban buses, the forces transmitted to the pavement and the chassis are mostly determined by tire and suspension properties. Low spring rate suspensions are desirable for reducing chassis and pavement loads, but pose increased demand for rattle space and adversely affect roll stability. Alternatively, suspension designs with adequate damping properties offer considerable potential to minimize high magnitude resonant vibration and forces transmitted to the road and chassis.

The primary objectives of this study were formulated to help improve driver- and road-friendliness, and chassis loads of urban buses. The specific objectives of the study, linked with the Transportation Development Centre's (TDC's) Urban Bus Technology Program, included: (i) design optimal passive suspension damping to enhance road- and driver-friendliness of urban buses; (ii) study the role of optimal suspension in reducing magnitudes of dynamic chassis forces to develop a basis for achieving optimal light-weight chassis structures; (iii) study the effects of variations in operating conditions; and (iv) develop optimal suspension dampers for most practical ranges.

The two-phase study was carried out in close collaboration with Nova Bus Corporation and the *Societé de transport de la Rive-Sud de Montréal*. The initial phase of the study involved identification of optimal suspension damping through the analysis of reduced roll plane computer models of the Classic and Low Floor System (LFS) buses, and development of a suspension tuning test stand and methodology. The final phase of the study involved suspension optimization using total vehicle models, validations through field measurements, the development of optimal dampers, and potential performance benefit analysis. This report summarizes the results achieved in both phases of the study. Detailed results are documented in 10 interim reports submitted to collaborators and TDC.

Given the considerable variations in operating conditions (passenger load, speed, road roughness, tire inflation pressure) of urban buses, it was considered vital to develop computer models that were valid over a wide range of operating variables. The static and dynamic characteristics of suspension components and tires employed in Classic and LFS buses were identified over a wide range of operating conditions through a series of laboratory tests performed on many different dampers, air springs and tires currently employed in Classic and LFS axle suspension.

The test results for the candidate dampers invariably revealed single- or multi-stage compression damping and considerably larger multi-stage rebound damping. The damping and seal friction properties of Arvin dampers, employed in LFS buses, were generally considerably larger than those of the dampers employed in Classic bus suspension. These dampers may be considered adequate for control of body roll motion, but inadequate for preserving the ride vibration environment. The pressure-deflection and force-deflection properties of different air springs, characterized over a wide range of operating loads, revealed a low spring rate at the design height, a progressively hardening spring rate during compression, and a reduced spring rate in rebound. Because of large variations in the operating loads of tires, static and dynamic characteristics of different tires were evaluated as functions of static load and inflation pressure. The measured data revealed that tire stiffness increases with increasing inflation pressure.

The measured data were used to derive generic, nonlinear component models based on regression analyses and physical laws. The proposed component models were analyzed for a wide range of operating loads and deflections, and the resulting static and dynamic characteristics were compared with the measured data. The comparisons revealed significant agreement between the model results and measured data for all of the dampers, air springs and tires considered in the study, irrespective of operating load, tire inflation pressure and deflection.

The validated component models were used to develop nonlinear roll plane models of the candidate vehicles in the initial phase, assuming negligible contributions of pitch and lateral dynamics. Three-dimensional models of candidate urban buses were developed in the final phase to derive optimal suspension dampers and performance potential. A general 13 degrees-of-freedom model was formulated, which could be applied for both the Classic and LFS designs. The models comprised the lumped sprung and unsprung masses, air springs, inclined shock absorbers, anti-roll bar and tires.

In the absence of well-defined roughness data for urban roads, the roll plane models were initially analyzed under known roughness data for highways and secondary roads. The validity of the models was examined in three stages. In the first stage, the response characteristics of suspension components and tires were compared with the data acquired from laboratory tests and manufacturers. The acceleration responses of the sprung mass were then compared with field-measured data acquired from the *Insitut de recherche en santé et sécurité du travail* (IRSST) of Quebec. In the final stage, the dynamic wheel force responses were compared with the field-measured data acquired from the Institute for Research in Construction (IRC). The comparisons revealed reasonably good agreement between the model results and the available measured data, with certain errors at higher excitation frequencies. Such errors were attributed to the structural flexibility and simplified point-contact tire model used in this study.

An instrumented two-axis axle-suspension test stand was developed for efficient tuning and assessment of dampers, and to acquire suspension response data for further validations of analytical models under a wide range of operating conditions. The test stand was designed to accommodate the axle assembly, comprising tires supported on two electrohydraulic exciters, the axle, suspension springs and dampers mounted between a fixed reference and the axle shaft, the ride height valve and torque rods. From the tests it was concluded that the test stand could serve as an effective tool to perform relative assessments of suspension components and contributory factors, such as tire load and tire inflation pressure.

Because of a lack of roughness data for representative urban roads, a measurement program was undertaken by TDC to characterize roughness properties of selected roads in the cities of Montreal and Longueuil, Quebec. The elevations of both the left- and right-tire tracks of six different roads were acquired by the *Centre de recherche et de contrôle appliqué à la construction inc.* and analyzed to derive roughness properties at the macro and micro levels. An analysis of the urban road roughness data in relation to those of other roads suggested that spectral density of urban roads is higher than that of highways and lower than those of rough runways and gravel roads. The roughness data were used to generate drive files to synthesize urban road excitations in the laboratory.

Thirteen-DOF computer models of the Classic and LFS buses were analyzed for excitations arising from the selected roads and different speeds. A set of performance measures was defined to assess driver- and road-friendliness, and chassis load performance characteristics. Frequency-weighted vertical, pitch and roll root mean square (rms) accelerations were derived to assess the vehicles' driver-friendliness, while the pavement-damaging potential of tire forces was assessed in terms of dynamic load coefficient (DLC) and peak tire forces. The magnitudes of dynamic forces transmitted to the chassis were assessed in terms of chassis load coefficient (CLC).

A comprehensive road test program was undertaken to acquire the response of an LFS bus on different roads at forward speeds near 30 and 50 km/h. A total of 15 accelerometers were installed on the bus's floor and axles to measure vertical and roll accelerations of the axles, as well as vertical, pitch and roll accelerations of the body. A string potentiometer was mounted on the rear axle to measure its relative deflection with respect to the chassis during turns. The measured data were analyzed to derive spectral densities of acceleration response characteristics, which were used to examine the validity of the LFS model. The validity of the Classic bus model was examined on the basis of data acquired from IRSST and IRC. The comparisons revealed reasonably good agreement between the models results and the measured data.

The validated models of the candidate buses were analyzed to assess the performance characteristics of currently used suspension under varying operating conditions, such as load, speed, tire inflation pressure and road roughness. Almost all the performance measures of both models deteriorated with an increase in vehicle speed and road roughness, and a decrease in the operating load. The LFS model yielded considerably larger magnitudes of vertical and pitch accelerations as well as DLC of rear-axle tires, when compared to the Classic model. The results consistently showed a higher DLC of right-tire forces, specifically for the LFS, because of its eccentric load distribution and greater roughness of the right track. The peak force for the rightmost tire of the rear axle increased most significantly with higher vehicle speeds and road roughness. Although the CLC for both candidate vehicles increased with higher vehicle speeds and road roughness, the LFS chassis experienced considerably larger loads. The results showed that a reduction in tire inflation pressure could enhance most performance measures for both vehicles. The results also suggested that medium compression damping coupled with a lower degree of asymmetry is desirable for improving driver-friendliness and dynamic chassis loads. High compression damping coupled with high asymmetry, on the other hand, was considered desirable for improving DLC, peak tire force and vehicle roll response.

A multi-variable optimization problem based on the weighted sum of DLC and the frequency-weighted rms vertical acceleration was formulated to identify optimal suspension dampers. Given the strong dependency of the performance measures on various damper parameters, an equality constraint was imposed on the equivalent compression mode damping coefficients. Limit constraints were also imposed on asymmetry and reduction factors as well as blow-off velocities in an attempt to derive feasible damper parameters. The constrained optimization problem was solved under medium-rough road excitation conditions at a speed of 50 km/h.

A comparison of the optimal damper parameters with those of the baseline dampers revealed considerably larger rebound damping coefficients of the baseline LFS suspension dampers. While the compression mode damping coefficients of the baseline dampers were considerably lower than the range considered in the optimization studies, the optimal dampers showed rebound blow-off at relatively low velocities. Analyses of vehicle models with optimal dampers revealed their excellent performance potential with regard to most of the performance measures. The optimal solutions achieved for 20-percent low-speed compression damping (OPT3) provided the best compromise between the driver- and road-friendliness measures for both vehicles. The results showed most significant performance gains for the LFS design with regard to all performance measures (approximately a 12 percent reduction in frequency-weighted rms vertical acceleration and a 10 to 28 percent reduction in DLC), while the gains for Classic bus were relatively small (5 percent reduction in the frequency-weighted rms vertical acceleration, and a 3 to 10 percent reduction in DLC).

Damper tuning was performed by Nova Bus Corporation to achieve near optimal dampers on a subjective basis, since the optimization results were not available in time. The resulting tuned dampers were installed on an LFS bus, and an objective field assessment of the tuned dampers was undertaken by CONCAVE to determine the potential benefits of the tuned dampers. Road tests were performed on the candidate LFS bus, equipped with tuned dampers and simulated passenger load. The force-velocity characteristics of tuned dampers were acquired in the laboratory and assessed in relation with the optimal damping characteristics derived in this study. While the compression damping characteristics of the tuned and optimal dampers were quite similar, their rebound properties differed considerably. The front-axle dampers were tuned to achieve higher rebound damping and reduce roll motions. It is believed that the front axle, coupled with an anti-roll bar and proposed optimal damper, would yield superior performance. The optimal rear-axle dampers, on the other hand, revealed considerably higher rebound damping.

The field-measured data was used to further examine the validity of the computer models with the tuned dampers. Comparisons of the model results with the road-measured data clearly demonstrated the validity of the models. A comparison of the results with those recorded for baseline Arvin dampers clearly demonstrated superior performance of the tuned dampers. In view of the differences between tuned and optimal dampers, further assessments of both types of dampers were performed through computer simulations. The potential performance benefits of the baseline, OPT3 and tuned dampers were analyzed under different operating conditions such as speed, operating load, road roughness and tire inflation pressure.

The potential performance benefits of both the tuned and optimal dampers were apparent under medium-rough and rough road conditions for both candidate vehicles, where dynamic tire-road interactions predominate. Optimal dampers offered the most significant potential to enhance driver-friendliness performance and achieve the lowest values of frequency-weighted vertical and pitch accelerations. The tuned dampers, however, provided the most significant reductions in roll acceleration and tire load responses of the LFS vehicle under rough road excitations, while optimal dampers provided considerably lower DLC values for most tires, irrespective of road roughness, speed and operating load. The tuned dampers for the rear-axle suspension, with low rebound damping, resulted in higher values of DLC. The results suggest that higher rebound damping would help improve the road-friendliness of vehicles on rough roads. In comparison with the DLC of tire forces of the LFS with baseline dampers, the optimal dampers provided 10 to 27 percent and 10 to 32 percent reductions in DLC on medium-rough and rough roads, respectively. For the Classic bus, the optimal dampers yielded 7 to 8.6 percent lower values of DLC, and 6 to 24 percent reductions in frequency-weighted vertical, pitch and roll accelerations. The optimal dampers also yielded considerably lower values of CLC for the front-axle suspension and higher values for the rear-axle suspension. These results suggest that light rebound damping is desirable for attenuating the transient forces transmitted to the chassis.

From the results, it was concluded that the design/selection of adequately tuned dampers for urban buses is vital for preserving the driver vibration environment and optimizing the service lives of urban roads and vehicle chassis. The results of the study also suggest that lower tire inflation pressure offers considerable potential to enhance the road- and driver-friendliness of the vehicles. The low pressure, however, may result in rapid tire wear and poor handling under certain loading conditions. Given the wide variations in the operating load, the use of a passenger-load dependent central tire inflation system may be considered desirable. Because of the significant wheel-hop vibration modes in the 10 to 12 Hz frequency range, further studies incorporating structural flexibility are desirable for the development of optimal suspensions and light-weight structure designs for urban buses.

