Vehicle Weights and Dimensions Study

Technical Steering Committee Report

December 1986

PREFACE

The report which follows was prepared by the Technical Steering Committee of the Vehicle Weights and Dimensions Study to provide a synthesis of the principle findings of the research program as they relate to the regulation of commercial vehicle weights and dimensions. As such the report draws on the findings and conclusions contained in a series of sixteen technical reports prepared by contract researchers who participated in the study. Judgements have been made by the Technical Steering Committee in interpreting these findings and in proposing regulatory principles which are supported by the research.

The points of view expressed herein are those of the committee and do not necessarily reflect the opinions or policies of Canroad Transportation Research Corporation or its suppporting agencies.

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TABLE OF CONTENTS

PART 2: PAVEMENT RESPONSE TO TRUCK AXLE LOADS

PART 3: CANDIDATE REGULATORY PRINCIPLES

LIST OF FIGURES

LIST OF TABLES

VEHICLE WEIGHTS AND DIMENSIONS STUDY

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1.0 INTRODUCTION

1.1 The Context

In a country with six time zones; a land territory of 9,922,330 square kilometers; a climate that ranges from an Arctic tundra to a temperate south (parts of which lie south of California's northern boundary), a geography that includes great plains, large areas of mountains and hundreds of thousands of rivers and lakes, road transportation plays a central role. Canada spends approximately $8 billion (1984 dollars) annually on a road infrastructure of more than 5,000 kms. of federal highways, 250,000 kilometers of provincial highways and more than 600,000 kilometers of municipal roads and streets.

A sharp division of jurisdictional powers exists between Canada's ten provincial governments, two territorial governments and the federal government. This means that each level of government is virtually sovereign with respect to the powers it exercises. Road transportation, jurisdiction of weights and dimensions regulatory practice falls largely under the ten provincial and two territorial governments. Each province or its municipalities is largely responsible for financing, building and operating the nation's road and highway system. Road and highway funding is raised through direct or indirect taxation. The level of taxation is determined by overall fiscal policy and not specifically by transportation funding requirements.

In the context of this highway transportation system, the role of the motor carrier within the Canadian economy is a major one. It has been estimated that for hire motor carriers accounted for 47% of total operating revenues of all Canadian freight carriers in 1980. In contrast, rail accounted for 38%. Estimates of goods moved by both private and for hire truck carriers indicate that in 1980, these groups moved some 80 billion tonne-km of freight. Operating costs for both of these groups in 1983 were in the range of 15 to 18 billion dollars.

This significant role is not new to the industry since it has in fact been playing a substantial part in the transportation of goods in Canada for fifty years. It has succeeded in providing a level of service which offers both flexibility and efficiency as well as adaptability to the changing needs of the marketplace. The industry's desire to provide more efficient service, coupled with the continual pursuit of new markets and commodities has brought with it relatively rapid growth in the size and weight of commercial vehicles in our country, especially over the past decade.

As a consequence, the Canadian trucking industry currently operates some of the longest, heaviest, and widest heavy commercial vehicles in regular use anywhere in the world. This distinction brings with it a fleet of trucks and equipment which is to a large degree, unique to Canada, reflecting the heavy loads carried across a wide variety of highways in a demanding range of geographic and climatic conditions.

1.2 Size and Weight Issues In Canada

Changes in size and weight regulations in Canada over the years have been evolutionary in nature and because of disparate technical viewpoints in individual jurisdictions, the implications on vehicle stability and controllability of such changes have not always been fully understood. Due to the fractured nature of regulatory responsibility in Canada, a considerable degree of non-uniformity has come about which renders the efficient operations of a motor carrier fleet across multiple provinces difficult.

The Canadian Vehicle Weights and Dimensions Study was launched largely due to a desire to achieve a greater degree of uniformity in size and weight regulations affecting interprovincial motor carriers across the country. A number of agencies, however, were extremely concerned for the impact of changes on highway safety. Uniformity and productivity increases were viewed as essential but these had to be based on sound, proven, rational performance criteria and infrastructure impacts. Bridges and bridge capacities were originally thought to be a limiting factor, however, a cooperative study carried out from 1975 to 1979 indicated that bridges could withstand significantly higher loads than originally expected and suggested further research be conducted into pavement structures and limitations they might impose.

Work in defining the research needed resulted in the launching of the VWD study in Canada, the key highlights of which are summarized in this report. Vehicle stability and pavement response issues were seen as the critical areas requiring immediate attention if a sound technical basis was to be provided for bringing weights and dimensions uniformity to Canadian regulatory practice.

A number of related issues are being examined through the coordinated efforts of different agencies in the country. In developing recommendations for national-level uniform regulatory principles, these issues will be considered in conjunction with the findings of the research program.

Among areas under study are:

— development of a methodology for the evaluation of the economic impacts of regulatory rationalization

— the interaction of heavy vehicles with other elements of the traffic stream on highways

— issues relating to the sensitivity of bridges to variations in axle spacings and loadings which might occur with new vehicle configurations

The role of the driver was also recognized as an important element in the vehicle/highway environment interaction process. In concentrating on understanding the effects of vehicle parameter variation on dynamic performance, it was assumed that all drivers must have access to the best equipment appropriate to the job at hand.

PART 1: VEHICLE STABILITY AND CONTROL

1.0 Introduction

The largest series of investigations carried out under the Vehicle Weights and Dimensions Study were examinations and testing of the stability and control characteristics of heavy articulated vehicles used in interprovincial carriage of goods.

The University of Michigan Transportation Research Institute carried out extensive computer simulation of the behaviour of existing configurations, and a wide range of variations on these configurations. The results are reported in detail in Technical Reports Volumes 1 and 2.

The Ontario Ministry of Transportation and Communications undertook the testing of the "Baseline" vehicle configurations, three "special case" configurations, and a test investigation of the characteristics of the B Dolly converter. The findings of these test programs are documented in Technical Reports Volumes 3 through 6.

The Centre de Recherche Industrielle du Quebec undertook a program of testing on a tilt table device to explore the sensitivity of articulated vehicle roll stability to changes in parameters and equipment. These findings are documented in Technical Report Volume 7.

The discussion in this section is based primarily on the work of the University of Michigan Transportation Research Institute, but is also supported by the findings of the other investigations. While there are many technical findings described in the detailed reports referenced previously, those contained herein were selected for their relevance to the issue of regulating vehicle size and weight.

The specific aspects of performance addressed in this report cover the stability and control behaviour of vehicles in response to steering and braking manoeuvers. The findings have been formulated in terms of measures of performance which are seen as expressing certain safety qualities of vehicles. Thus, insofar as new weights and dimensions regulations must recognize the potential safety implications of truck allowances, this body of findings serves as an information base to aid in making public policy. ***To the degree that the results indicate deficiencies in the performance levels of one existing truck configuration relative to another, they also identify opportunities for improving the overall safety of truck transportation***. As will be shown, these findings establish that:

a. There is a great range of performance quality exhibited across the spectrum of truck configuration types currently in Canada.

b. Dynamic performance will be strongly sensitive to changes in weights and dimensions in various cases. It is clear that it cannot simply be assumed that modest variations in weights and dimensions allowances will have negligible effects upon stability and control qualities.

c. Similarly, dynamic performance is also strongly sensitive to variations in the selection of optional components on heavy duty vehicles. Recognizing that the truck purchaser specifies component installation to a far greater degree than does the layman purchasing his automobile, it is highly significant that such selections include the entire range of components which directly determine stability and control behavior.

d. The control quality of the truck system is determined by:

(1) basic configuration
(2) weights and dimensions constraints
(3) purchaser-specified components

Consequently, there is both risk of attaining undesirable performance in a given vehicle today, as well as a distinct opportunity for improvement in the future through careful regulation of the types of truck configuration, and their corresponding weight and dimension constraints. Vehicle stability and control qualities can also benefit from wide dissemination of the research findings to the trucking industry so that the controllability implications of their vehicle component selection practices are better recognized.

In this section, the substance behind these general findings will be reviewed in terms of the following:

— the means used to characterize performance

— a summary of the prominent parametric sensitivities of each type of truck configuration currently employed in Canada

— an overall comparison of the performance profiles of all the differing types of truck configurations

— a summary of the general findings of the study

— recommendations supported by these findings

— candidate regulatory principles which may be applied in the formulation of public policy

2.0 Summary of Research Procedures

The conduct of a large-scale analytical effort for evaluating the stability and control properties of truck combinations required that various pieces of missing information be gathered and that protocols be developed for analyzing performance over the broad spectrum of Canadian truck combinations. The study effort contained the following major elements:

1. In order to identify the specific vehicle configurations for study, a series of meetings was conducted in which persons from the trucking industry were convened in six Provincial centers and asked to identify the popular trucking equipment, primarily in terms of configuration type, geometric layout, loading, and component selection, in their respective regions of the country.

2. Given the descriptions of truck combinations, a study matrix was designed providing coverage of all prominent vehicle types and the maximum feasible range of weight and dimension variables and component selections. These vehicle types were divided into six categories as depicted in Figure 1.

3. Where components were found to be popular in Canada, but the mechanical properties had not been characterized through previous research, laboratory measurements were conducted.

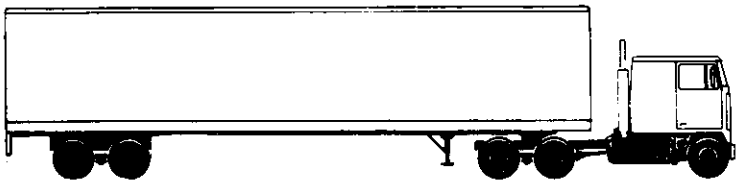
4. A matrix of computerized simulations was then run, encompassing the range of vehicle types for various selections of weights and dimensions as well as component properties, and for various maneuvering conditions which constitute a challenge to vehicle control.

5. To provide visual depictions of vehicle performance, full scale track testing of the baseline vehicles from each of the six categories and selected other configurations was carried out. Test data and video tape summaries serve to complement the computer simulation based analyses and findings upon which this document is based.

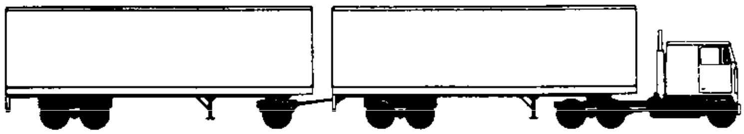
Figure 1: Vehicle Classification Framework

Category | Baseline Configuration

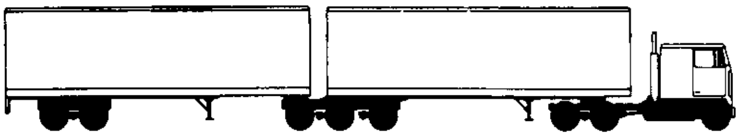
1. Tractor Semitrailer



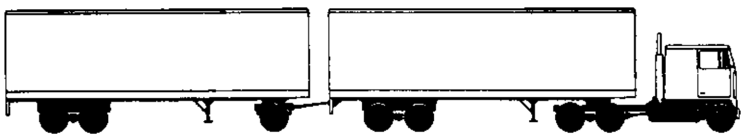
2. A Train Double



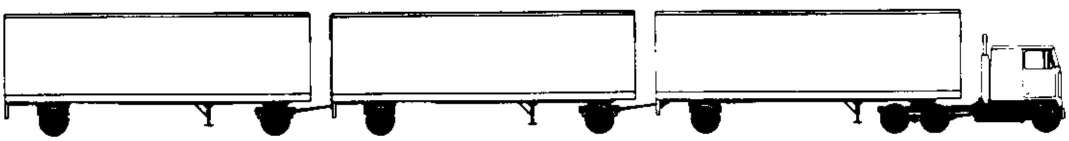
3. B Train Double



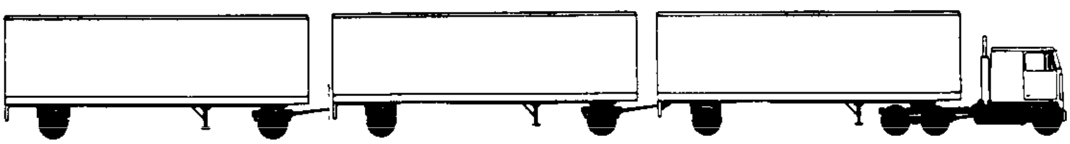
4. C Train Double



5. A Train Triple



6. C Train Triple



6. To further supplement and verify the computer simulation of static rollover threshold, a tilt table test program was conducted with vehicles configured appropriately to illustrate the influence of parameter and equipment variables on this performance measure.

7. As a means of addressing the objective of improving Canadian research capabilities in the field of heavy vehicle stability and control, a Visiting Researcher program was implemented under the aegis of the study. Five Canadian researchers were supported to build or acquire expertise in particular aspects of this field and were required to conduct workshops and provide technical reports on their respective investigations as means for disseminating information and acquired technology.

2.1 Technology Transfer

As part of the objective of improving Canadian research capabilities in the field of heavy vehicle stability and control, the computer simulation and modeling technology was obtained from the University of Michigan Transportation Research Institute. Copies of the models and parametric data files were obtained and installed at the Systems Laboratory of the National Research Council of Canada under the guidance of Dr. Roland Gagne, and two of the visiting researchers, Drs. Jo Wong and Mustafa El Gindy. Following several months of study and exploration, Dr. Wong and Dr. El Gindy prepared a users guide to the models and conducted an instructional course on their use for interested parties from the Canadian transportation community.

The models have been made available on request to any interested parties from Canada and are seeing growing usage within the research and academic environments in the country.

2.2 Performance Measures

In conducting the analysis of vehicle performance using computerized simulations, a variety of measures were employed for characterizing the nature and level of the maneuvering limits of the overall matrix of vehicle cases. The focus of the study's findings are presented later in terms of a specific group of seven of these measures, grouped in two classes; Stability and Control Measures and Offtracking Measures. Definitions of these measures are as follows:

STABILITY AND CONTROL MEASURES:

A. The ***Static Rollover Threshold*** defines the maximum severity of steady turn which a vehicle can tolerate without rolling over. The measure, itself, expresses the level of lateral acceleration, in units of g's of lateral acceleration, beyond which overturn occurs. In general, loaded trucks exhibit rollover threshold values in the range of 0.25 to 0.40 g — a range which lies modestly above the severity levels encountered in the normal driving of passenger cars. This measure of truck roll stability is known to correlate powerfully with the incidence of rollover accidents in highway service.

Measure: lateral acceleration in g's
Range: 0.0 to 1.0

B. *Dynamic Rollover Stability* characterizes the extent to which a vehicle approaches the rollover condition in a dynamic steering maneuver such as in avoiding an obstacle in the roadway. This measure is expressed in terms of the fractional change in tire loads between left- and right-side tires in the manoeuver, thus indicating how close the vehicle came to lifting off all of its tires on one side, and rolling over. The value which is determined reflects the so-called amplification tendencies by which multiple-trailer combinations tend to "crack the whip" in rapid steering maneuvers. This measure was especially tailored to the study of Canadian specialty truck combinations such as B Trains and C Trains which incorporate roll-rigid couplings between successive trailers, and thus provide for a dynamic type of load sharing response which impedes rollover.

Measure: Load Transfer Ratio = $\text{sum}|F_L - F_R| / \text{sum}(F_L + F_R)$

where: F_L = Left side tire loads
F_R = Right side tire loads

Range: 0.0 to 1.0

C. The measure termed, ***Friction Demand in a Tight Turn***, pertains to the resistance of multiple, non-steered axles to travelling around a tight-radius turn, such as at an intersection. Especially with semitrailers having widely spread axles, the resistance to operating in a curved path results in a requirement, or demand, for tire side force at the tractor's tandem axles. When the pavement friction level is low, such vehicles may exceed the friction which is available and produce a jackknife-type response. The friction demand measure describes the minimum level of pavement friction on which the vehicle can negotiate an intersection turn without suffering such a control loss. When the vehicle design is such that a high friction level is demanded, the vehicle is looked upon as inoperable under lower-friction conditions such as prevail during much of the Canadian wintertime.

Measure: Peak Frictional Coefficient (u)
Range: 0.0 to 1.0

D. A ***Braking Efficiency*** measure was employed to indicate the ability of the braking system to fully utilize the tire/pavement friction available at each axle. It is defined as the percentage of available tire/road friction limit that can be utilized in achieving an emergency stop without incurring wheel lockup. For example, a vehicle achieves only a 50% braking efficiency level when it suffers wheel lockup while braking at 0.2 g's on a surface which could ideally support a 0.4 g stop. The braking efficiency measure is meant to characterize the quality of the overall braking system as the primary accident avoidance mechanism.

Measure: ratio (in %) of deceleration (in g's) at which first wheel lockup occurs over highest friction coefficient demanded by any axle if no lockup is to occur
Range: 0% to 100%

OFFTRACKING MEASURES:

E. *Low-Speed Offtracking* was defined as the extent of inboard offtracking exhibited in a typical 90 degree, 11 meter radius intersection turn. In a right-hand turn, for example, the rearmost trailer axle follows a path which is well to the right of that of the tractor, thus making demands for lateral clearance in the layout of pavement intersections. This property is of concern to compatability of the vehicle configuration with the general road system and has implications for safety as well as abuse of roadside appurtenances.

Measure: maximum distance (in meters) last axle of vehicle tracks inside path followed by tractor steering axle in 900 turn
Range: 0 m to infinity

F. A ***High-Speed Offtracking*** measure has been defined as the extent of outboard offtracking of the last axle of the truck combination in a moderate steady turn of 0.2 g's lateral acceleration. This measure is expressed as the lateral offset, in meters, between the trailer and tractor paths. Recognizing that the driver guides the tractor along a desired path, the prospect of trailer tires following a more outboard path that might intersect a curb, or an adjacent vehicle or obstacle poses a clear safety hazard.

Measure: maximum distance (in meters) last axle of vehicle tracks outside path followed by tractor steering axle in steady turn at 100 kph around circular path of 393 m radius
Range: 0 m to infinity

G. *The* ***Transient High-Speed Offtracking*** measure is obtained from the same obstacle avoidance manoeuver as that used to define the dynamic rollover stability level and is defined as the peak overshoot in the lateral position of the rearmost trailer axle, following the severe lane-change-type maneuver. The amount of overshoot in the rearmost-axle path can be viewed as a relative indication of the extent of potential intrusion into an adjacent lane of traffic, or the potential for striking a curb (risking an impact-induced rollover). In layman's terms, this measure quantifies the magnitude of the "tail-wagging" in response to a rapid steer input.

Measure: maximum lateral distance (in meters) last axle of vehicle is displaced relative to the path followed by the tractor steering axle while negotiating an obstacle avoidance manoeuver
Range: 0 m to infinity

3.0 Parametric Sensitivities for Respective Vehicle Types

In this section, the prominent sensitivities in dynamic performance to variations in component selection and weights and dimensions variables will be presented for each type of vehicle configuration. The results simply relate those particular types of manoeuvering conditions in which each vehicle type exhibits some significant change in behaviour when the indicated parametric feature is changed.