SOMMAIRE

Les interactions dynamiques des autobus urbains avec les chaussées relativement mauvaises des villes génèrent des forces importantes aux interfaces pneu-chaussée et suspension-châssis, et produisent dans toute la carrosserie des vibrations basse fréquence qui se transmettent au conducteur. Il est établi que de telles forces dynamiques des pneus sur la chaussée causent une détérioration prématurée de celle-ci, tandis que les forces exercées sur la suspension raccourcissent la durée de vie utile du châssis. Pour les conducteurs, l'exposition aux vibrations du véhicule est à l'origine de fatigue, d'inconfort et de diverses blessures musculo-squelettiques.

Les charges dynamiques et les trépidations verticales des roues d'un véhicule lourd dépendent largement du poids et des dimensions du véhicule, des charges aux essieux, et des propriétés de la suspension et des pneus. Si le poids et les charges aux essieux des autobus urbains sont régis par les codes provinciaux de la route et l'économie des transports, les forces transmises à la chaussée et au châssis sont surtout fonction des propriétés des pneus et de la suspension. Ainsi, des suspensions peu élastiques sont souhaitables, car elles réduisent les charges sur le châssis et sur la chaussée, mais elles accentuent le rebond et le roulis des véhicules. En même temps, une suspension présentant un bon amortissement peut réduire de façon importante les vibrations en résonance et les forces de grande magnitude transmises à la chaussée et au châssis.

Les grands objectifs de l'étude étaient d'améliorer les conditions de conduite des autobus urbains, de rendre ceux-ci moins agressifs à l'endroit de la chaussée, et de réduire les charges sur le châssis de ces véhicules. Quant aux objectifs particuliers de cette recherche, entreprise dans le cadre du Programme de technologie des autobus du Centre de développement des transports (CDT), ils consistaient à : (i) définir l'amortissement optimal d'une suspension passive pour améliorer le confort du conducteur et préserver la chaussée; (ii) étudier dans quelle mesure une suspension optimale diminue les forces dynamiques exercées sur le châssis, afin d'asseoir la conception de structures de châssis optimales pour autobus allégés; (iii) étudier les effets des variations des conditions d'exploitation des véhicules; (iv) mettre au point des amortisseurs de suspension optimisés pouvant convenir à la plupart des conditions d'exploitation.

L'étude, qui comportait deux phases, a été réalisée en étroite collaboration avec Nova Bus Corporation et la Société de transport de la Rive-Sud de Montréal. La première phase a consisté à définir l'amortissement optimal de la suspension, par l'analyse, à l'aide de modèles informatiques simplifiés du plan de roulis (pour l'étude des oscillations verticales, longitudinales et transversales) des autobus Classic et à plancher surbaissé (LFS, pour *Low Floor System*), ainsi que la mise au point d'un banc d'essai de réglage de la suspension et de la méthodologie connexe. La deuxième phase a comporté l'optimisation de la suspension à l'aide de modèles de véhicules détaillés, la validation des modèles par des mesures sur le terrain, la mise au point d'amortisseurs optimaux et une analyse des avantages potentiels de la suspension optimale sur le plan des performances. Le présent rapport résume les résultats

des deux phases de l’étude. Pour un compte rendu complet, on peut consulter les 10 rapports provisoires soumis par le contractant au CDT et aux parties intéressées.

Étant donné les conditions d’exploitation extrêmement variables des autobus urbains (nombre de passagers, vitesse du véhicule, inégalités de la route, pression de gonflage des pneus), il a été jugé essentiel de développer des modèles informatiques adaptables à une vaste gamme de conditions. Des essais en laboratoire des amortisseurs, ressorts pneumatiques et pneus équipant présentement la suspension aux essieux des autobus Classic et LFS ont permis de déterminer les caractéristiques des différentes forces statiques et dynamiques des composants de la suspension et des pneus de ces véhicules, dans un large éventail de conditions d’exploitation.

Tous les essais portant sur les amortisseurs candidats ont révélé un amortissement mono-étagé ou multi-étagé en phase de compression, et un amortissement multi-étagé beaucoup plus important en phase de détente. En général, les amortisseurs Arvin, qui équipent les autobus LFS, étaient de beaucoup supérieurs, du point de vue de l’amortissement et de la friction, aux amortisseurs utilisés dans la suspension de l’autobus Classic. En effet, ces derniers amortisseurs peuvent être considérés adéquats pour limiter le mouvement de roulis, mais ils sont médiocres pour atténuer les vibrations. Les données de flexion sous la pression et sous la force des différents ressorts pneumatiques, déterminées dans une large gamme de chargements, ont révélé une faible constante de rappel du ressort à la hauteur nominale, une constante allant croissant en phase de compression, et une constante réduite en phase de détente. Étant donné la grande variabilité des charges exercées sur les pneus en service, les caractéristiques statiques et dynamiques des différentes forces exercées sur les pneus ont été évaluées en fonction de la charge statique et de la pression de gonflage. Ces données ont révélé que la raideur des pneumatiques augmente avec la pression de gonflage de ceux-ci.

Les données obtenues en laboratoire ont servi à établir des modèles génériques et non linéaires des composants de la suspension, fondés sur des analyses de régression et les lois physiques. Ces modèles ont été analysés dans un large éventail de conditions de chargement et de flexion, et les caractéristiques statiques et dynamiques ainsi obtenues ont été comparées avec les données issues des essais. Ces comparaisons ont révélé une corrélation élevée entre les résultats de la modélisation et les résultats des essais, pour tous les amortisseurs, ressorts pneumatiques et pneus étudiés, peu importent la charge transportée, la pression de gonflage des pneus et la flexion.

Les modèles ainsi validés ont servi à développer des modèles non linéaires du plan de roulis des véhicules étudiés lors de la première phase, en tenant pour négligeable le rôle des forces longitudinales et transversales. La dernière phase a consisté à développer des modèles tridimensionnels des autobus urbains candidats afin de définir les amortisseurs optimaux et les performances potentielles de ceux-ci. Un modèle générique à 13 degrés de liberté a été formulé, qui pouvait être appliqué aux autobus Classic et LFS. Les modèles comprenaient des masses localisées suspendues et non suspendues, des ressorts pneumatiques, des amortisseurs inclinés, une barre antiroulis et des pneus.

Faute de données précises sur la rugosité des circuits urbains, les modèles ont d'abord été analysés en fonction de données de rugosité connues pour des grands-routes et des routes secondaires. La validité des modèles a été étudiée en trois étapes. Premièrement, les données de performance des composants de la suspension et des pneus ont été comparées aux données obtenues en laboratoire et aux données des constructeurs. L'accélération des masses suspendues a alors été comparée à l'accélération mesurée en grandeur réelle, selon les données fournies par l'Institut de recherche en santé et sécurité du travail (IRSST) du Québec. Finalement, les forces dynamiques exercées sur les roues ont été comparées avec les données mesurées sur le terrain par l'Institut de recherche en construction (IRC). Les comparaisons ont révélé une corrélation raisonnable entre les résultats obtenus avec les modèles analytiques et les résultats obtenus en vraie grandeur, de même que certaines erreurs aux fréquences d'excitation élevées. Ces erreurs ont été attribuées à la flexibilité de la structure et au modèle simplifié de point de contact pneu-chaussée utilisé dans cette étude.

Un banc d'essai instrumenté à deux axes pour suspension sur essieu a été mis au point pour le réglage et l'évaluation des amortisseurs, et pour la collecte de données sur la réponse de la suspension, aux fins de valider les modèles analytiques dans une vaste gamme de conditions de fonctionnement. Le banc d'essai a été conçu pour recevoir l'ensemble essieu, soit les pneus posés sur deux vérins électro-hydrauliques, l'essieu, les ressorts de suspension et les amortisseurs montés entre un point de référence fixe et les arbres de roue, le dispositif de réglage de la garde au sol et les bielles de poussée. Au terme des essais, il a été conclu que le banc d'essai pouvait servir d'outil pour comparer des composants de suspension et mesurer des facteurs comme la charge sur le pneu et la pression de gonflage des pneus.

Constatant l'absence de données représentatives sur la rugosité des chaussées urbaines, le CDT a entrepris un programme de mesure visant à caractériser l'état de rugosité de circuits choisis, à Montréal et Longueuil, au Québec. Le profil des chemins de roulement des pneus gauches et droits de six circuits différents a été établi et numérisé par le Centre de recherche et de contrôle appliqué à la construction inc., qui a ainsi déterminé le degré de micro et de macrorugosité des circuits. L'analyse des données de rugosité relatives aux circuits urbains par rapport aux données touchant les autres routes donne à penser que la densité spectrale des circuits urbains est plus élevée que celle des routes interurbaines et plus faible que celle des pistes rudimentaires et des routes de graviers. Les données de rugosité ont servi à générer des logiciels de simulation des circuits urbains en laboratoire.

Des modèles à 13 degrés de liberté des autobus Classic et LFS ont été analysés selon les excitations découlant de circuits choisis parcourus par les véhicules à différentes vitesses. Un ensemble de critères de performance a été défini pour évaluer le confort du conducteur et l'agressivité du véhicule à l'endroit de la chaussée, de même que la tenue du châssis aux sollicitations. Pour mesurer la douceur de roulement du véhicule du point de vue du conducteur, les valeurs efficaces, pondérées selon la fréquence, des accélérations verticale, longitudinale et transversale ont été calculées, tandis que l'agressivité du véhicule à l'endroit de la chaussée a été déterminée à partir du coefficient de charge dynamique (CCD) et des forces maximales exercées par les pneus. L'importance des forces dynamiques transmises au châssis a été exprimée sous forme de coefficient de charge sur le châssis (CCC).

Une campagne d’essais sur route a été réalisée, qui visait à recueillir des données sur le comportement d’un autobus LFS roulant sur différents circuits à des vitesses approximatives de 30 km/h et de 50 km/h. Au total, 15 accéléromètres ont été installés sur le plancher et les essieux de l’autobus : ils devaient mesurer les accélérations verticale et transversale aux essieux, de même que les accélérations verticale, longitudinale et transversale du roulis dans la carrosserie. Un potentiomètre à fil monté sur l’essieu arrière mesurait la flexion de celui-ci par rapport au châssis en virage. L’analyse des données ainsi acquises a permis d’établir les densités spectrales des réponses de la suspension en accélération, qui à leur tour ont servi à évaluer la validité du modèle d’autobus LFS. La validité du modèle d’autobus Classic a été étudiée à partir des données obtenues de l’IRSST et de l’IRC. Les comparaisons ont révélé une bonne corrélation entre les résultats obtenus avec le modèle et les mesures effectuées en vraie grandeur.

Les modèles ainsi validés des autobus candidats ont été soumis à une analyse qui visait à évaluer les performances des suspensions existantes dans diverses conditions de fonctionnement, comme la charge transportée, la vitesse du véhicule, la pression de gonflage des pneus et les inégalités de la route. Presque tous les paramètres de performance relatifs aux deux modèles se dégradaient à mesure qu’augmentaient la vitesse du véhicule et la rugosité de la chaussée, et que diminuait la charge transportée. Le modèle LFS affichait des accélérations verticale et longitudinale, et un CCD sur les pneus de l’essieu arrière de beaucoup supérieurs à ceux du modèle Classic. Le CCD sur les pneus de droite était immanquablement plus élevé que le CCD sur les pneus de gauche, en particulier dans le cas du modèle LFS, en raison de la distribution excentrique de la charge et de la plus grande rugosité du chemin de roulement de droite. C’est sur le pneu le plus à droite de l’essieu arrière que s’accentuaient le plus les forces lorsqu’augmentaient la vitesse du véhicule et la rugosité de la chaussée. Dans le cas des deux véhicules candidats, le CCC augmentait en raison directe de la vitesse du véhicule et des inégalités de la route; mais des charges beaucoup plus importantes étaient imposées au châssis de l’autobus LFS. Les résultats ont révélé qu’en gonflant moins les pneus, on pouvait améliorer la plupart des mesures de performance des deux véhicules. Les résultats donnent également à penser qu’un amortissement à compression moyenne conjugué à un faible degré d’asymétrie est souhaitable pour améliorer le confort du conducteur et diminuer les charges dynamiques sur le châssis. À l’inverse, un amortissement à forte compression conjugué à une forte asymétrie a été jugé souhaitable pour améliorer le CCD sur les pneus, la résistance maximale des pneus et le comportement en roulis du véhicule.