3.1 Tractor Semitrailers

The following primary sensitivities were seen in the case of tractor semitrailer combinations:

Tractor and trailer length
Increased length of either the tractor or the semitrailer also implies an increase in the wheelbase of either unit. As wheelbase increases, the most significant effect is that the low speed offtracking dimension increases. For trailers in the vicinity of 14.6 m (48 ft) in overall length, an increase of 1 meter (3.3 ft) in the typical wheelbase dimension results in some 0.6 m (2 ft) increase in low speed offtracking. The tractor also plays a significant role in low speed offtracking. A 1 m (3.3 ft) increase in tractor wheelbase results in an approximate 0.35 m (1.1 ft) increase in the inboard offtracking response. However, tractors with longer wheelbase values are less prone to exhibiting an unstable yaw response to steering while also making recovery from impending jackknife more likely (Volume 1 p73).

Trailer Axle Spread
An increase in the spread dimension between adjacent axles has a direct effect on vehicle behavior only in the case of friction demand during tight-radius turning. Analysis shows that the friction demand at the tractor's rear tires goes up with the square of the spread between axles on the semitrailer. The worst such case examined was a quad-axle semitrailer having a spread of some 8.7 m (28.5 ft) over the set of four trailer axles. This vehicle required a friction level of 0.71 in order to negotiate an intersection turn. Available friction levels would typically be in the range from 0.1 for icy or snow covered roads to 0.4 to 0.7 for dry pavement. While such a problem could be overcome by incorporating air-suspended axles which are lifted for negotiating tight turns, the pavement overloading which results from such a practice was not assumed to be justified and such cases were not studied here (Volume 1 p76).

Tractor and Trailer Suspension Selection
Substantial variations in static roll stability were seen to result when various suspensions were installed. It is clear, however, that the variation in performance with differing suspensions is more a result of design details than to the type of suspension, per se, (such as air vs. steel leaf or walking beam vs. 4-spring). The common practice in which truck purchasers specify the suspension to be installed on a new vehicle has significance for safety because of the

general absence of information on the stability implications of this specification process. This situation can result in roll stability levels of vehicles in service which are less than current technology can provide (Volume 1 p 85).

Payload Centre of Gravity Height
The height of the payload center of gravity is the single most powerful determinant of the stability and control behavior of a motor truck. The static roll stability level, tractor yaw response, high-speed offtracking, and braking efficiency are all generally degraded by an increase in the payload c.g. height. Thus, any increase in the load allowance which causes the c.g. height of the typical payload to rise (such as when a greater load level is allowed for the same trailer floor area) will degrade stability and control properties unless compensatory steps such as increasing axle widths or improving suspension stability characteristics are taken (Volume 1 p 92).

Axle Loading
Increased axle loading, without compensatory changes in suspension, brake and tire selections, results in generally degraded control qualities. The degraded properties include static roll stability, tractor yaw response, high speed offtracking, braking efficiency and friction demand in a tight turn (especially if only trailer axle loads are increased) (Volume 1 p 103).

Steerable Belly Axles
Recognizing that non-steerable belly axles tend to make high demands on the available friction in tight turns, passively steerable belly axles were also considered. When a single steerable belly axle is placed near the trailer's mid-wheelbase position, no significant degradations in performance are seen relative to a conventional 2-axle semitrailer (Volume 1 p 115, Volume 2 — Appendix E).

Tractor Width
An increase in the outside width across tractor axles from the current dimension of 2.44 m (96 in) to 2.59 m (102 in) is seen to afford a substantial improvement in both roll stability and tractor yaw response (Volume 1 p 92).

3.2 A and C Train Doubles Combinations

Parametric sensitivities which were peculiarly evident with A and C Train doubles combinations are discussed below. The A-type double is defined as a tractor towing two trailers, the second of which couples by means of a conventional dolly through a single pintle hitch connection to the rear of the lead trailer. The C-double employs a dual-drawbar dolly which couples to the lead trailer by means of two side-by-side pintle hitches and incorporates a passively steerable dolly axle to minimize tire scrubbing in tight turns.

Trailer Length and Hitch Placement Dimensions
Trailer length, primarily as a result of its influence on trailer wheelbase, is known to have strong influence on the following:

— low speed offtracking

— high speed offtracking

— dynamic rollover stability

— transient high speed offtracking

Increasing wheelbase causes low speed offtracking to increase. Conversely, the longer the wheelbases, the more favourable will be the performance level in the latter three properties, listed above. Thus, for example, a turnpike double employing long, 14.6 m (48 ft), trailers exhibits poorer low speed offtracking but much better dynamic properties than an A-train double with short, 8.2 m (27 ft) trailers. While C-type doubles show considerably higher levels of dynamic stability than A-doubles, the basic sensitivities of these two configuration categories to trailer length are rather similar.

The key hitch-placement parameter involves the extent of *rear overhang* in the placement of the pintle connections on the rear of the lead trailer. The dynamic responses of both A-and C-trains degrade as this overhang dimension is increased. The C-train, in particular, is sensitive to extra-long overhang layouts, especially when a long drawbar length is employed. In such cases it is possible to establish a growing oscillatory response at highway speeds.(Volume 1 p 117)

Axle Loading
The dynamic behavior of A- and C-type doubles is generally degraded by any increase in axle load. Both the dynamic tracking and stability properties are aggravated by the increase in payload c.g. height which accompanies increased payload weight, and also by the altered tire properties accompanying increased tire loading. (Volume 1 p 126)

Partial Loading
A significant partial loading problem with doubles is the practice of operating one trailer loaded while an empty is pulled along behind. In this case, the second trailer is overbraked and can become unstable in an emergency stopping situation. (Volume 1 p 134)

Tire Selection
The cornering properties of the installed tires has a profound influence on the dynamic response of differing doubles combinations to steer input. In general, radial tires are much preferred insofar as they provide a considerably higher level of "stiffness" in development of cornering forces. (Volume 1 p 145)

Steer-Centering Properties of C-train Dollies
Variation in the steer-centering behavior of a C-train dolly can significantly influence dynamic tracking and stability characteristics, especially when long drawbar lengths are employed. When the steer-centering forces are reduced, the dolly wheels steer too readily in dynamic maneuvers such that the rear trailer can exhibit a large lateral overshoot motion in a rapid maneuver and can even tend toward a growing oscillation at high speeds.(Volume 1 p 150)

Reversed Order of Placement of Trailers in Mixed-Length Doubles
Only minor changes in dynamic performance are observed when the shorter trailer in a mixed-length double is placed in the lead instead of the rear position. (Volume 1 p 141)

3.3 B Train Doubles Combinations

The parametric sensitivities of B-type doubles are generically similar to those of other doubles as regards the influence of trailer length, axle loading, partial loads, and suspension selection. The results do show, however, that the B-train is superior in many respects to the A- and C-type doubles such that the strength of these sensitivities is lower. A special investigation of the use of one of the most commonly selected *compensator-type fifth wheels* at the inter-trailer coupling of B-trains showed that this specific component introduces no significant degradation in dynamic performance. Also, the use of a *steerable belly axle* does not significantly degrade the performance of B-trains in the configurations which were examined. (Volume 1 p 156-191)

3.4 A and C Train Triples Combinations

The parametric sensitivities of various triples combinations were seen to be generically the same as those observed with the corresponding A- and C-type doubles configurations. That is, variations in *trailer length, hitch placement, axle loading, centering properties of C-train dollies, and partial loading* tend to influence the performance of triples with the same trends as with doubles. The magnitude of the sensitivities, however, is considerably greater in every case such that the net performance exhibited by the triple is generally much below that of the corresponding double. One promising exception is the high level of dynamic stability of the C-triple when a nearly rigid dolly device is installed. (Volume 1 p 192-209)

4.0 Relative Dynamic Performance Characteristics of Vehicle Configurations

The most significant finding of this study is that there exists a very large range of stability and control performance among the differing truck configurations currently operating in Canada. Many of the differences in performance are seen as implicating higher or lower safety risks. Although it is not generally possible to quantify the magnitude of the safety risks, there is good reason to believe that the probability of involvement in certain kinds of accidents is significantly higher with some types of vehicles than others, when operated under identical conditions.

A set of measures of productivity, coupled with the seven performance measures previously decribed were used to summarize the respective qualities of the vehicles. This evaluation provides a useful means of identifying the strong and weak points in the productivity and performance characteristics of each vehicle. The simple productivity indicators which were used covered only the payload volume and weight capacities of each configuration and do not reflect more subtle operating efficiencies which distinguish one vehicle type from the next. Also, the comparative performance levels do provide a somewhat narrowed view of the properties of each vehicle insofar as they only represent the reference, full load, condition.

Shown in Figure 2 are example profiles representing the %-better or-worse measures of capacity and dynamic performance for two vehicles which occupied rankings near the top and the bottom, respectively, of the overall performance evaluation. That is, the 8-axle B-train configuration exhibits a set of properties which are all as good or better than the reference performance values which were selected. Conversely, the 8-axle A-train triples combination exhibits decidedly poorer performance in a number of the dynamic response categories which were studied. On the other hand, although both of these example vehicles can carry approximately the same payload weight, the triple is clearly advantageous in terms of payload volume. Reference values against which dynamic performance was rated were selected by the researchers using a combination of:

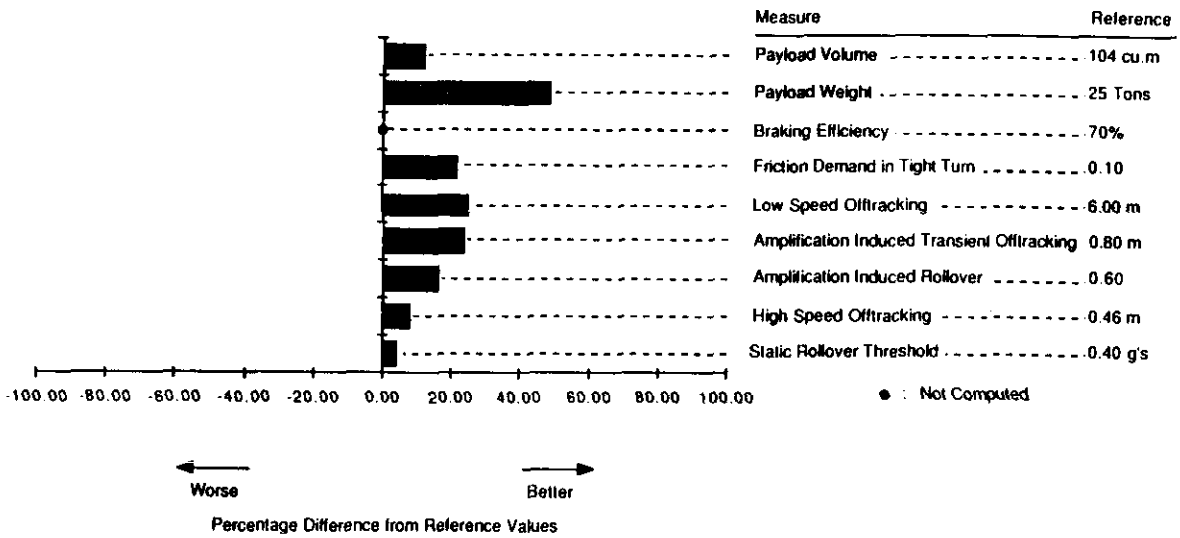
(a) the performance level of the 5-axle tractor semitrailer
(b) a specific value which could be rationalized on the basis of a clear operational constraint
(c) a value which was in the nominal mid-range of performance for truck combinations in Canada.

The reference levels of performance are benchmarks chosen by vehicle dynamics experts on the basis of stability and control properties which would be desirable for combination vehicles using the public highway system. These reference performance levels are not currently used by any jurisdiction as minimum standards which must be complied with. Table 1 provides a summary of this breakdown for the twenty two different vehicle configurations examined in simulation (Volume 1 p 217-238).

The construction of a breakdown such as this involves some judgement as to the relative seriousness of differing performance limitations. And yet, insofar as this project was explicitly designed to assist the formulation of a public policy, it is expected that the categorization will have value for decisionmakers. It must be pointed out, however, that stability and control properties are only part of the traffic-safety picture and safety is certainly only one consideration in the formulation of road-use regulations.

Figure 2: Example Vehicle Performance Profiles

Baseline 8-Axle B-Train



Baseline 8-Axle Triples (A-Train)

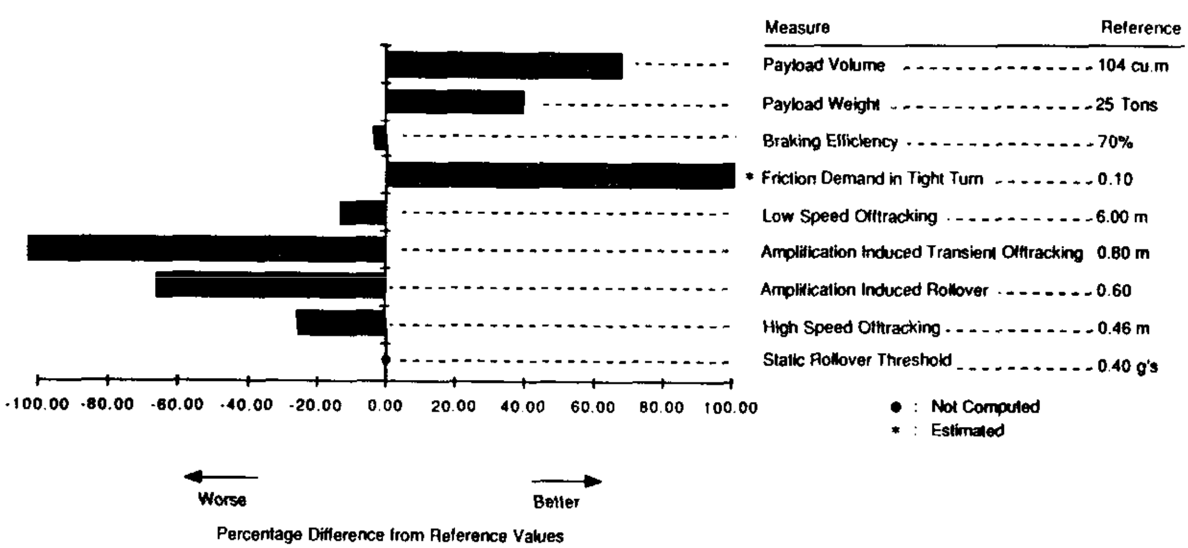


Table 1: Comparison of Vehicle Performance

CONFIGURATION	PAYLOAD		STABILITY AND CONTROL MEASURES				OFFTRACKING MEASURES		
	Volume	Weight	Static Rollover	Dynamic Rollover	Friction Demand	Braking Efficiency	Low Speed	High Speed	Transient High Speed
Reference levels	104 m	25 t	0.4 g	0.60	0.10	70%	6 m	0.46 m	0.80 m
TRACTOR SEMITRAILERS									
Baseline 5 Axle	—	—	○	○	○	○	○	○	○
Close Spread Tridem	—	+	○	○	○	N/A	○	○	○
Wide Spread Tridem	—	+ +	◐	○	●	N/A	○	◐	○
Quad Axle	—	+ +	◐	◐	●	N/A	○	○	○
Belly Axle with Tandem	—	+ +	○	○	●	N/A	○	○	○
A TRAIN DOUBLES									
Baseline 8 Axle	+	+ +	○	●	○	○	○	○	○
7 Axle	+	+ +	◐	●	○	○	○	◐	●
6 Axle	+	+	○	●	○	○	○	◐	◐
Turnpike Doubles	+ +	+ +	○	○	○	○	●	○	○
Rocky Mountain	+ +	+ +	○	◐	○	○	●	◐	○
C TRAIN DOUBLES									
Baseline 8 Axle	+	+ +	○	○	◐	○	○	◐	○
7 Axle	+	+ +	◐	○	○	○	○	◐	◐
6 Axle	+	+	○	○	○	○	○	●	○
Rocky Mountain	+ +	+ +	○	○	○	○	●	●	○
B TRAIN DOUBLES									
Baseline 8 Axle	+	+ +	○	○	○	N/A	○	○	○
7 Axle	+	+ +	○	○	○	○	○	○	○
6 Axle	+	—	○	○	○	○	○	○	○
Belly Axle	+ +	+ +	○	○	○	N/A	○	◐	○
A TRAIN TRIPLES									
Baseline 8 Axle	+ +	+ +	N/A	●	○	◐	◐	●	●
11 Axle	+ +	+ +	N/A	●	○	◐	◐	◐	●
C TRAIN TRIPLES									
Baseline 8 Axle	+ +	+ +	N/A	○	○	◐	◐	●	●
11 Axle	+ +	+ +	N/A	○	◐	◐	○	●	●

LEGENDS:

PAYLOAD MEASURES
- — = Equal to reference
- + = up to 20% better
- + + = More than 20% better

STABILITY, CONTROL & OFFTRACKING MEASURES
- ○ = Meets or exceeds reference performance
- ◐ = Less than 20% below reference performance
- ● = More than 20% below reference performance
- N/A = Performance not available

5.0 Technical Findings: Vehicle Stability

1. The tractor with close-tridem semitrailer provides improved productivity at no significant cost to stability and control performance, relative to the baseline tractor and two-axle semitrailer.

The close-tridem axle group, whether incorporated on the single long semitrailer or the center-group of a B train, introduces improved stability insofar as these axles are characteristically underloaded relative to two axle tandems and insofar as more nearly level loading of freight is permitted (given details concerning load distribution constraints).

It should be noted, however, that the use of tridems on long semitrailers may encourage a more frequent forward-placement of the trailer axle group, on behalf of load distribution. Such practices may exacerbate the occurrence of the rear-underride type of accident and potential "swing-out" motions of the trailer during intersection turning, unless the rear extremity of the trailer is protected. To overcome these problems, it may be prudent to require hardware for preventing rear-underride or to limit the minimum trailer wheelbase when tridem-axle arrays are installed on long semitrailers.

2. The B train doubles combinations is a superior basic configuration for applications which (a) require the higher productivity and maneuverability of multiple trailers, and (b) can tolerate non-interchangeable trailers.

Among the B-doubles, the eight-axle variety, with tridem center-group, offers the greatest productivity advantages while suffering no significant loss in dynamic performance (relative to the five-axle tractor-semitrailer). Recognizing the safety benefits of the reduced exposure which accompanies increased payload capacity plus the high performance, yet simplicity, of this vehicle, the eight-axle B-train is looked upon as the closest to ideal configuration of the overall group of vehicles.

3. The C-doubles combination, with a steerable-axle, dual-drawbar, dolly installed in place of the conventional A-train dolly, offers great improvements in dynamic response characteristics over the A-train, particularly in the range of 8.2 m (27 ft) trailer lengths.

Nevertheless, the ranking of such vehicles would be substantially improved, especially in terms of steady-state and transient high-speed offtracking, if dolly-steering schemes were both improved and closely regulated. At the current juncture, the lack of regulatory control over dolly-steering behavior (except in certain provinces granting special permits), together with the potential for performance degradation due to dolly properties, gives the C-train a somewhat unresolved status.