Un problème d’optimisation à plusieurs variables a été formulé, à partir de la somme pondérée des CCD, et de la valeur efficace de l’accélération verticale pondérée selon la fréquence, afin de définir des amortisseurs de suspension optimaux. Comme les mesures de performance sont grandement tributaires des divers paramètres des amortisseurs, une contrainte d’égalité a été imposée aux coefficients d’amortissement correspondant à des modes de compression équivalents. Des limites ont également été imposées relativement à l’asymétrie et aux facteurs de réduction, de même qu’aux vitesses de purge, afin de tirer des paramètres réalistes pour les amortisseurs. Le problème d’optimisation contraint a été résolu dans des conditions d’excitation représentant une chaussée de rugosité moyenne et une vitesse de 50 km/h.

Une comparaison des paramètres des amortisseurs optimaux et de ceux des amortisseurs existants a révélé des coefficients d’amortissement sensiblement supérieurs, en détente, chez les amortisseurs existants des autobus LFS. Mais en compression, les amortisseurs existants affichaient des coefficients d’amortissement beaucoup plus faibles que les valeurs découlant des études d’optimisation, tandis que les soupapes des amortisseurs optimaux entraient en action à des vitesses relativement faibles. Des analyses des deux modèles de véhicules équipés des amortisseurs optimaux ont fait entrevoir la possibilité d’excellentes performances, selon la plupart des paramètres. Les solutions optimales conduisaient à un amortissement de 20 p. cent en compression à faible vitesse (pour les amortisseurs OPT3), compte tenu du meilleur compromis entre la douceur de roulement et la préservation de la chaussée. C’est le véhicule LFS qui a enregistré les gains de performance les plus importants, selon toutes les variables étudiées (diminution d’environ 12 p. cent de la valeur efficace de l’accélération verticale pondérée pour la fréquence, et une diminution de 10 à 28 p. cent du CCD). Quant au véhicule Classic, les gains de performance étaient relativement faibles (diminution de 5 p. cent de la valeur efficace de l’accélération verticale pondérée pour la fréquence et diminution de 3 à 10 p. cent du CCD).

Nova Bus Corporation a procédé au réglage des amortisseurs de façon à obtenir «par intuition» des amortisseurs optimaux, les résultats de l’étude d’optimisation tardant à lui être communiqués. Les amortisseurs accordés résultants ont été installés sur un autobus LFS, et CONCAVE les a évalués sur route, avec une charge simulée de passagers, afin de déterminer les avantages potentiels d’amortisseurs accordés. Par ailleurs, des essais en laboratoire ont permis de mesurer les caractéristiques des amortisseurs accordés en fonction des forces et de la vitesse, aux fins de comparaison avec les caractéristiques d’amortissement optimal telles que définies lors de l’étude. Pour ce qui est de l’amortissement en compression, les amortisseurs accordés et les amortisseurs optimaux affichaient des résultats assez semblables, mais en détente, leur comportement différait grandement. Les amortisseurs de l’essieu avant ont donc été réglés de façon à mieux amortir la phase détente et à réduire le roulis. Il est permis de penser qu’en accouplant l’essieu avant avec une barre stabilisatrice et l’amortisseur optimal proposé, on obtiendrait une performance supérieure. Les amortisseurs optimaux de l’essieu arrière, par contre, ont affiché un amortissement beaucoup plus grand en détente.

Les données acquises sur le terrain ont servi à étudier la validité des modèles analytiques par rapport aux amortisseurs accordés. La comparaison des résultats de modélisation et des données découlant des essais sur route a démontré la validité des modèles. La comparaison des données relatives aux amortisseurs accordés avec celles concernant les amortisseurs Arvin existants a quant à elle clairement démontré la supériorité des amortisseurs accordés. Compte tenu des différences entre les amortisseurs accordés et optimaux, d’autres évaluations des deux types d’amortisseurs ont été réalisées par simulation. Les avantages relatifs potentiels des amortisseurs existants, des amortisseurs OPT3 et des amortisseurs accordés, ont été analysés dans différentes conditions de fonctionnement, comme la vitesse du véhicule, la charge transportée, les inégalités de la route et la pression de gonflage des pneus.

Les avantages potentiels des amortisseurs accordés et des amortisseurs optimaux sont ressortis, dans le cas des deux véhicules, dans des conditions de route de rugosité forte et moyenne, alors que les interactions pneu-chaussée prédominent. Les amortisseurs optimaux ont offert le meilleur potentiel d'amélioration de la douceur de roulement, associé aux plus faibles valeurs, pondérées pour la fréquence, des accélérations verticale et longitudinale. Les amortisseurs accordés, toutefois, ont généré les plus fortes diminutions de l'accélération transversale et des charges sur le pneu pour le véhicule LFS, dans des conditions simulées de route dure, tandis que les amortisseurs optimaux ont donné des valeurs CCD beaucoup moindres pour la plupart des pneus, peu importent la rugosité de la chaussée, la vitesse du véhicule et la charge transportée. Les amortisseurs accordés équipant la suspension de l'essieu arrière, avec leur faible amortissement en détente, ont conduit à des valeurs CCD élevées. D'où l'on peut penser qu'un meilleur amortissement en phase de détente contribuerait à préserver les chaussées à forte rugosité. Pour ce qui est des forces exercées sur les pneus de l'autobus LFS, les amortisseurs optimaux ont généré des CCD de 10 à 27 p. cent et de 10 à 32 p. cent inférieurs à ceux des amortisseurs standard sur des chaussées à rugosité moyenne et à forte rugosité, respectivement. Dans le cas de l'autobus Classic, les amortisseurs optimaux affichaient des CCD de 7 à 8,6 p. cent inférieurs, et des accélérations verticale, longitudinale et transversale, pondérées pour la fréquence, de 6 à 24 p. cent inférieures. Les amortisseurs optimaux ont également produit des valeurs CCC considérablement moindres pour la suspension de l'essieu avant et des valeurs supérieures pour la suspension de l'essieu arrière. Ces résultats donnent à penser qu'un amortissement léger en phase détente est souhaitable pour atténuer la transmission des forces transitoires au châssis.

Les résultats ont mené à conclure que la conception/sélection d'amortisseurs correctement accordés pour les autobus urbains est essentielle pour garder le conducteur à l'abri des vibrations et pour optimiser la durée de vie des chaussées et des châssis de véhicules. Les mêmes résultats laissent penser qu'en diminuant la pression de gonflage des pneus, on peut augmenter considérablement le confort du conducteur et réduire d'autant les dommages à la chaussée dus au passage du véhicule. Mais une pression de gonflage inférieure risque de diminuer la durée de vie des pneus et de nuire à la manoeuvrabilité du véhicule dans certaines conditions de chargement. Compte tenu des grandes variations de la charge transportée, le recours à un système central de gonflage des pneus asservi à la charge peut être souhaitable. En raison des sautillements de roue accentués dans la gamme des fréquences de 10 à 12 Hz, il est recommandé d'entreprendre d'autres travaux pour étudier le rôle de la flexibilité de la structure dans la mise au point de suspensions optimales et la conception de structures d'autobus urbains allégés.

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GLOSSARY

CDN	Côte-Des-Neiges
CLC	Chassis load coefficient
CRCAC	Centre de recherche et de contrôle appliqué à la construction inc.
DLC	Dynamic load coefficient
DOF	Degree-of-freedom
IRC	Institute for Research in Construction
IRSST	Institut de recherche en santé et en sécurité du travail
LFS	Low Floor System
LVDT	Linear variable differential transducer
PSD	Power spectral density
RI	Roughness index
rms	Root mean square
SAP	Saint-Patrick
STRSM	Societé de transport de la Rive-Sud de Montréal
TDC	Transportation Development Centre

1. INTRODUCTION

High axle loads of urban buses, coupled with dynamic interactions of tires with relatively rough urban roads, yield considerable magnitudes of dynamic loads transmitted to both the chassis and the road. Such dynamic interactions also yield higher levels of ride vibration transmitted to the driver and passengers. The coupled vehicle-road interactions form a closed-loop system, where the high levels of dynamic tire forces cause further deterioration of the road surface, which in turn increases the ride vibration levels and dynamic forces transmitted to the chassis and the road. The average gross vehicle weight of urban buses has continued to increase over the past two decades to satisfy operational requirements. Although fuel and road infrastructure maintenance costs rank among the highest, the dynamic tire-road interactions yield additional costs related to: (*i*) discomfort and inefficient performance of the driver attributed to the relatively severe vibration environment of urban buses; (*ii*) high suspension loads transmitted to the chassis, leading to reduced service life; and (*iii*) reduced pavement service life attributed to the high tire loads. The design and implementation of effective suspension dampers offer significant potential to achieve optimal light-weight structures and to reduce the costs associated with tire-induced road damage and driver vibration. The identification of adequate suspension designs and dampers, however, requires systematic studies on the dynamic behaviour of modern urban buses and the role of various contributory factors such as road roughness, vehicle speed, operating load, tire properties and inflation pressure, and vehicle weights and dimensions. The study of dynamic interactions between urban buses and roads poses considerable complexities because of the wide variations in many of the operating conditions, including passenger load, road roughness and tire inflation pressure. Bus manufacturers and suspension designers are thus faced with the formidable task of developing designs that are adequate for the wide range of operating conditions.

2. RATIONALE AND OBJECTIVES OF THE STUDY

The ride vibration environment, dynamic chassis loads and road damage potential of a vehicle derive from its dynamic deflection modes associated with the sprung and unsprung masses of the vehicle. A number of studies have emphasized the need to design optimal suspension to reduce road damage, which can also enhance chassis life by reducing the magnitudes of suspension forces transmitted to the chassis. Modern urban buses, mostly designed with air suspension, exhibit considerable dynamic vertical deflections predominant in the 1.0 to 1.5 Hz frequency range, which may further contribute to road structure fatigue as a result of spatial repeatability of the dynamic tire forces. Such suspension designs also yield high levels of low frequency vertical vibration at the driver's location, resulting in possible bottoming of the seat suspension.

Considering that the gross weight and axle loads of urban buses are selected according to provincial road laws and the transportation economy, the magnitudes of resonant forces transmitted to the pavement and the chassis are mostly affected by tire and suspension properties. Soft suspension springs and tires are considered desirable for improving the road-friendliness of heavy vehicles. While tires offer very light damping, inflation pressure determines their stiffness characteristics. Urban buses and commercial heavy vehicles employ tires inflated at a relatively high pressure – around 110 psi (≈758 kPa) – to improve fuel economy and extend the tires' load-carrying capacity. The resulting high stiffness of such tires yields relatively higher dynamic wheel loads. A low suspension spring rate, although desirable for reducing chassis and pavement loads, poses increased demand for rattle space and adversely affects the roll stability. Alternatively, suspension designs with adequate damping properties offer considerable potential to minimize the high magnitude resonant vibration and forces transmitted to the road and chassis.

The primary objectives of this study were formulated to help improve driver- and road-friendliness, and chassis loads of urban buses through systematic analytical and experimental studies on suspension dampers. The specific objectives of the study, linked with the Transportation Development Centre's (TDC's) Urban Bus Technology Program, are summarized as follows:

- To enhance road- and driver-friendliness of urban buses by reducing the magnitudes of dynamic wheel loads transmitted to the roads, and ride vibration transmitted to the driver, through optimal suspension damping.

- To study the role of suspension damping in reducing the magnitudes of dynamic chassis forces to develop a basis for achieving optimal light-weight chassis structures.

- To study the effects of variations in operating conditions of urban buses and design optimal suspension dampers for the practical ranges of operating conditions.

The study was carried out in two phases. The primary objective of the initial phase was to identify optimal passive suspension damping through the analysis of reduced roll plane computer models of the Classic and Low Floor System (LFS) buses. The final phase of the study involved suspension optimization using total vehicle models, validations through field measurements, and the development of optimal dampers.

Detailed results achieved during the course of the study have been documented in a number of interim reports, which are listed in Appendix A. This report is a synthesis of the interim and final (Phase I and Phase II) reports, and it highlights the methods employed and results achieved.

3. HIGHLIGHTS OF THE STUDY

The initial phase of the study involved laboratory characterization of suspension components, the development of component and reduced vehicle models, model validation, analyses of the role of operating conditions and their variations, an analysis of various commercial dampers, and damper optimization. An axle suspension test stand was developed in the laboratory to provide data for the experimental validation of the models and to facilitate suspension tuning under a wide range of operating conditions. Three-dimensional models of the candidate vehicles were formulated in the final phase of the study on the basis of validated component models derived in the initial phase of the study. The models were thoroughly validated through a series of field measurements performed on different roads within the Montreal and

South Shore regions of Quebec. Designs of optimal dampers were developed through multi-parameter optimization. The tuned optimal dampers were developed with support from Sachs Automotive of America. Additional road tests were performed on the LFS bus equipped with tuned optimal dampers and the data were used to demonstrate the effectiveness of the dampers and computer models. Highlights of the methods employed and results achieved are summarized in sections 3.1 through 3.10.

3.1 Component Characterization and Model Development

The design specifications of front- and rear-axle suspensions, and weights and dimensions of Classic and LFS vehicles were thoroughly reviewed to formulate the reduced models. All the axles revealed certain similarities in terms of suspension components (i.e., layout and linkages), while the geometric and inertial properties differed considerably. The primary differences among the various axles included the use of an anti-roll bar in some of the axle suspensions, and variations in the spring and damper tracks, axle loads, and properties of springs, dampers and tires. Figure 3.1 illustrates a ZF-front axle of the LFS vehicle, which was generated from the two-dimensional design drawing supplied by Nova Bus Corporation. While the weights and dimensional data for the candidate vehicles were obtained from the bus manufacturer and operator, the nonlinear properties of the tires and suspension components were measured in the laboratory under a wide range of operating conditions.

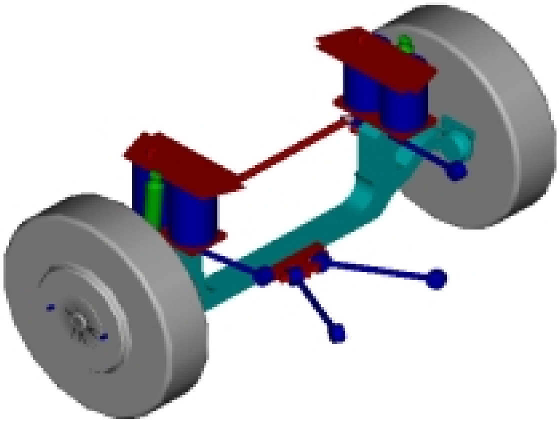

Figure 3.1: Design of the ZF-front axle suspension of the LFS

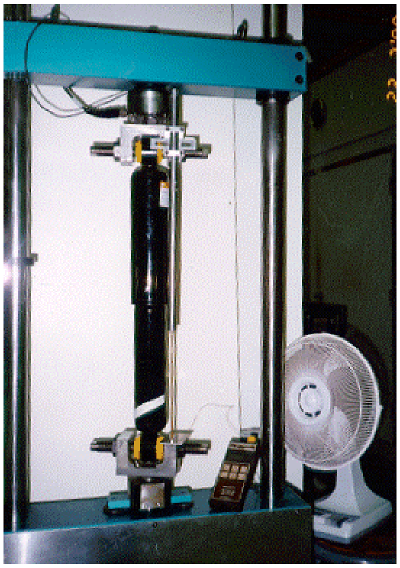

Figure 3.2: Suspension damper test system

The laboratory tests were performed on five different dampers currently employed in Classic and LFS axle suspension, and on 19 other dampers considered suitable for bus suspension applications (manufactured by Gabriel, Monroe and Arvin). Tests were also performed on new dampers supplied by Nova Bus Corporation and the *Societé de transport de la Rive-Sud de Montréal* (STRSM), and the test program included a few sets of two identical dampers.

The damping properties of currently used and many other commercial dampers were characterized in the laboratory in terms of their multi-stage force-velocity and seal-friction characteristics, as a function of the operating temperature. An instrumented damper test stand was developed as shown in Figure 3.2.

Each damper was tested for approximately one hour and its body temperature was monitored and controlled during the test. The test results showed quite surprising damper characteristics in view of their quality. Some of the dampers developed a leak during the laboratory tests. Moreover, the sets of identical dampers selected in this study showed notably different damping and friction characteristics under identical test conditions.

In general, all the candidate dampers revealed: (*i*) multi-stage rebound damping considerably larger than the compression mode damping; (*ii*) single- or multi-stage compression damping; and (*iii*) higher damping coefficients at low velocities and lower coefficients at higher velocities. The damping and seal friction properties of Arvin dampers, employed in LFS buses, were generally considerably larger than those employed in Classic bus suspension. The high magnitudes of damping forces yielded by the Arvin dampers were considered to be inadequate for preserving the passenger and driver ride vibration environment of the LFS vehicles. These dampers, however, were considered to provide adequate control of the body roll motion.

The measured data were analyzed to develop a generic, regression-based, nonlinear mathematical model of the suspension damper, assuming negligible force due to the gas charge. The model coefficients were identified from the measured data and the proposed model was thoroughly validated for all candidate dampers.

The pressure-deflection and force-deflection properties of different air springs employed in the candidate bus suspensions were measured in the laboratory using the test system shown in Figure 3.3. The measurements were performed under different preloads to characterize the spring properties under a wide range of operating loads, while the ride height was held constant. The measurements revealed a low spring rate at the design height, a progressively hardening spring rate during compression, and a reduced spring rate in rebound. The measured data was analyzed to develop a generic analytical model on the basis of physical laws and a regression function. The model was used to describe the instantaneous spring force as a function of the load, deflection, volume and charge pressure corresponding to static ride height and effective area. The effective area was further expressed as a nonlinear function of the instantaneous spring height. The proposed model was analyzed for a wide range of loads and deflections, and the resulting force-deflection characteristics were compared with the measured data to demonstrate the model’s validity. The comparisons revealed significant agreement between the model results and measured data for all of the air springs considered in the study, irrespective of the static load.

In general, the static force-deflection characteristics of tires are strongly related to tire design factors, static load and inflation pressure. Urban bus tires may encounter considerable variations in the static load as a result of extreme variations in the number of passengers during service. The urban buses employ different tires, such as Goodyear 12.5R22.5, Michelin 305/70R22.5 XDA TL 152/148L and Michelin 305/70R 22.5 XZU2 TL 150J. Urban bus operators recommend a tire inflation pressure of 110 psi to comply with manufacturers' specifications, which corresponds to the maximum load rating of the tire (i.e., when the bus is loaded to its maximum passenger capacity). Although manufacturers and operators recommend a tire inflation pressure of 110 psi, inflation pressures ranging from 85 to 110 psi were reported during the study. Low inflation pressures yield lower tire stiffness, which may provide better cushioning properties and lower magnitudes of peak dynamic forces but at the expense of an increased rate of tire wear. Considering the wide variations in the operating loads of urban buses and the beneficial effect of reduced inflation pressures under a light load, it would be desirable to vary the tire pressure as a function of the operating load. Load-dependent variations in tire pressure can be achieved through a central tire inflation system. It is thus essential to characterize the tire properties over a wide range of preloads and inflation pressures. In this study, the force-deflection and force-velocity characteristics of commonly used tires were characterized from the data acquired from manufacturers and laboratory tests. Nonlinear mathematical models for two different Michelin tires were identified from the measured data supplied by Nova Bus Corporation. Similar properties of the Goodyear 12.5R22.5 tires were identified through a series of tests performed in the laboratory.

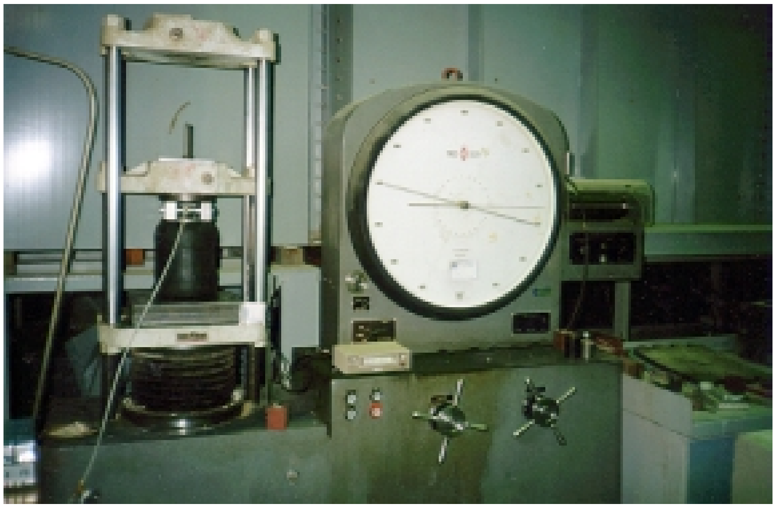

Figure 3.3: Test system used for characterization of air springs

A tire test stand, comprising an electro-hydraulic actuator and an instrumented tire platform, was fabricated as illustrated in Figure 3.4. A load cell was installed in the platform to measure the tire force, while the tire deflection was measured using a Linear Variable Differential Transducer built into the actuator. A pressure sensor was also installed to monitor the initial charge pressure under a specified preload. The static force-deflection characteristics of the tire were measured under different preloads, ranging from 17.8 kN (4000 lb.) to 31.1 kN (7000 lb.), and inflation pressures, ranging from 79 to 129 psi. The tests were also performed under sinusoidal excitations at different frequencies to identify the dynamic force-deflection properties of the tire.

Figure 3.4: Tire test stand

The measured data revealed that the static vertical stiffness of tires increases considerably with increased inflation pressure. The dynamic force-deflection characteristics revealed certain hysteresis as a result of the visco-elastic nature of the carcass plies and tread material. The energy dissipated per cycle by the tire was computed and equated to that of a viscous damper to identify local viscous damping coefficients as a function of the relative velocity across the tire. A regression model of the tire was formulated to describe the load and pressure-dependent stiffness as well as the damping properties of the tire. The data acquired from laboratory tests and manufacturers were used to examine the validity of the model.

3.2 Development of Simplified Analytical Models

Simplified roll plane models of the candidate vehicles were formulated on the basis of the validated component models as well as the weight and dimensional data supplied by Nova Bus Corporation and STRSM. Figure 3.5 illustrates the reduced roll plane model, comprising the lumped sprung and unsprung masses, air springs, inclined shock absorbers, anti-roll bar and tires. The sprung mass, m_s, represents the lumped mass of body, chassis and passengers, supported by the axle considered. The mass of axle and wheel assemblies is represented by the unsprung mass, m_u. The suspension components (air springs and shock absorbers) are assumed to generate forces along their respective axes as nonlinear functions of the axial deflections and velocities, respectively. The anti-roll bar, whenever present, is represented by an equivalent roll stiffness, derived from its geometry and material properties. Assuming negligible contributions of pitch and lateral dynamics, each roll plane of the vehicle is represented by a four-degrees-of-freedom (DOF) system comprising vertical and roll motions due to sprung and unsprung masses. The equations of motion for the roll plane model were derived upon considering nonlinear force-deflection and force-velocity properties of the suspension components.

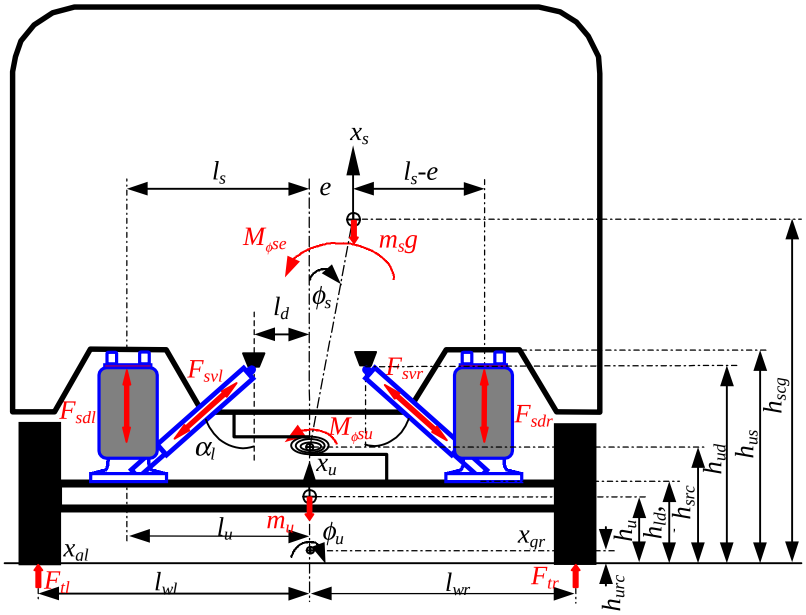

Figure 3.5: Generalized roll plane model of an urban bus

In the absence of well-defined roughness data for urban roads, the simplified models were analyzed under known roughness data for highways and secondary roads. The measured road profiles of different roads in the Ottawa region were considered for this study. The measured profiles of right and left tracks of the roads were characterized by their roughness index (RI) values, and referred to as “smooth” or “medium-rough” based on the RI values. Since urban roads may exhibit a higher degree of roughness than most secondary roads, the roughness profile of the medium-rough road was multiplied by a factor of 2 to synthesize a relatively “rough” road. A total of three road profiles – smooth, medium-rough and rough – were thus considered in this study. The RI values of the smooth, medium-rough and rough roads varied from 1.2 to 1.3, 3.2 to 3.4, and 6.4 to 6.8, respectively. The spatial power spectral density (PSD) and temporal displacement PSD spectra of the three road profiles were evaluated at speeds of 50 and 70 km/h.