4. The C-train triples combination, particularly in the eight-axle version, holds promise for the future.

Firstly, the triple with 8.2 m (27 ft) trailers is a particularly productive combination for the transport of low density freight. Secondly, the C-train implementation resolves most of the severe deficiencies in performance exhibited by the A-train triple while retaining the basic features of a general freight transportation system; namely, interchangeable trailers, detachable dollies, and van trailer configurations that can be conveniently loaded from the rear, at conventional loading docks. Nevertheless, in its current implementation, the C-train triple does exhibit a disturbingly high level of transient high-speed offtracking and is capable of oscillatory instabilities if unfavorable dolly steering properties prevail. Resolution of the remaining shortcomings, perhaps together with regulation of the steerable dolly to assure its performance qualities, would render the C-train triples attractive (simply considering productivity and dynamic performance).

5. The tractor and belly axle semitrailer configuration, with the belly axle steerable rather than fixed, exhibits performance only marginally below reference levels.

In this implementation, all of the performance characteristics of the vehicle are as good or better than those with the rigid (non-steerable) belly axle. Additionally, this vehicle is not perceptibly sensitive to the centering properties of the steerable axle.

6. The quad-axle semitrailer, without lift or selfsteering axles, is seen as exhibiting a major performance limitation in the friction demands which it develops during tight turning and in its roll stability characteristics.

Although the friction demand deficiencies can be, and are, overcome in service through the use of lift axles, it was not assumed that the use of lift axles is justified, given the accompanying overloading which occurs. The large payload weight capacity of this vehicle suggests that the roll stability level would be regularly quite low, thus posing the threat of more frequent rollovers.

7. Rocky Mountain doubles exhibit only modest limitations in all performance qualities, relative to the reference values, except in the case of low-speed offtracking performance.

This configuration's dynamic properties would merit a higher rating if the concerns over limitations in roadway geometrics did not apply, such as where more generous provisions are available in the selected road system.

8. The Turnpike Double exhibits high levels of dynamic performance that are tempered only by its inferior offtracking characteristics.

For example, the use of turnpike doubles on turnpike facilities in the U.S., where easy access to breakdown areas is provided at the exits of the turnpike, appears to be a practice which is in harmony with the findings on the total performance characteristics of this vehicle.

9. The use of computer simulation models as tools to predict the dynamic behaviour of heavy articulated vehicles has proven to be a valid, accurate, and cost effective research methodology.

A computer simulation carried out using a close representation of the actual vehicles tested, and the test conditions, showed that there was generally good agreement between test and simulation. While not a strict validation of the computer program, this work showed that the simulation technique would be expected to give acceptable results over the range of vehicle configurations and manoeuvres being studied.

Going beyond the immediate domain of weights and dimensions regulation, certain additional principles and observations deserve note, namely,

1. Increased speed tends to deteriorate the stability and control properties of truck systems in a marked way.

Braking, high speed offtracking, and dynamic stability characteristics all tend to degrade with speed. Thus, speed enforcement with heavy duty trucks is more urgent and any prospect of an increase in the legal speed allowance should be reviewed with special attention to the truck safety part of the picture.

2. For truck combinations which exhibit unusually low levels of roll stability, or which pose more serious consequences from rollover, tight control on the selection of tractor and trailer suspensions should be considered.

A global means of controlling the roll stability of the overall truck system could be provided through a tilt-table-based performance requirement.

6.0 Recommendations

Concerning the study of vehicle dynamics, recommendations are made for further research work on various issues concerning vehicle response and the safety significance thereof. Also there is a need to obtain improved understanding on certain aspects of tire, suspension, and dolly performance in order to generally upgrade truck safety.

Among these considerations, the key item that appears to stand in the way of a fully rational approach toward regulating multiple trailer combinations for general freight transportation concerns the alternative to the conventional A Train.

1. A vigorous development of dolly hardware for replacing the conventional dollies used in A Train doubles and triples should be encouraged, if the C Train configuration is to be promoted in interprovincial transportation.

2. The use of the most stable and controllable basic types of truck configuration should be encouraged, with preference given in this order:

1) Tractor semitrailers and B-doubles
2) C-doubles (as dolly technology supports)
3) A-doubles

PART 2: PAVEMENT RESPONSE TO HEAVY VEHICLES

1.0 Introduction

One of the major thrusts of the Vehicle Weights and Dimensions Study is an investigation of issues related to the impact of heavy vehicles on pavement structures. The wide range of pavement designs, constructions, geography and climate in twelve jurisdictions across Canada dictated the research needs in this field.

Over the years the AASHO (American Association of State Highway Officials) Road Test results have constituted the principal basis for pavement design in most highway agencies in Canada. However, changes in axle loads, suspension systems, speeds and gross vehicle weights have moved the utility of data from the AASHO Road Test from the realm of interpolation to extrapolation. Pavement impacts attributable to heavy vehicles are critical in assessing transportation costs and include consideration of the effects of specific suspensions or vehicle configurations where differences are clearly apparent. New design techniques, and the use of new construction materials has resulted in several new types of pavement structures whose response characteristics merit further investigation.

2.0 Summary of Research Procedures

2.1 Pavement Test Site Investigations

The objective of this program was to determine the relative damaging effects of a variety of truck axle loading conditions on different pavement structures used on the interprovincial highway system. Fourteen test sites were instrumented to measure pavement strain and deflection under vehicle loading. The site selection was made by a committee of pavement engineers from each jurisdiction. Each site was considered representative of the designs of pavements which will be used in the 1990's in the five geographic regions of Canada and each reflected a unique construction and design practice using local materials (Table 1).

A test loading program was carried out at each site to determine the relative potential damaging effects (in terms of Load Equivalency Factors) of:

— single axle (single tires) loadings from 3500 kg to 5500 kg
— single axle (dual tires) loadings from 9000 kg to 11000 kg
— tandem axle loadings from 5500 kg to 22000 kg
— tandem axle spacings at 1.2 m, 1.5 m and 1.8 m
— triaxle loadings from 20000 kg to 32000 kg
— triaxle spacings at 2.4 m and 3.7 m
— tandem axle plus belly axle configuration from 25000 kg to 32000 kg

The effect of vehicle speed on pavement response was also examined for each loading condition.

Technical Reports Volumes 8 and 9 prepared by the Alberta Research Council contained detailed summaries of the test data collected at each site and analyses of the Load Equivalency Factors calculated with this data for each test loading condition. The discussion and findings which follow are based on overall average test results and consistently supported trends.

2.2 Investigations of Truck Suspension Characteristics

The primary objective of this program was to examine the ability of different heavy vehicle suspensions types to share loading equally between all axles in a group under the variety of conditions encountered in trucking operations. The results of these investigations are documented in Technical Report Volume 11.

An axle instrumentation procedure was developed by the National Research Council, based on the installation of strain gauges and accelerometers. This technique provides a continuous profile of the wheel forces being transmitted to the pavement by each axle of the vehicle. The instrumentation was calibrated both statically and dynamically using static scales and an electro-hydraulic shaker installation.

Two different tandem axle tractor drive suspensions and three different trailer suspensions were fitted with instrumented axles and loading profile data collected as the vehicle was driven over a standard highway course which included varying pavement conditions from smooth to rough. Pavement roughness was documented using a Mays Meter and converted to a Riding Comfort Rating using a conversion scale provided by the Ontario Ministry of Transportation and Communications. Other issues examined in this study included:

— Dynamic wheel loading as functions of suspension type and axle spacing (suspension spread)
— Dynamic wheel loading as a function of the number of axles in a suspension group
— Axle to axle dynamics for load sharing suspensions
— Load transfer due to braking
— The load carrying characteristics of an air suspended lift axle
— Impact loads associated with grade level railway crossings

Table 2: Pavement Test Sites: Summary Description

Site/Province	Surfacing mm	Base mm	Subbase mm	Subgrade	AADT (% trucks)
Atlantic Region					
1 New Brunswick	225	76	460	silty sand	10,390 (8)
2 Nova Scotia	160	275	200	gravel/clay	5,300 (17)
Quebec Region					
3a Quebec	130	375	450	granitic gravel	
3b Quebec	135	200	625	granitic gravel	
4 Quebec	56	150	450	clay	
5 Quebec	56	200	550	clay	
Ontario Region					
6 Ontario	110	150	350	silty sand	7,800 (12.5)
7 Ontario	170	200	250	sandy loam	8,400 (20)
8 Ontario	190	300	90+/-	clay loam	4,950 (6)
Prairie Region					
9 Alberta	136	167		clay	1,700 (11)
10 Alberta	136	250		clay	1,700 (11)
Pacific Region					
11 British Cloumbia	75	145 BTB/160	580	shot rock/peat/sand	690 (1)
12 British Columbia	85	155 BTB/150	625	silty/sand	1,035 (0.3)
13 British Columbia	100	545	450	clay	

— Dynamic bridge loading
— Tire scuffing in turns as a function of axle spread
— Suspension load equalization characteristics due to variations in trailer pitch angle

3.0 Pavement Test Site Investigations: Summary of Findings

3.1 Introduction

It is evident from the test data and conclusions that many factors affect the response of flexible pavement structures to truck axle loads. Not all sites exhibited the same response, in terms of strain and deflection, to the standard test loading configurations. In many instances the potential destructive effect of an axle loading, expressed in terms of a calculated Load Equivalency Factor, exhibited a wide variation between strain and deflection based results.

To achieve the goal of the Vehicle Weights and Dimensions Study, improved uniformity in interprovincial weight and dimension regulations, a firm foundation of general conclusions and consistently supported trends is essential. With this in mind, the results of the pavement test program have been viewed in aggregate and conclusions drawn as described in the following sections

It is possible to find instances where test results at a particular site or under particular loading conditions conflict with the conclusions as stated. However, the principles laid out in the following sections are supported by the majority of the test results, as well as past research findings in Canada and elsewhere.