The analyses were initially performed to examine the model’s validity in three systematic stages. The validity of the analytical models was initially examined by comparing the response characteristics of the suspension components and tires with the data acquired from laboratory tests and manufacturers. The validity of the roll plane models was then examined by comparing the vertical and roll acceleration response of the sprung mass with the data acquired from the *Insitut de recherche en santé et sécurité du travail* (IRSST) of Quebec.

The sprung mass acceleration response characteristics of a number of Classic and Newlook buses, operating on different roads on the island of Montreal at varying speeds, were recently acquired by IRSST to define spectral classes of the whole-body vibration environment of urban buses. The study involved measurements on 14 Classic and 6 Newlook buses operating on 39 different routes. The acquired data was analyzed to determine the spectral classes of vibration characteristics of urban buses along the translational (vertical, longitudinal and lateral) and rotational (roll and pitch) axes. The data was also analyzed to define the range of vehicular vibration that may be encountered during operation at different speeds over a wide range of roads. In this study, the proposed envelopes in vertical and roll accelerations were used to examine the validity of simplified roll plane models.

The dynamic wheel force response characteristics were compared with the field-measured data acquired by the National Research Council of Canada’s Institute for Research in Construction (IRC) to further examine the validity of the models. The dynamic forces developed at rear-axle tires were extensively measured by IRC under excitations arising from roads and a wooden plank at speeds of 35 and 50 km/h to study the impact of tire-road forces on the structural vibration of homes. In this study, the data acquired during different tests were analyzed to derive a range of PSDs of left- and right-wheel forces.

The vertical and roll acceleration as well as the dynamic wheel force responses of the simplified models were compared with the ranges of measured responses derived from data acquired from IRSST and IRC, respectively. The comparisons revealed reasonably good agreement between the model results and the available measured data. The proposed models were thus considered appropriate for further analyses on the contributions of various design and operating factors, and for identification of optimal suspension dampers.

A two-axis axle-suspension test stand was also developed to acquire suspension response data for further validations of the simplified analytical models under a wide range of operating conditions, and to examine its feasibility for performance analyses and tuning of suspension components under representative excitations. The test stand was designed to accommodate the axle assembly, comprising tires supported on two electrohydraulic exciters, the axle, suspension springs and dampers mounted between a fixed reference and the axle shaft, the ride height valve and torque rods, as shown in Figure 3.6.

The test stand and axle suspension were instrumented to measure dynamic forces due to tires and damper, spring pressures and deflections, and vertical and roll accelerations of the axle, under both vertical and roll excitations. The tests were performed to assess the dynamic characteristics of the front-axle suspension of the LFS urban bus under deterministic and synthesized road excitations. From the tests, it was concluded that the test stand could serve as an effective tool to perform relative assessments of the suspension components and contributory factors, such as tire load and tire inflation pressure.

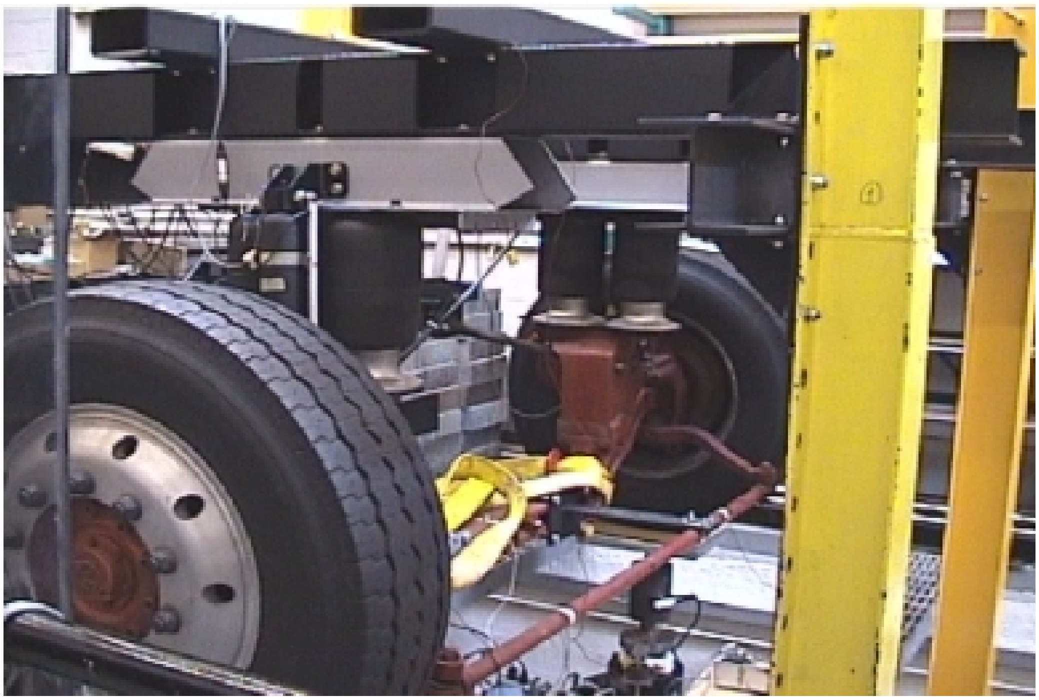

Figure 3.6: Axle suspension test stand

3.3 Development of Total Vehicle Models

Although the effectiveness of the simplified models was clearly demonstrated to study the performance characteristics of the urban bus suspension related to vertical and roll dynamic response, the effects of the coupling of the front and rear axles, and the pitch dynamics of the vehicle were ignored. Identification of optimal suspension damping necessitates appropriate consideration of the pitch dynamics of urban buses. Three-dimensional models of the candidate urban buses were developed in the second phase of the study to investigate the optimal suspension damping and its performance benefits. A general 13-DOF model was formulated, which could be applied for both the Classic and LFS designs. The degrees-of-freedom included: vertical (z_{sb}), pitch (θ_s), roll (φ_s), and longitudinal (x_{sb}) motions of the sprung mass; vertical (z_{uf}), roll (φ_{uf}) and longitudinal (x_{uf}) motions of the unsprung masses due to front and rear axles; bounce motions of the driver seat (z_s); and bounce motions of the two masses representing the driver (z_1 and z_2). The analytical model was formulated by integrating various component models and component characteristics identified during the first phase of the study. A nonlinear driver-suspension-seat model was derived by integrating a single-DOF driver model with the two-DOF suspension-seat model. The resulting driver-seat-suspension model was coupled with the three-dimensional model of the urban bus to assess the ride vibration performance of the vehicle. While an identical model structure was used to describe the dynamics of both types of candidate vehicles, their differences in weight and dimension, as well as suspension properties were appropriately incorporated. Figure 3.7 illustrates the pitch and roll planes of the vehicle model.

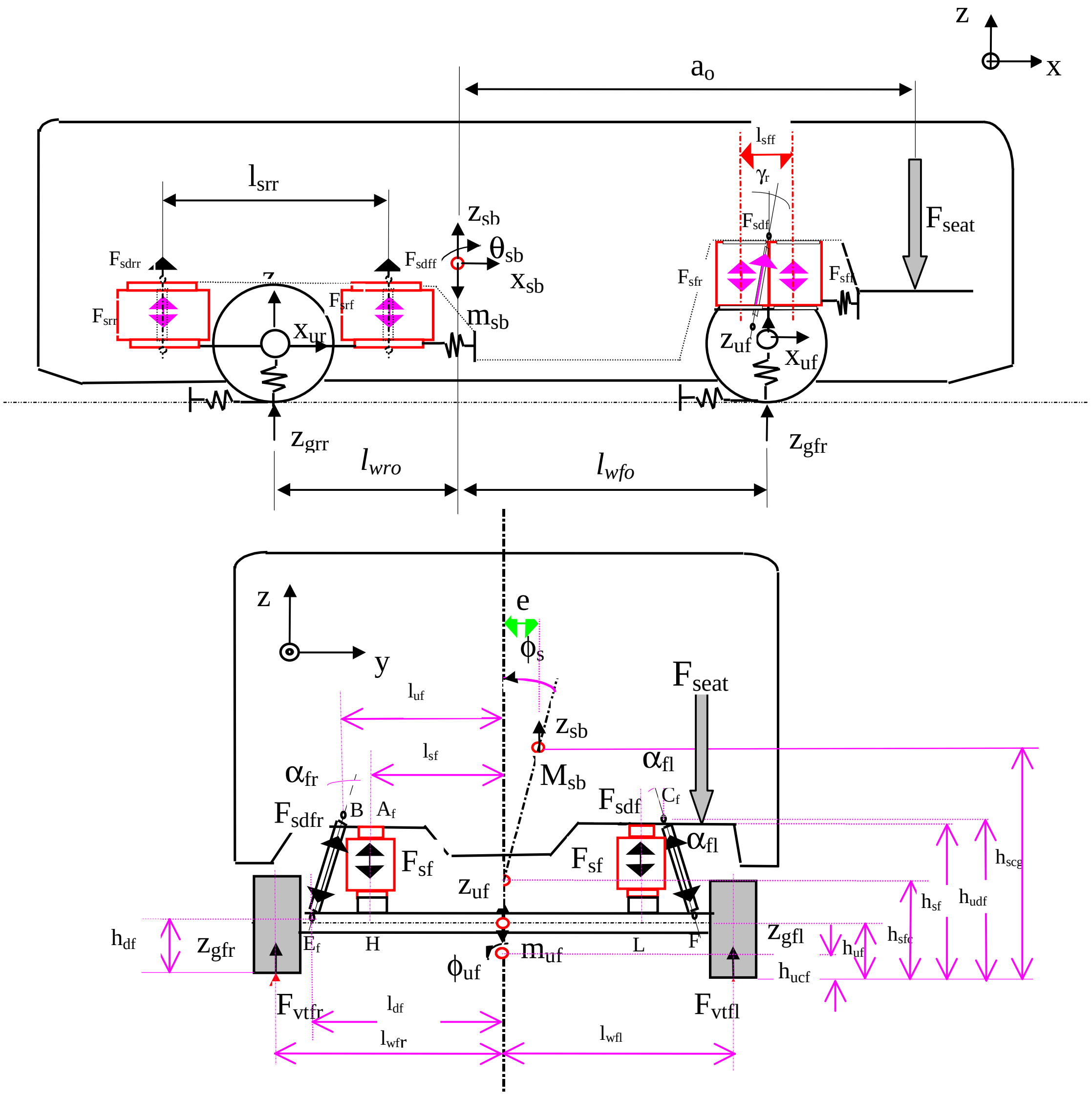

Figure 3.7: Pitch and roll planes of the three-dimensional model of an urban bus

3.4 Roughness Properties of Urban Roads

Because of a lack of roughness data for the representative urban roads, a measurement program was undertaken by TDC to characterize the roughness properties of selected roads in the cities of Montreal and Longueuil, Quebec. The measurements were performed to characterize the elevations of both the left- and right-tire tracks. Six different roads were considered, in close collaboration with STRSM, for their roughness characterization. The elevations of the selected roads were acquired by the *Centre de recherche et de contrôle appliqué à la construction inc.* (CRCAC) over different segments of approximately 100 m in length. The roads were characterized over a total distance ranging from 538 to 1370 m, and the measurements were performed over two different passes. The average speed was maintained nearly constant over the various segments, varying from 43 to 66 km/h.

The elevations of the selected roads, measured by CRCAC, were made available to the CONCAVE group for deriving the roughness properties at the macro and micro levels. The measured data was processed to eliminate the effects of local slopes, and spectral analyses of the resulting filtered road profiles were performed to derive spatial spectral density of roughness of the selected roads. The spatial spectral densities of urban roads, as shown in Figure 3.8, were compared with those reported for airport runways, highways and gravel roads. The comparison revealed that the spectral density of urban roads is higher than that of highways and lower than those of rough runways and gravel roads. The roughness characteristics were further processed to generate drive files to synthesize urban road excitations in the laboratory, using the servo-hydraulic motion simulator.