3.2 General Conclusions

1. Based on Load Equivalency Factors derived from both pavement strain and deflection data, it is evident that the potential damaging effect of a particular axle configuration at a given load varies greatly between the fourteen sites tested in the study. This site to site variation indicates that it would be impossible to establish a standard set of Load Equivalency Factors for different axle configurations and loads which could be applied uniformly to all flexible pavement structures used in Canada.(Volume 8)

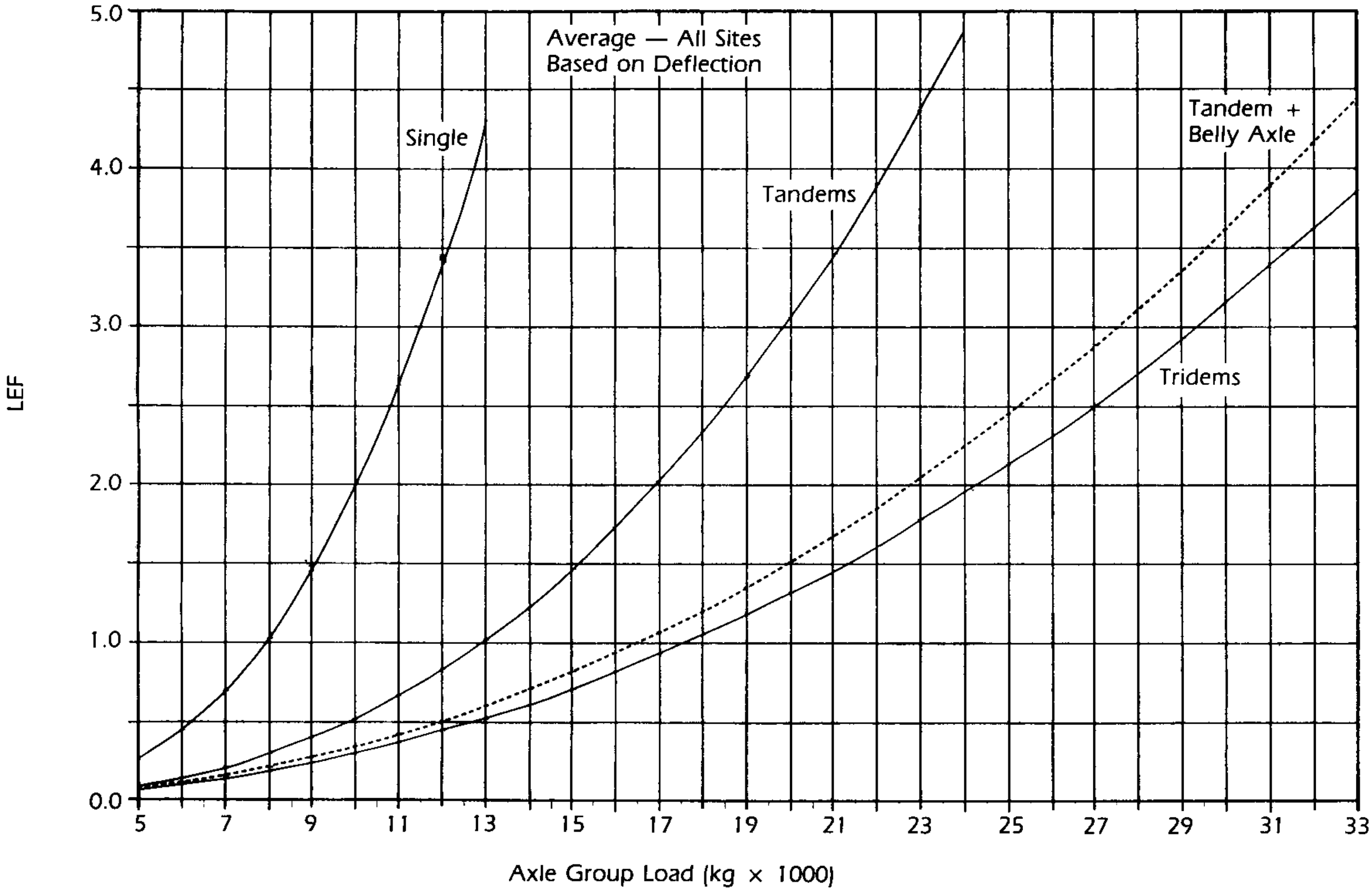
The overall average Load Equivalency Factors for all configurations tested (based on deflections) are summarized in Figure 3. This plot serves to illustrate trends and general conclusions observed at all test sites. The reader is cautioned that the Load Equivalency Factors plotted in Figure 5 are provided solely to illustrate trends in the generally observed response of the pavement structures tested. There are distinct limitations on the applicability of this data to other purposes or evaluations.

2. While wide variations in actual Load Equivalency Factors were observed between sites, the relative damaging effects of single axles, tandem axles and tridems at comparable load levels exhibited consistency throughout the program. Based on Load Equivalency Factors derived from both strain and deflection data, the following observations can be made:

> ***In the 8000 to 12000 kg range, single axles (dual tires) are, on average, approximately four times as destructive as tandem axle arrangements.***
>
> ***In the 20000 to 24000 kg range, tandem axles are, on average, approximately two and one half times as destructive as tridem arrangements.***

3. In comparison with the commonly used Load Equivalency Factors published in the "AASHO Interim Guide for Design of Pavement Structures" (1972 and 1986), the following observations are made:

Figure 3: Load Equivalency Factors



a. Single Axle: At axle loads tested in the 8000 to 12000 kg range, the test data correlates closely with the AASHO Load Equivalency Factors.

b. Tandem Axles: At axle group loads tested in the 5000 to 15000 kg range, the calculated Load Equivalency Factors were higher than those recommended in the AASHO Guide. As the axle group load approached 20000 kg, the Load Equivalency Factors calculated with the test data fell into agreement with those recommended by AASHO.

The preceding observations are based on the data plotted in Figure 4.

The AASHO Load Equivalency Factors are based on the experience gained in the AASHO Road Test which entailed monitoring pavement performance under known loading conditions. The Load Equivalency Factors determined in the Weights and Dimensions Study are based on measured pavement response to loads, using an accepted relationship between response and long term performance.

3.3 OBSERVATIONS

Using overall average Load Equivalency Factors derived for all test axle loads and configurations at all sites, ***based on both strain and deflection data*** the following conclusions can be drawn:

3.3.1 SINGLE AXLES (Single Tires)

1. While limited test data was collected on single axles fitted with single tires, the steering axle of a tractor loaded in the 3500 to 5500 kg range would appear to have the same destructive effect as a single axle with dual tires at twice the loading (ie. 7000 to 11000 kg).

3.3.2 SINGLE AXLE (Dual Tires)

1. An increase of 1000 kg on a single axle with dual tires in the 8000 to 12000 kg range would, on average, increase the potential damaging effect approximately 25% to 30%.

Example:

Increasing the load on a single axle from 8000 to 12000 kg would increase the potential damaging effect approximately 150%.

3.3.3 TANDEM AXLES

1. An increase of 1000 kg on a tandem axle group in the 16000 kg to 24000 kg range would, on average, increase the potential damaging effect approximately 10% to 15%.

Examples:

a. Increasing a tandem axle group loading from 16000 kg to 20000 kg would, on average, increase the potential damaging effect approximately 75%.

b. Increasing a tandem axle group loading from 20000 kg to 24000 kg would, on average, increase the potential damaging effect approximately 50%.

2. Under the same range of loads, the potential damaging effects of tandem axles spaced at 1.2 m (48"), 1.5 m (60") and 1.8 m (72") appears to be approximately the same. For particular sites tested in the program, reductions in damaging effect were observed with increasing axle spacing, but in general it was not possible to establish a correlation between axle spread (within the range tested) and damaging effect.