Table 3.1: List of urban roads considered for roughness characterization

City	Street	Direction	Longitudinal Distance (m)
Montreal	Côte-Des-Neiges, The Boulevard to Atwater Du Parc, Saint-Joseph to Saint-Viateur Saint-Patrick, Charlevoix to Pitt	South North West	600 686 1335
Longueuil	Marie-Victorin, Guillerm to Jean-Paul Vincent Roland-Therrien, Curé-Poirier to Jacques-Cartier Roland-Therrien, Du Lac to Frechette	West South North	640 1370 538

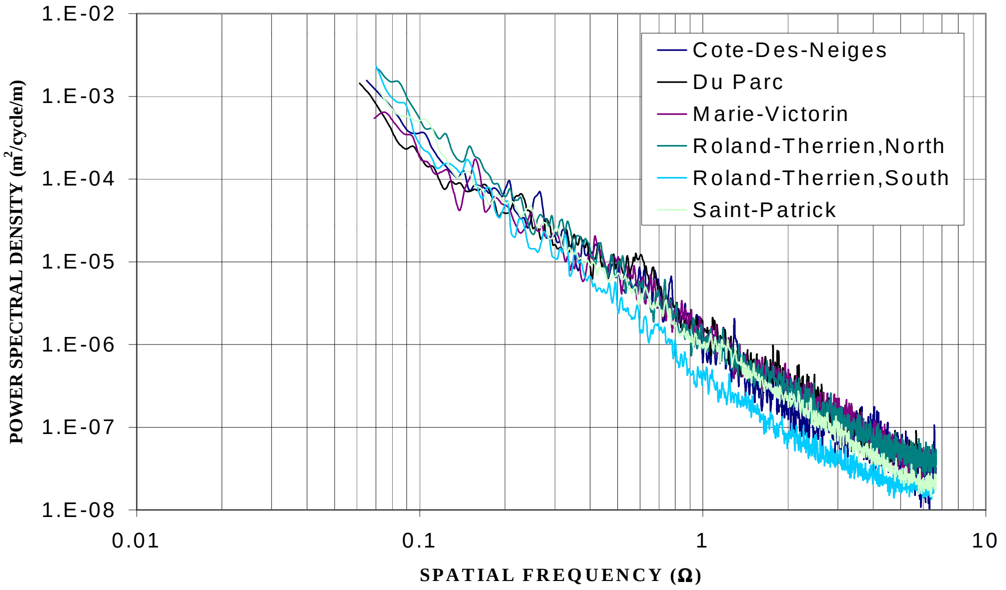

Figure 3.8: Power spectral density of roughness properties of selected roads

3.5 Road Tests and Model Validations

Analytical models are formulated, in general, with a number of simplifying assumptions. The validity of such models is thus vital to gain confidence in analytical investigations and to develop reliable computer-assisted design tools. A comprehensive road test program was undertaken to acquire the response of an LFS bus on different roads (Table 3.1) at forward speeds near 30 and 50 km/h. The candidate bus was instrumented to measure vertical and roll accelerations of the axles, as well as vertical, pitch and roll accelerations of the body. A total of 15 accelerometers were installed on the bus's floor and axles, and a string potentiometer was mounted on the rear axle to measure its relative position response with respect to the chassis during turns. Figure 3.9 illustrates the locations of the sensors on the candidate vehicle. The measured data were analyzed to derive spectral densities of the acceleration response characteristics, which were then used to examine the validity of the analytical model of the LFS bus. The validity of the Classic bus model was examined on the basis of data acquired from IRSST and IRC.

Thirteen-DOF computer models of the Classic and Low Floor buses were analyzed for excitations arising from the selected roads and different speeds. The model results were expressed in terms of PSD of vertical, pitch and roll accelerations of the body and axles, and dynamic tire forces. The acceleration PSD results were compared with those derived from the road measurements to examine the validity of the models for both candidate vehicles. The comparisons revealed reasonably good agreement between the model response and the measured data, with certain errors at higher excitation frequencies. Such errors were attributed to the structural flexibility and simplified point-contact tire model used in this study. The PSDs of the tire forces, derived from the models, were also compared with the range of data derived from measurements performed by IRC. The comparison revealed reasonably good agreement between the model and the measured response characteristics.

3.6 Parametric Sensitivity Analyses

The validated models of the candidate buses were analyzed to assess the performance characteristics of currently used suspension under varying operating conditions, such as load, speed, tire inflation pressure and road roughness. A set of performance measures was defined to assess driver- and road-friendliness, and chassis load performance characteristics. Frequency-weighted vertical, pitch and roll root mean square (rms) accelerations were derived to assess the vehicles' driver-friendliness, while the pavement-damaging potential of tire forces was assessed in terms of the dynamic load coefficient (DLC) of tire forces and peak tire forces. The magnitudes of dynamic forces transmitted to the chassis, which are vital to effectively develop a light-weight bus structure, were assessed in terms of chassis load coefficient (CLC). In view of the eccentric loading of the sub-frame, specifically in the case of the LFS design, performance measures related to dynamic wheel loads and chassis loads were evaluated for all tires and suspension mounting locations. Because of the high surface roughness of the right track of most routes, CLC measures were reported only for the right track.

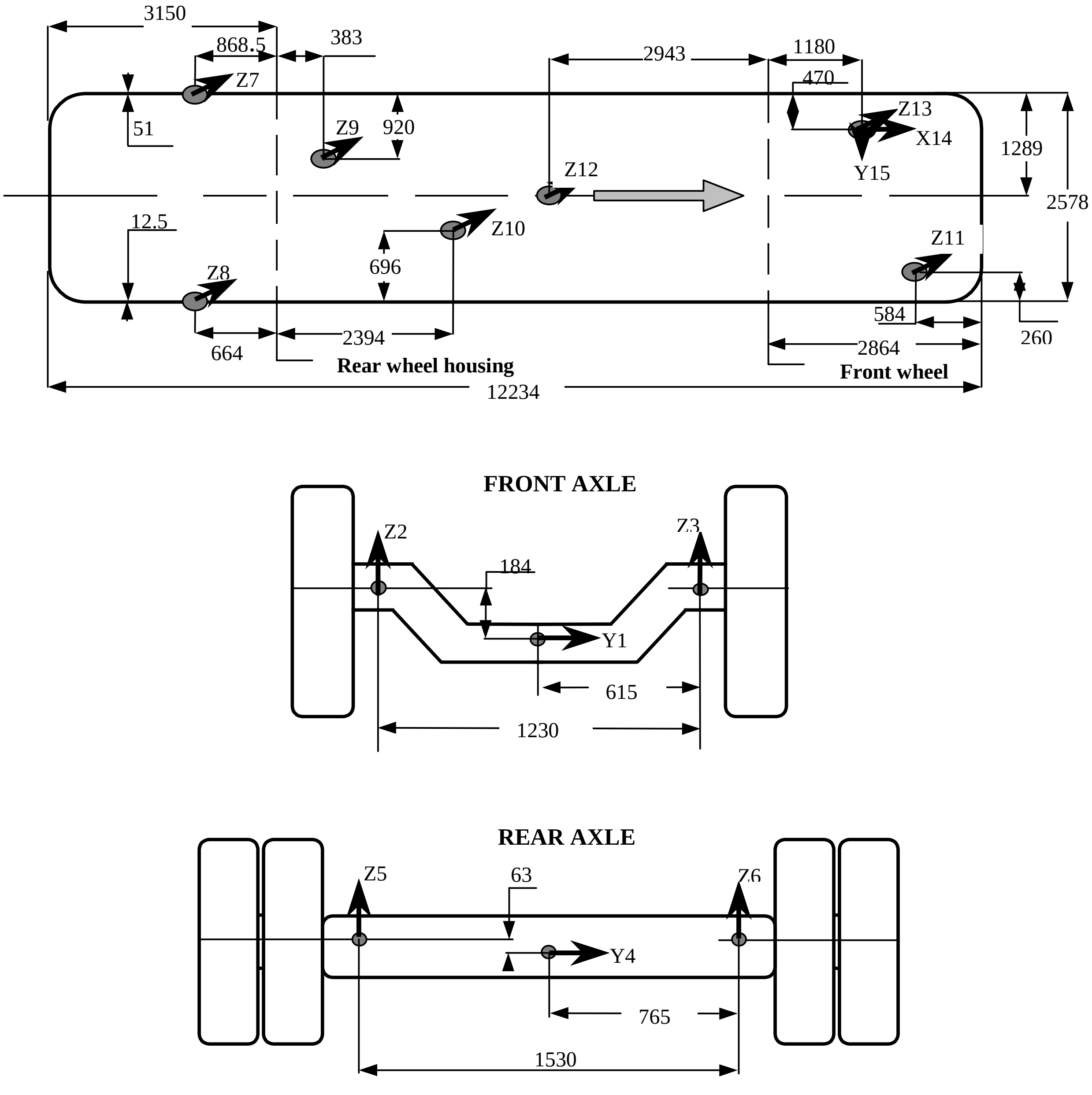

Figure 3.9: Location of accelerometers on the body, and the front and rear axles
(All dimensions are in millimeters)

The performance measures of both vehicles were strongly affected by variations in speed, road roughness, tire inflation pressure, operating load and damper parameters. Almost all performance measures deteriorated with an increase in vehicle speed and road roughness, and a decrease in the operating load. In view of the most significant influence of road roughness on all performance measures, it is apparent that adequate maintenance of urban roads is vital to minimize the magnitudes of transient forces transmitted to the chassis, the road-damaging potential of the buses, and the health and safety risks posed to the drivers by the whole-body ride vibrations.

The results of the study showed that the LFS bus model yields considerably larger magnitude of vertical acceleration response, when compared with that of the Classic bus model. The pitch rms acceleration response of the LFS model was also higher than the Classic model, specifically at higher speeds. The LFS model, however, yielded lower roll acceleration response than the Classic bus model at speeds of 30 and 70 km/h, while it was higher at a speed of 50 km/h, which may be attributed to the spatial distribution of the cross-slope of the road considered. The magnitudes of pitch and vertical vibration as well as DLC measures of the dynamic tire forces increased considerably with higher vehicle speeds and road roughness for both candidate vehicle models. The Classic bus model yielded slightly higher values of DLC for front-axle tires than the LFS bus model at a low speed of 30 km/h, and slightly lower values at higher speeds. The DLC of rear-axle tires was observed to be considerably higher for the LFS bus model, irrespective of vehicle speed and road roughness. The results consistently showed that the DLC of right-tire forces is higher than for left-tire forces. This difference was observed to be considerably greater for the LFS, which was partly attributed to the eccentric load distribution of the LFS design and the greater roughness of the right track of the road. The peak force for the rightmost tire of the rear axle increased most significantly with higher vehicle speeds and road roughness, specifically for the LFS bus model. Although the CLC for both candidate vehicles increased with higher vehicle speeds and road roughness, the LFS chassis experienced considerably larger loads.

The results also showed that a reduction in tire inflation pressure could enhance most performance measures for both vehicles. The magnitude of frequency-weighted vertical rms accelerations and DLC decreased by 6 to 7 percent and 5 to 18 percent, respectively, for both vehicles, when tire inflation pressure was reduced from 100 to 85 psi. While the influence of tire inflation pressure on the pitch ride quality and CLC was insignificant, the rms roll accelerations increased slightly under lower tire pressure as a result of reduced roll stiffness. The magnitudes of rms vertical acceleration response of both vehicles increased with lower operating loads. The increase, however, was more significant for the Classic bus. The magnitude of frequency-weighted rms vertical acceleration of an empty Classic bus was observed to be approximately 23 percent higher than that attained under full load conditions. The difference for the LFS bus was approximately 2 percent. The DLC of tire forces, owing to its definition, increased under empty-load conditions. The CLC of suspension forces also increased with lower operating loads in a similar manner, which was also attributed to its definition. A comparison of DLC values attained under empty- and full-load conditions revealed that the DLC of front-axle tire forces of empty vehicles is 43 to 44 percent higher for the LFS and 51 to 55 percent higher for the Classic bus.