Figure 4: Comparison of AASHO and RTAC Equivalencies

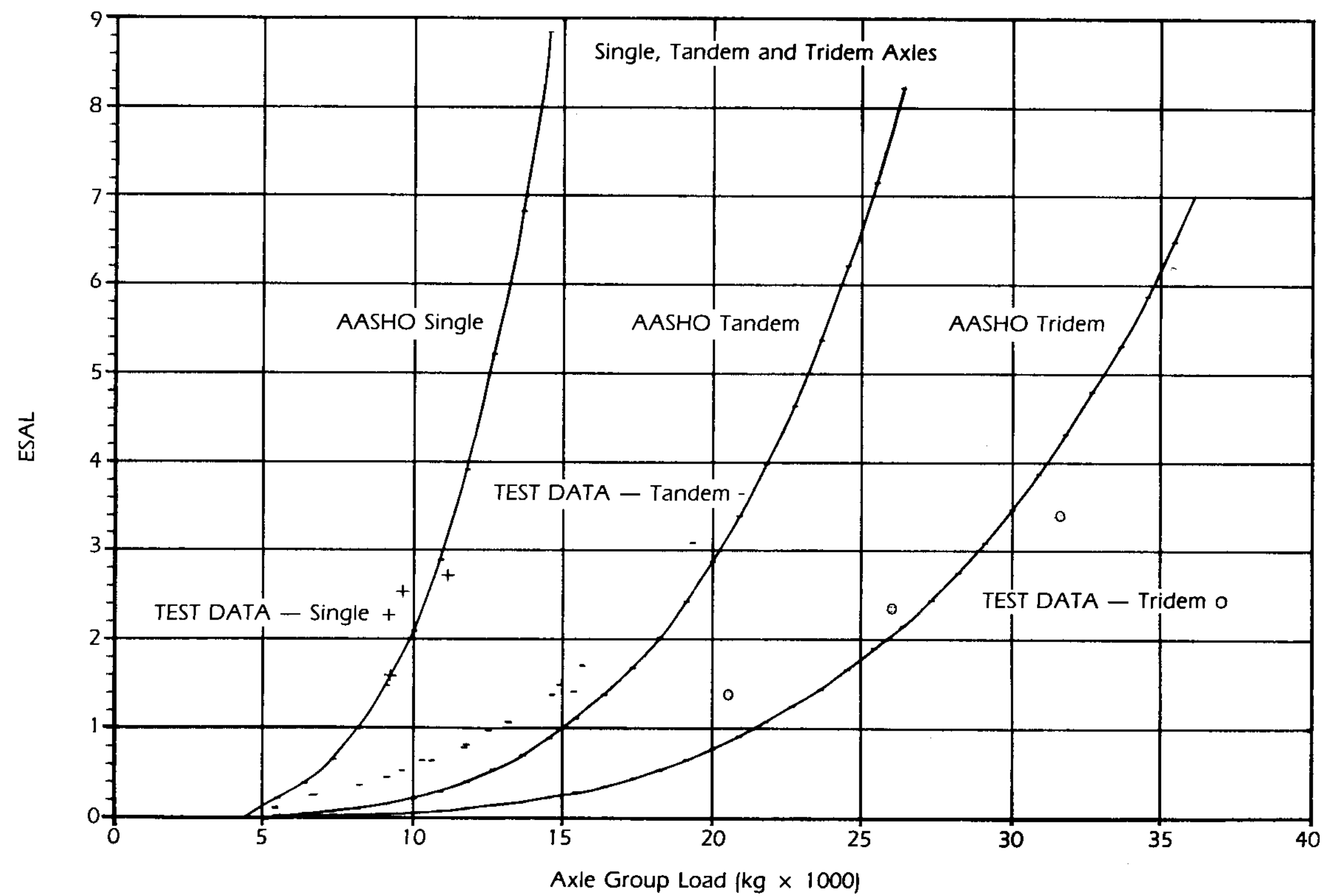
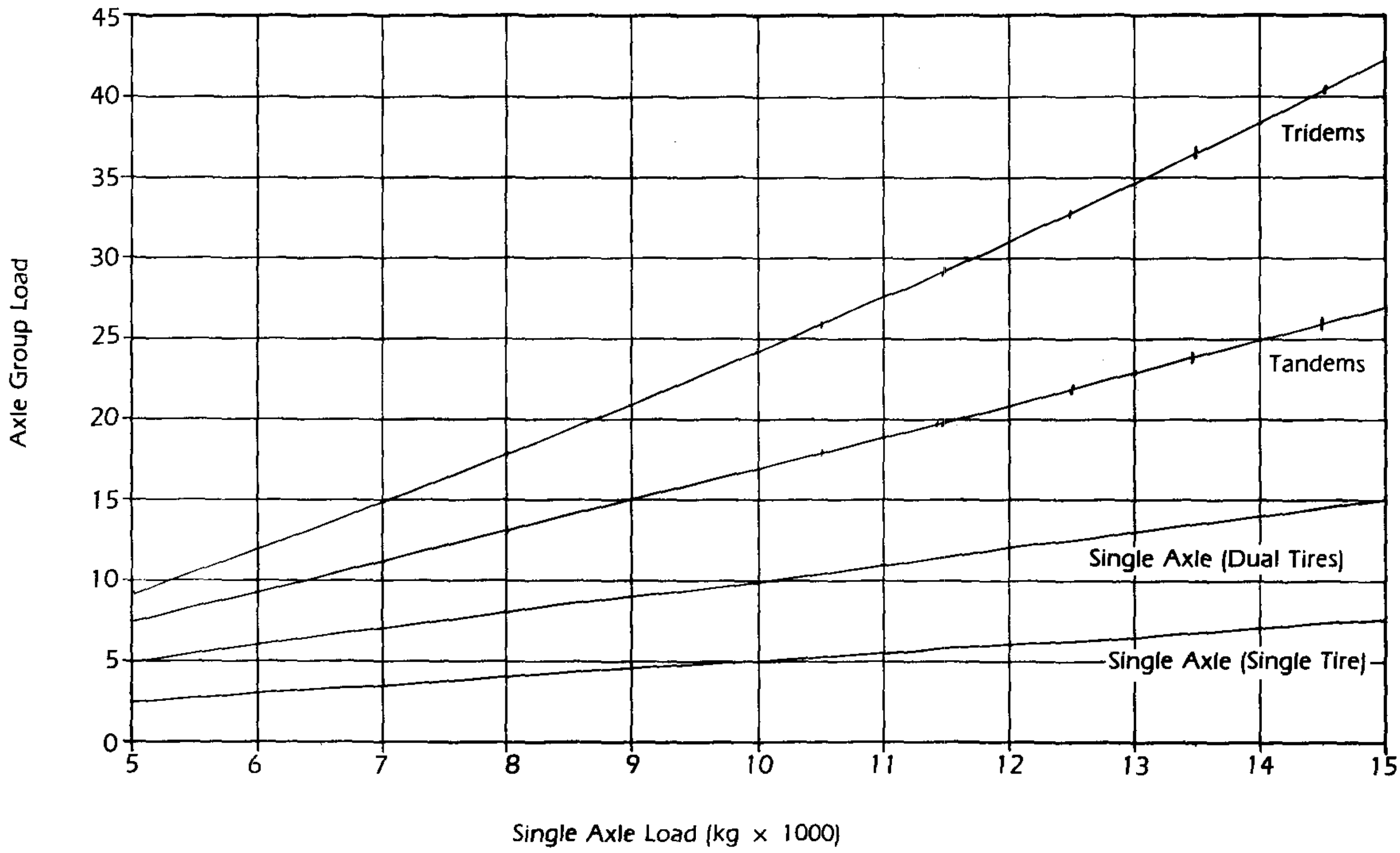


Figure 5: Axle Group Load for Equivalent Damaging Effect as Single Axle



3.3.4 TRIDEMS

1. An increase of 1000 kg on a tridem axle group load in the 20000 kg to 32000 kg range would, on average, increase the potential damaging effect approximately 6% to 10%.

Examples:

a. Increasing a tridem axle group load from 20000 kg to 25000 kg would, on average, increase the potential damaging effect approximately 50%.

b. Increasing a tridem axle group load from 25000 kg to 32000 kg would, on average , increase the potential damaging effect approximately 60%.

2. At axle group loads in the 20000 kg to 32000 kg range, three axles equally spaced 1.2 m (48") apart appear to be equal in potential damaging effect to three axles equally spaced 1.8 m (72") apart. As was observed with tandem axle groups, there were particular pavement structures which exhibited consistently lower responses to the wider spread tridem, but in general, a correlation between axle spacing and potential damaging effect could not be drawn (for the range of spacing tested).

3.3.5 TANDEM AXLE GROUP WITH BELLY AXLE

1. In the axle group load range from 25000 kg to 32000 kg, the 4.9 m (192") overall spread, tandem axle group (1.8 m spacing) plus belly axle (widespread single axle) configuration appears to be approximately 15% more destructive than an equally loaded, symmetrical tridem with a 3.7 m (144") overall spread.

3.3.6 VEHICLE SPEED

1. Maximum pavement strains and deflections occurred in all cases at the slowest vehicle speed tested.

2. At speeds above 15 kph, significant (10% to 15%) reductions in peak pavement strains and deflections were observed. However, the adopted measure of relative potential damaging effect, Load Equivalency Factor, is independent of vehicle speed. This measure describes the damaging effect of an axle load or configuration relative to an 8180 kg single axle with dual tires. Consequently, while actual pavement response increases with decreasing vehicle speed, the ratio of responses remains relatively constant.

3.3.7 PAVEMENT TEMPERATURE

1. Pavement strain and deflection increases with increasing pavement temperature, however as with vehicle speed, the Load Equivalency Factor calculation is independent of pavement temperature.

4.0 Truck Suspension Characteristics Investigations: Summary of Findings

4.1 Introduction

The study of heavy truck suspension characteristics is highly complex and difficult to control experimentally. Technical Report Volume 11 documents in detail the findings of the National Research Council's examinations of two different tractor suspensions and three different trailer suspensions. The authors caution that the experimental results documented therein are highly dependent on the actual hardware which was tested. All equipment examined in the program was provided by the manufacturer in new condition and was properly installed and maintained. Equipment which has been in service for extended periods, new designs or design modifications, variations in installation procedure and maintenance practices could affect these results significantly.

However, while the actual test data is hardware dependent and does not provide generally applicable findings, the range of performance exhibited by equipment examined in this study is of interest and provides a valid basis from which the conclusions which follow can be drawn.

4.2 General Discussion

Traditionally the treatment of truck axle loadings in pavement design has not explicitly taken into account the impact or dynamic wheel loads which would be expected when a suspended axle travels at speed over a moderately rough road or bumps. While the subject of axle dynamics has begun to receive a good deal of research attention in recent years, it is evident the additional destructive effect which should be attributed to dynamic loading is very difficult to quantify. Without question, dynamic loading of pavement structures is destructive and it might be presumed that the higher dynamic loadings which have accompanied higher allowable static axle loads may have contributed to the more rapid degradation of pavement structures experienced in recent years.

However, dynamic loading of pavement structures by heavy vehicles is certainly not a new phenomenon which has been introduced by the vehicles in use today. The AASHO Road Test was influenced by axle dynamics in the monitoring of pavement performance. The test vehicles involved in the program were using some of the most dynamically active truck suspensions available while driving over sections with degrading surfaces. It is not, however, possible to separate the damaging effects which could be attributed to the dynamic component of the loading history from the relationships developed linking number of axle passes of known static load with pavement performance.

4.3 Observations

4.3.1 Load Equalization Characteristics of Multiple Axle Bogies

1. All types of suspensions examined are capable of providing good static equalization between axles if properly installed and adjusted for the application being served.

2. Variations in trailer pitch angle (operationally a result of different tractor fifth wheel heights) affect the load equalization capability of different suspensions to differing degrees. The walking beam suspensions and the air suspensions were relatively insensitive (3%-6% imbalance) to changes in trailer pitch, while the spring suspension showed a 14%-17% load imbalance between axles at the maximum angle tested.

3. In the dynamic wheel load testing, both axles in tandem groups exhibited approximately the same dynamic loading coefficients, regardless of the suspension type.

4.3.2 The Load Carrying Characteristics of the Lift Axle

1. The ability of the air suspended lift axle to carry its share of the vehicle load over various conditions of road roughness and bumps was found to be very good. This characteristic is dependent on proper installation and maintenance of the axle and the air pressure regulator.

4.3.3 Dynamic Wheel Loading as a Function of Vehicle Speed

1. Dynamic wheel loading exhibited strong relationships with pavement roughness and vehicle speed. Over rough surfaces the dynamic wheel loading increased exponentially with increasing speed, typically rising most significantly when vehicle speed increased from 60 kph to 80 kph.

4.3.4 Dynamic Wheel Loading as a Function of Suspension Type

1. Under smooth road conditions (RCR > 8), all five types of suspensions tested exhibited relatively low levels of dynamic wheel loads, generally in the range from 6% to 12% of static load.

2. Under rougher road conditions (RCR = 5), the dynamic loading coefficient (DLC) increased much more drastically for some types of suspensions than others. At 80 kph, the air bag suspensions exhibited dynamic loading coefficients of 16%, the spring suspension DLC rose to 24%, while at the extreme, the rubber spring walking beam DLC increased to 39%.

4.3.5 Dynamic Wheel Loading as a Function of Axle Spread

1. Dynamic wheel loading appears to be insensitive to changes in axle spread.

4.3.6 Interaxle Load Transfer Due to Braking

1. Only the spring suspension exhibited significant load transfer between axles during braking, in the order of 15%-20% from front to back in the tandem group.

5.0 Technical Findings: Pavement Response

Influence of Pavement Structure:

1. The destructive effect of a particular truck axle load or configuration varies greatly between flexible pavement structures of differing designs.

2. The *relative* destructive effects of different truck axle loads or configurations remains relatively constant with differing flexible pavement structures.

Single Axles:

3. Single axles (dual tires) are, on average, four times as destructive as tandem axles at the same group loading.

Tandem and Tridem Axle Groups:

4. Tandem axles are, on average, two and one half times as destructive as tridems at the same group loading.

5. Changes in interaxle spacing of tandem and tridem groups, within the ranges tested, appear to have little or no influence on the destructive effect of the group or on the magnitude of dynamic wheel loadings.

> Commentary:
> Flexible pavement structures are less sensitive to variations in loading on tandem and tridem axle groups than on single axles. Symetrically spaced axles within the range of spacings tested provided a degree of deflection and strain relief to the pavement due to the overlapping response effects of each axle in the group. Consequently multiple axle groups with interaxle spacings of less than about 4 to 5 meters will exhibit less damaging effect than a single axle at the same loading or a series of similarly loaded axles spaced sufficiently far apart to be acting independently.

Air Suspended Lift Axles or Belly Axles:

6. A properly installed and maintained air suspended lift (belly) axle will carry a predetermined loading without significant deviation under all typical operating conditions.

7. A tandem axle plus belly axle configuration appears to be in the order of 15% more destructive than a symmetrically spaced, load equalized tridem.

Dynamic Axle Loadings:

8. Dynamic wheel loads are significant in normal highway operation and are highly dependent on vehicle speed, pavement roughness and suspension type.

9. Under the worst conditions (ie. rough road, highway speed, lightly damped suspension), the actual dynamic wheel loadings can be in the order of 140% of static loads.

10. Dynamic wheel loadings may contribute significantly to pavement degradation.

Load Equalization in Multiple Axle Groups:

11. All of the tractor and trailer suspensions tested can provide static and dynamic load equalization if properly installed, maintained and adjusted for the application being served.

12. Multiple axles in load sharing groups are less destructive than the same number of independently suspended axles collectively loaded to the same level.

Commentary:
The total distress experienced by pavement structures under loading is proportional to the maximum strain or deflection induced by any one of the load carrying axles. Consequently, two or three equally loaded axles will cause less pavement distress than two or three axles which have the same total loading but uneven load distribution.

6.0 Recommendations

The research findings show that two or three axle groups with proper load equalization between axles are less destructive than two or three axles collectively loaded to the same level. Consequently, enforcing load equalization between axles in tandem and tridem groups would ensure that the destructive effects of the axle group are not unnecessarily increased, a consideration which is also reinforced by the potential damaging effects of axle dynamic loadings. It is therefore recommended that:

1. Enforcement of allowable axle group loads for multiple axle bogies should be carried out with single axle weigh scales to ensure proper load equalization between axles.

PART 3: CANDIDATE REGULATORY PRINCIPLES

1.0 Candidate Regulatory Principles: Vehicle Stability and Control

In order to assist those who will rationalize the stability and control issues within future weights and dimensions policies in Canada, certain statements of principle are provided in this section. These principles, firstly, take it to be axiomatic that traffic safety will be promoted by weights and dimensions regulations which reflect the realities of vehicle stability and control behavior. Of course, such regulations must also be designed to allow the trucking industry to do its job with a high degree of productivity and efficiency. Nevertheless, to the degree that the dynamic qualities of vehicles can be enhanced while satisfying the other practicalities, the long term interests of truck transportation and public safety are assumed to benefit from more enlightened weights and dimensions constraints.

It is believed that the research conducted here, together with the general state of knowledge, support the contention that vehicle control and traffic safety will be enhanced when:

1. Trailer lengths are increased within the constraints of:

low speed offtracking considerations at intersections (generally to be kept within a net offtracking of 6 m (20 ft) while negotiating a 90 degree turn of 11 m (36 ft) outside radius.)

"swing-out" considerations (striving to keep the ratio, A/L, less than a value of approximately 1.5, where (A) is the distance from the trailer kingpin to the rearmost point on the trailer and (L) is the effective wheelbase of the trailer.)

2. Tractor wheelbase is increased within the constraints of:

both low speed offtracking and minimum turning circle considerations (recognizing that the tractor's contribution to low speed offtracking is a significant portion of the total for typical tractor semitrailers.)

3. The spread across a group of axles on a semitrailer is minimized

such that the value of "friction demand" is kept within approximately 0.10 in order to handle wintertime driving conditions. One wide-spread layout that does not pose the friction demand problem, of course, is the case of a steerable belly axle. The research does not suggest that such configurations should be discouraged.

4. The pintle overhang dimension is minimized in all A and C Train configurations.

5. The length of the drawbar on C Train dollies is minimized.

It may result that minimization of both the drawbar length and the pintle overhang dimension is in opposition to bridge formula considerations which tend to promote a larger spread between axles, for hauling heavier loads.

6. Axle width is increased.

In particular, there is a substantial improvement in stability characteristics to be gained if tractor axles were to be widened to 2.59 m (102 inches). More generally, it should be recognized that any future increase in width allowance should be accompanied with the requirement that the greater width be incorporated also as an outside width across the tires and not simply through widening of the freight bed alone.

7. Overall height is kept tightly limited.

Recognizing that increased height allowance results in elevation of the center of gravity which strongly degrades stability and control properties. In fact, since greater height would only be desired by those operations which currently load to the existing full height allowance, additional height provision will cause the degradation of roll stability in the trucking operations which are already at the bottom of the stability spectrum.

8. The load allowed on individual axles is kept tightly limited.

Of course, since trucks are used to carry payloads, a general attitude of load minimization is ludicrous. Nevertheless, when increased loads are considered, it should be recognized that higher loading on individual axles generally implies degraded stability and control properties with contemporary equipment. Thus, for example, a tridem axle array on a semitrailer is preferable, from a dynamics point of view, to a tandem axle carrying the same load.

9. The ratio of payload weight to bed area is kept tightly limited.

It should be recognized that increased load allowances, while keeping length and width dimensions fixed, results in elevation of the payload center of gravity which again provides a significant mechanism for degrading stability and control.

2.0 Candidate Regulatory Principles: Pavement Response

1. Single axle allowable loads and tolerances should be closely controlled and enforced because of the extreme sensitivity of pavement structures to small changes in load level.

Commentary:
For single axles loaded in the 8000 kg to 12000 kg range, a 10% increase in axle load increases the destructive effect 20% to 25%. Recognizing that dynamic wheel loading can amount to an additional 5% to 40% of static loading, the destructive potential of single axles is very significant.

2. If tolerances on maximum allowable axle or axle group loadings are to be used in regulations, the potential destructive effects of percentage or discrete load increments should be borne in mind for differing axle configurations.

Commentary:
Within the load ranges tested in the program, 1000 kg increases on tandem or tridem axles groups increased the detructive effect 15% and 10% respectively. Similar increases on single axle loads increases the destructive effect approximately 25%. If axle or axle group loadings were increased 10%, the increase in destructive potential would increase 25% to 30% for all three configurations.

3. From the standpoint of potential pavement damage, axles which can be lifted by the vehicle operator are undesirable.

Commentary:
The research showed that air suspended lift axles can carry a predetermined loading without significant deviation, in normal highway operations. However, these axles must be lifted to enable the vehicle to negotiate tight turns, generally at slow speeds. The pavement structure is then subjected to increased loading on the remaining axles during a slow speed turn, when the pavement response is greatest. Replacing lift axles with non lifting, self steering axles would provide an equivalent payload opportunity while reducing the potential for overload condition.