The results recorded for variations in the damping parameters revealed that medium compression damping coupled with a lower degree of asymmetry is desirable for improving performance measures related to driver-friendliness and dynamic chassis loads. Light compression damping coupled with a lower degree of damping asymmetry resulted in lower values of frequency-weighted vertical rms acceleration for both vehicles. Such damping properties also resulted in lower values of CLC. High compression damping coupled with high asymmetry, on the other hand, was considered to be desirable for improving DLC of tire forces, peak tire force and vehicle roll response. The DLC of tire forces of both vehicles increased with light low-speed compression damping. A 25 percent decrease in compression damping of the Classic bus suspension resulted in a 4 to 5 percent increase in the DLC of rear-axle tires and an 8 to 13 percent increase in the DLC of the front-axle tires. Such a decrease in the compression damping of the LFS suspension, however, caused a 15 to 20 percent increase in the DLC of rear-axle tires and a 9 to 14 percent increase for the front-axle tires.

3.7 Optimal Suspension Damping

In view of the conflicting requirements for suspension damping, a multi-variable optimization problem based on the weighted sum of DLC and the frequency-weighted rms vertical acceleration was formulated to identify optimal suspension damping properties. A number of equality and limit constraints on the design vector were imposed to derive feasible solutions for the optimization problem. For the optimization study, a generic model of the suspension damper was considered with multi-stage compression and rebound damping, as shown in Figure 3.10. The damping forces of the front- and rear-axle dampers were expressed as functions of the compression mode damping ratios (ξ_{c1f} and ξ_{c1r}), the asymmetry factor (p), the damping reduction factors ($\gamma_{c1}, \gamma_{c2}, \gamma_{e1}$ and γ_{e2}), and the transition velocities. Since the performance measures are related to the damper parameters in a highly complex manner, the optimization problems were formulated by introducing different equality constraints for compression mode damping coefficients. The compression mode damping coefficient is expressed by the uncoupled damping factor ξ_{c1}, defined as the ratio of the low-speed compression damping coefficient (C_{c1}) to the uncoupled critical damping coefficient of the sprung mass.

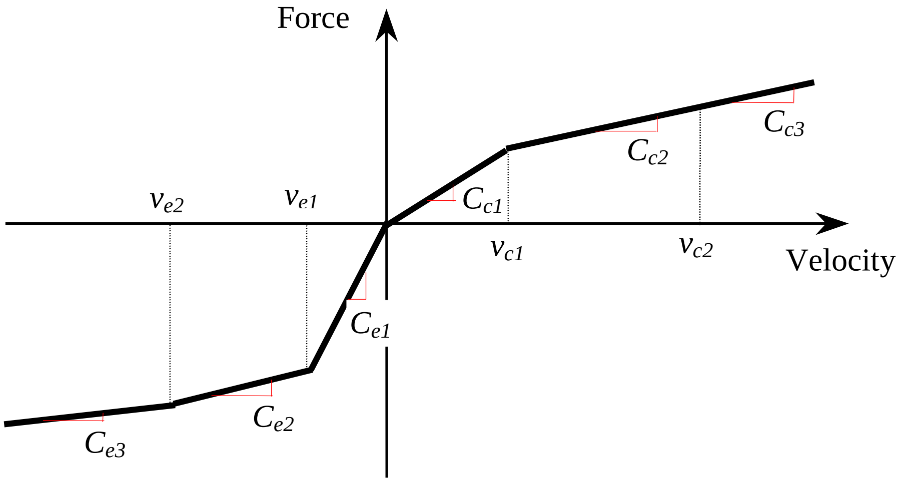

Figure 3.10: Generalized mean force-velocity characteristics of the hydraulic damper considered for determination of optimal parameters

The solution of the optimization problem also depended on various operating factors such as road roughness, speed and load conditions. The minimization problem was thus solved under conditions believed to be more common. Solutions were attempted for excitations arising from a medium-rough road (Saint-Patrick, SAP), half-full load conditions and a vehicle speed of 50 km/h. The validity of the optimal solutions, however, was examined for different operating conditions. Five sets of optimal solutions were obtained for each axle suspension damper corresponding to five different values of low-speed compression damping ratio. These sets are referred to as OPT1, OPT2, OPT3, OPT4 and OPT5, and correspond to low-speed compression damping ratios of 0.10, 0.15, 0.20, 0.25 and 0.30, respectively.

3.8 Performance Analyses of Optimal Dampers

A comparison of the optimal and baseline (currently used) damper parameters revealed that rebound damping coefficients of all the baseline dampers, with the exception of those employed in Classic suspension, are considerably larger than those of optimal dampers. While the compression mode damping coefficients of the baseline dampers were considerably lower than the range considered in the optimization studies, the optimal dampers showed rebound blow-off at relatively low velocities. Analyses of vehicle models with optimal dampers revealed their excellent performance potential with regard to most of the performance measures. The optimal solutions achieved for 20 percent low-speed compression damping (OPT3) provided the best compromise among the driver- and road-friendliness measures for both vehicles, as illustrated in Figure 3.11, in which driver-friendliness is expressed by the frequency-weighted rms acceleration ($\ddot{z}_{w,rms}$) and road-friendliness in terms of the DLC_{ij} ($i=f, r$; and $j=r, l$). The first subscript (f, r) denotes the front- or rear-axle tire, while the second subscript (r, l) denotes right or left tire. The results showed most significant performance gains for the LFS design with regard to all performance measures, while the gains for the Classic bus were relatively small. The optimal dampers for the LFS bus resulted in approximately a 12 percent reduction in the frequency-weighted rms vertical acceleration response of the sprung mass, and a 10 to 28 percent reduction in the DLC of front-axle tire forces. The optimal dampers, corresponding to 20 percent compression damping, however, resulted in a 5 percent reduction in the frequency-weighted rms vertical acceleration, and a 3 to 10 percent reduction in the DLC of tire forces for the Classic vehicle.

3.9 Damper Tuning and Field Assessments

The simulation results clearly showed considerable potential performance benefits of the optimal dampers, derived on the basis of the weighted minimization function. The effectiveness of the optimal dampers, however, needed to be assessed through field measurements. Such field assessment tasks involved achieving optimal damping characteristics using appropriate damping valves, installing the tuned dampers and gathering field measurements. In this study, the damper tuning was performed by Nova Bus Corporation with technical support from Sachs Automotive of America. Since the optimal results were not available on time, the professionals from Sachs performed the damper tuning on the basis of their experience. The resulting tuned dampers were installed on an LFS bus, and Sachs performed further refinements on a subjective basis. An objective field assessment of the tuned dampers was undertaken by CONCAVE Research Centre to determine the potential benefits of the tuned as well as the optimal dampers (derived from the optimization studies).

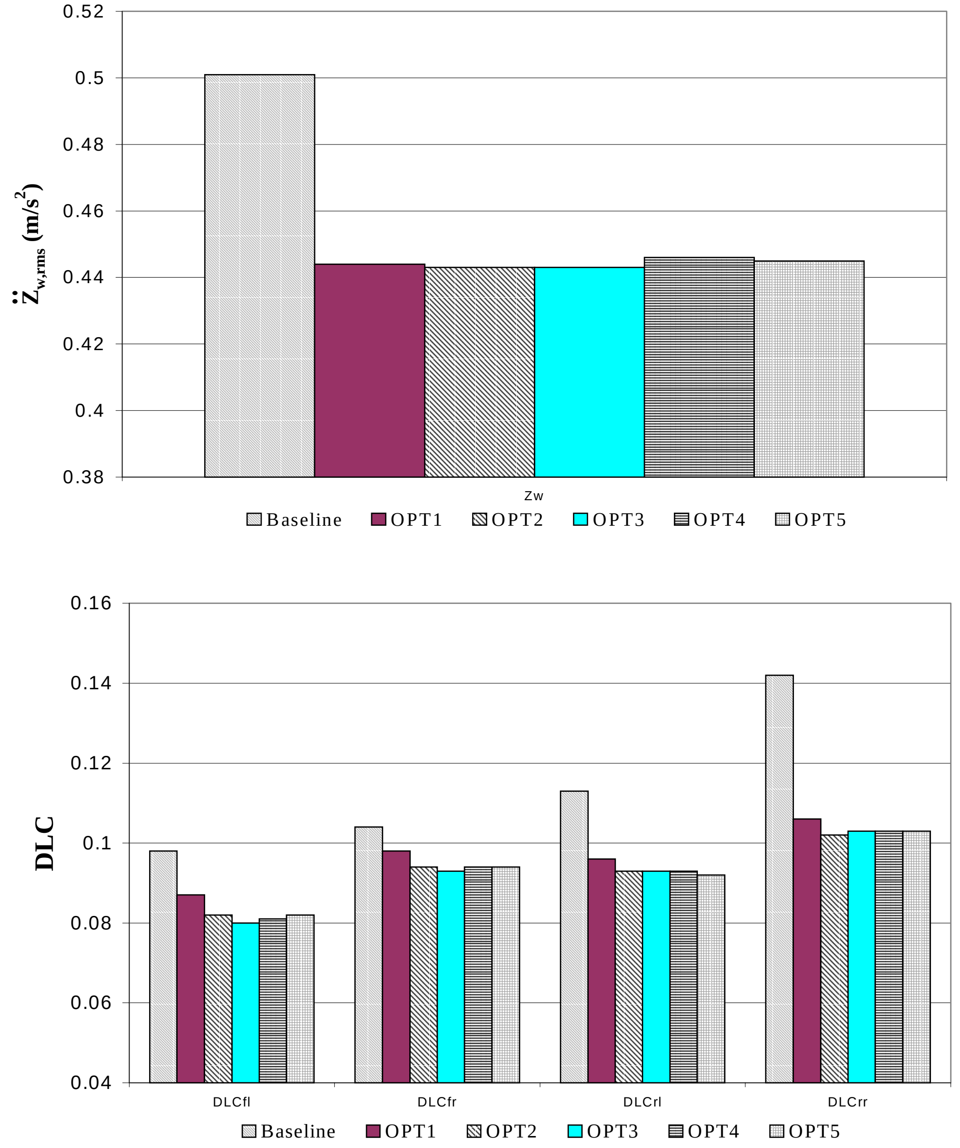

Figure 3.11: Comparison of performance of the LFS bus with optimal and baseline dampers

The candidate LFS bus, equipped with tuned dampers and a simulated passenger load was instrumented as described in section 3.5. Measurements were taken at different speeds on the selected routes, which are described in Table 3.1. The acquired data were digitized and analyzed to derive: *(i)* the PSD of the vertical, longitudinal, lateral, roll and pitch accelerations of the sprung mass; *(ii)* the PSD of the vertical and roll accelerations of the front and rear axles; and *(iii)* vertical accelerations at different locations on the bus floor. A comparison of these results with those reported for the bus with baseline Arvin dampers revealed that tuned dampers yield considerably superior roll performance of the body near the front axle, and effectively suppress vehicle vibration near wheel-hop frequencies. The tuned dampers also yielded lower magnitudes of vertical vibration in the rear of the bus, while their vertical vibration response in the front section was comparable with those attained with the baseline dampers. The tuned dampers also yielded considerably lower magnitudes of vertical and roll acceleration responses of the front axle, while the corresponding gains for the rear axle were relatively small.

The force-velocity characteristics of the tuned dampers were acquired and assessed in relation with the optimal damping characteristics derived in this study. Figures 3.12 and 3.13 illustrate a comparison of force-velocity characteristics of the front- and rear-axle tuned dampers, respectively, with respective optimal dampers OPT1 through OPT5. While the compression damping characteristics of the tuned dampers were similar to those of the optimal dampers, their rebound damping properties were considerably different. The rebound damping forces of the optimal front-axle dampers were considerably lower than those of the tuned dampers, as shown in Figure 3.12. This high rebound damping of the tuned damper was most likely selected to achieve reduced roll motions of the front of the vehicle. It is believed that the front axle, coupled with an anti-roll bar and proposed optimal damper, would yield superior performance. The optimal rear-axle dampers, on the other hand, revealed considerably higher rebound damping, as shown in Figure 3.13.

In view of the differences between the tuned and optimal dampers, further assessments of both dampers were performed through computer simulations. Since OPT3 dampers ($\zeta_c = 0.2$) were considered to provide the best compromise between road- and driver-friendliness performance, further assessments were performed for OPT3 and tuned dampers only. The validity of the computer models, however, was re-examined with the tuned dampers to gain further confidence in the models. Comparisons of the model results with the road-measured data clearly demonstrated the validity of the models.

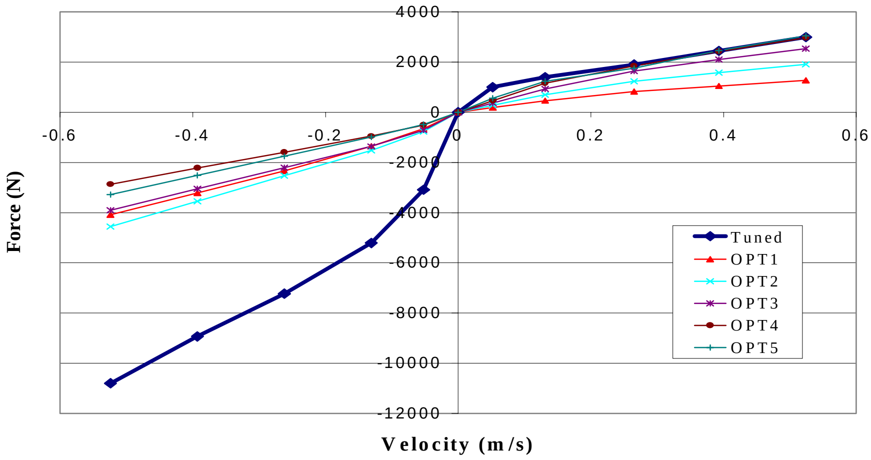

Figure 3.12: Comparison of damping characteristics of optimal, tuned and baseline front-axle suspension dampers

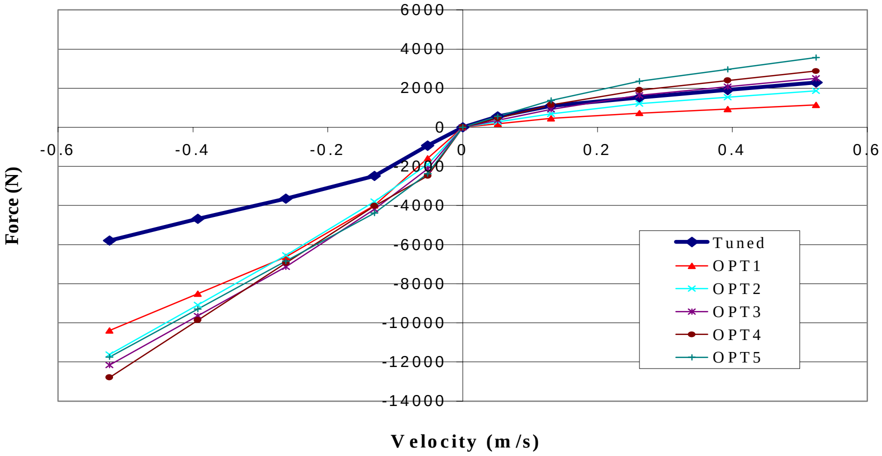

Figure 3.13: Comparison of damping characteristics of optimal, tuned and baseline rear-axle suspension dampers

3.10 Potential Performance Benefits of the Optimal Dampers under Varying Operating Conditions

The optimal dampers in this study were derived through computer simulations of the vehicle models under excitations arising from a medium-rough (SAP) road. The tuned dampers, on the other hand, were developed through subjective assessment of vehicle ride and handling performance. From the results presented in sections 3.8 and 3.9, the OPT3 dampers corresponding to $\zeta_c = 0.2$ were considered to be the optimal dampers, in view of their improved driver- and road-friendliness performance potential. The performance characteristics of the baseline, OPT3 and tuned dampers were further analyzed under different operating conditions such as speed, operating load, road roughness and tire inflation pressure. The results of the analyses are summarized as follows:

- The optimal dampers resulted in the superior performance of both vehicles with regard to both driver- and road-friendliness measures, when compared with that of the vehicles with baseline dampers, irrespective of road roughness, speed, tire inflation pressure and operating load.
- The tuned dampers offered certain performance gains for the LFS bus in terms of body roll and DLC of front-axle tire forces. The tuned dampers, however, provided considerably higher values of true and frequency-weighted rms vertical accelerations, irrespective of the operating conditions.
- The optimal dampers offered the most significant potential to enhance driver-friendliness performance and the lowest values of frequency-weighted vertical and pitch accelerations. The tuned dampers, however, provided the most significant reductions in the roll acceleration response of the LFS vehicle.

- The tuned dampers yielded better tire load performance of the LFS vehicle under rough road excitations, while the optimal dampers provided considerably lower DLC values of most tires, irrespective of road roughness, speed and operating load. The potential performance benefits of both tuned and optimal dampers were apparent under medium-rough and rough roads, where dynamic tire-terrain interactions predominated. In comparison with the DLC of tire forces of the vehicle with baseline dampers, the optimal dampers provided 10 to 27 percent and 10 to 32 percent reductions in DLC of all tire forces under medium-rough and rough roads, respectively. Under smooth and medium-rough road conditions, the DLC values with the tuned dampers were higher than those with optimal dampers. Tuned front-axle dampers with relatively high rebound damping, however, provided the lowest values of DLC for front-axle tire forces under rough road excitations. The tuned dampers for the rear-axle suspension, with low rebound damping, resulted in higher values of DLC than the optimal dampers. The results suggest that higher rebound damping would help improve the road-friendliness of vehicles traversing rough roads.
- The tuned dampers provided higher values of CLC for the front-axle suspension and lower values for the rear-axle suspension for the LFS bus. The optimal dampers, on the other hand, provided considerably lower values of CLC for the front-axle suspension and higher values for the rear-axle suspension. These results suggest that light rebound damping is desirable for attenuating the magnitudes of transient forces transmitted to the chassis.
- For the Classic bus, the optimal dampers yielded superior performance on medium-rough and rough roads, while their performance on smooth roads was either similar or inferior. Under rough road excitations (Côte-Des-Neiges, CDN), the DLC of tire forces of the Classic bus with optimal dampers was 7 to 8.6 percent lower than with the baseline dampers. The optimal dampers also provided approximately a 6 percent reduction in the magnitude of frequency-weighted vertical acceleration, approximately a 10 percent reduction in the magnitude of frequency-weighted pitch acceleration and a 24 percent reduction in the magnitude of frequency-weighted roll acceleration.
- The optimal dampers for the Classic bus further provided approximately a 14 percent lower value of CLC for front-axle suspension and a 2 percent reduction for the rear-axle suspension.

4. CONCLUSIONS

The results of the study demonstrated superior performance of the optimal dampers for both vehicles with regard to driver- and road-friendliness measures, irrespective of the variations in road roughness, speed, tire inflation pressure and operating load. The tuned dampers also offered certain performance gains for the LFS bus in terms of body roll and DLC of front-axle tire forces, while yielding considerably higher values of true and frequency-weighted rms vertical accelerations. The proposed optimal dampers offered the most significant potential to enhance driver-friendliness performance and yielded the lowest values of frequency-weighted vertical and pitch accelerations, while the tuned dampers offered the most significant reductions in the roll acceleration response of the LFS vehicle. Although the tuned dampers considerably improved the tire load performance of the LFS vehicle under rough road excitations, the optimal dampers provided lower DLC values of most tires, irrespective of the road roughness, speed and operating load. The tuned dampers provided higher values of CLC for the front-axle suspension and lower values for the rear-axle suspension of the LFS bus. The optimal dampers, on the other hand, yielded considerably lower values of CLC for the front-axle suspension and higher values for the rear-axle suspension. These results suggest that light rebound damping is desirable for attenuating the magnitudes of transient forces transmitted to the chassis and vertical vibration transmitted to the driver.

The optimal dampers also demonstrated considerable performance benefits for the Classic bus on medium-rough and rough roads, while their performance on smooth roads was either similar or inferior. Under rough (CDN) road excitations, the optimal dampers resulted in:
a 7 to 8.6 percent reduction in the DLC values of the tire forces; approximately 6 percent, 10 percent and 24 percent reductions in the magnitudes of frequency-weighted vertical, pitch and roll accelerations, respectively; and approximately 14 percent and 2 percent reductions in the CLC of front- and rear-axle suspensions, respectively.

The results of the study suggest that tire inflation pressure affects all performance measures considerably. Lower inflation pressures offer considerable potential to enhance the road- and driver-friendliness of the vehicles. The low pressure, however, may result in rapid tire wear and poor handling under certain loading conditions. Considering wide variations in the operating load, the use of a passenger-load dependent central tire inflation system may be considered desirable.

The results of the study revealed wheel-hop vibration modes in the 10 to 12 Hz frequency range, which may induce considerable bending and torsional stresses of the chassis. Further studies incorporating structural flexibility are therefore suggested to develop optimal suspensions for light-weight structure designs for urban buses.

5. RECOMMENDATIONS

On the basis of the results achieved, the following recommendations are made to develop driver- and road-friendly designs of urban buses and their suspension systems.

- The design/selection and implementation of tuned suspension dampers is vital to improve the ride vibration environment and preserve urban roads. Because of the differences in damping characteristics of identical dampers observed in this study, high-performance dampers known to provide consistent characteristics should be implemented.

- A routine damper inspection program should be developed by bus operators to ensure adequate in-service suspension damping. This would, however, require the development of an efficient damper assessment methodology. The body or axle response to a predefined road bump may be considered for a swift assessment of the damper in service.

- The optimal dampers should be selected with appropriate consideration of the design and the operating conditions, including suspension springs, anti-roll stiffeners, a range of operating loads, tire inflation pressure and local road conditions, using the proposed methodology.

- Semi-active dampers using magneto-rheological fluids offer considerable potential to achieve variable damping in response to varying operating conditions with minimal power requirement. It is recommended that the performance potential of such dampers be investigated for urban bus applications.

- The validity of the proposed methodology should be further investigated by developing optimal dampers in collaboration with damper manufacturers and taking into consideration additional field evaluations.

- Current axle suspension designs employ dampers with considerably high damping forces to limit the roll motions of the body. Such dampers yield relatively higher magnitudes of ride vibration and dynamic chassis loads. The use of an anti-roll mechanism in the front-axle of the LFS vehicle would permit the use of optimal dampers (with relatively light damping) and thus yield maximum benefits in terms of the driver- and road-friendliness performance of the vehicle.

- Designs for light-weight chassis for urban buses should be developed with appropriate consideration of the dynamic loads transmitted to the chassis. It is recommended that the vehicle models developed in this study be further enhanced to include the flexible chassis structure to study the impact of dynamic loads on peak stresses. Such analyses could provide a significant knowledge base for the design of optimal light-weight chassis structures.

- Given the considerable variations in passenger load and the influence of tire stiffness on pavement and chassis loads as well as the ride vibration environment, it is recommended that development and implementation of a central tire inflation system be investigated. A central tire inflation system could automatically adjust the tire pressure in response to the passenger load. Such implementation, however, would require the development of a control criterion that may be based on the airbag pressure, tire deflection or operating load. Automated central tire inflation systems that have been developed for military and forestry vehicles should be explored for the feasibility of implementing them on urban buses.

APPENDIX A

The detailed results attained from the study are presented in various interim reports submitted to TDC and the partners during the course of the study. These reports are listed below.

Feb. 1998	Laboratory Characterization of Shock Absorbers Employed in Classic Bus Suspension (Phase I)
June 1998	Laboratory Characterization of Air Springs Employed in Urban Bus Suspension (Phase I)
June 1998	Laboratory Characterization of Shock Absorbers Employed in Urban Bus Suspension (Phase I)
Jan. 1999	Development of Optimal Suspension Characteristics through Systematic Study of Reduced Models (**Final Report**, Phase I)
Jan. 1999	Detailed Work Plan for Phase II (Phase II)
Oct. 1999	Experimental Evaluation of Dampers for Application in Urban Bus Suspension (Phase II)
Oct. 1999	Roughness Characteristics of Urban Roads (Montreal and Longueuil) (Phase II)
Oct. 1999	Measured Data on Lateral Displacement of Rear-Axle of Low Floor Bus (Phase II)
Nov. 1999	Development of an Axle Test Stand and Laboratory Testing for Validation of Simplified Models (Phase II)
June 2000	Enhancement of Road- and Driver-Friendliness of Urban Buses through Optimal Suspension Damping (Draft Final Report, Phase II)
June 2000	Appendix I: Road-Measured Vibration Spectra of a Low Floor Bus (Phase II)
June 2000	Appendix II: Road-Measured Vibration Spectra of a Low Floor Bus with Tuned Dampers (Phase II)
Jan. 2001	Enhancement of Road- and Driver-Friendliness of Urban Buses through Optimal Suspension Damping (**Final Report**, Phase II)