A discussion of performance standards for configuration of heavy trucks

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Canada recently placed limits on configuration, loads and dimensions of heavy trucks to ensure they met objective performance standards for stability and turning within the space provided by the highway system. This is now accepted as a rational basis for development of truck weight and dimension regulations. The paper discusses this approach to setting truck performance standards, and how it might be used for regulating trucks. It identifies how performance standards relate to truck and highway factors. It discusses probabilistic performance assessment of truck safety in specific highway conditions as a possible future development.

1/ INTRODUCTION

The province of Ontario introduced heavy truck axle and gross weight regulation based upon the Ontario Bridge Formula (OBF) in 1971 [1], at a level considerably above then-current loads. An ongoing national effort began in 1972 to determine whether other provinces could also increase their loads. A bridge study, completed in 1978, showed that the apparently diverse truck weight and dimension regulations of most other jurisdictions were generally quite well represented by the OBF [2,3]. Substantial increases in allowable loads followed a program of bridge improvements. Most jurisdictions still retained tight control of truck configuration, because it was evident even then that regulation by overall dimensions and the OBF in Ontario promoted truck configurations that were undesirable both as vehicles and in terms of road and bridge loading [4].

The provinces agreed there would be no further increase in loads without study of the safety implications of the types of truck that might carry those loads. This second phase of the Vehicle Weights and Dimensions Study, completed in 1986, examined the stability and control characteristics of the principal heavy truck configurations used in interprovincial trucking, and the load equivalency of various axle arrangements [5]. The stability and control study introduced seven measures to rank the dynamic performance of the various truck configurations [6]. The concept of performance measures, and values proposed, were accepted as the basis of regulation [5], which culminated in a national Memorandum of Understanding on Vehicle Weights and Dimensions [7]. The concept has since been extended and more widely used as a basis for evaluation of the characteristics of heavy vehicles, for both study and regulatory policy purposes [8,9,10].

Heavy truck performance clearly has implications and relationships far beyond the field of vehicle dynamics. This paper therefore attempts to define the concept of performance measures a little more rigorously, extends it a little, and identifies a wide range of truck and highway factors that need to be considered in setting limits for performance measures. It then suggests a possible future approach to assessment of the truck population in the highway environment.

2/ DEFINITION OF PERFORMANCE MEASURES AND PERFORMANCE STANDARDS

This section suggests the following definitions related to evaluation of heavy vehicle performance, beyond that developed during the Weights and Dimensions Study [6] :

Truck manoeuvre means any action that a truck might be required to perform.

Performance measure means an objective quantity used to evaluate the performance of a truck on the highway system that is derived by a specified method of analysis from a specified truck manoeuvre.

Performance standard means a numerical limit assigned to a performance measure.

There is an important difference between the performance measure and the performance standard. The performance measure is an abstract quantity, simply a vehicle response that varies continuously as the vehicle is driven along a road. The value of a performance measure must be derived by a specified method of analysis from the continuous response to a specified truck manoeuvre. The manoeuvre may be conducted by means of computer simulation, or in a full-scale field test. When the truck manoeuvre is specified, it is also necessary to specify the method of analysis. The performance standard is a limiting value assigned to a performance measure, usually on the basis of safety or highway capacity, that serves as a boundary between acceptable performance and unacceptable performance.

If any one of the performance measure, truck manoeuvre or method of analysis is changed, then the assigned value of performance standard is inappropriate, and a value appropriate to the new condition must be developed.

The truck manoeuvre used as the basis for a performance standard should represent a manoeuvre that a truck is called upon to perform on the highway.

The manoeuvre used for these purposes will usually be idealized in some way. It needs to be structured so that it produces a significant response of the desired performance measure, and it can be performed cleanly, reliably, and, for tests, safely. This usually means that the manoeuvre is artificial, it is not what a driver would necessarily do on the highway. Nevertheless, such a manoeuvre is acceptable as long as it excites the desired performance measures and allows them to be determined so that, for instance, trucks can reliably be ranked against each other or compared with an absolute performance standard.

A performance standard should be related to the actual space available on the highway. However, the truck manoeuvre used as the basis for a performance measure may, for example, consume more or less space than is available on a highway designed to normal geometric standards. When the performance standard is set, it should be factored to take account of this difference.

3/ USES OF PERFORMANCE STANDARDS

3.1/ Regulation

Truck configuration could (in theory) be regulated entirely by performance standards, leaving designers free to configure trucks to meet the operational requirements. While this might foster innovation for productivity, it seems to have three major practical limitations in the North American environment where there are no type certification procedures for components and vehicles.

The first arises if the set of performance standards is incomplete. An example of an incomplete set of performance standards is Ontario's current system of regulation, based only upon axle and gross weight limits and certain dimensions. This system appears to control truck weights and dimensions as far as roadway and bridge loads are concerned. In fact, a lack of controls on equipment has led to the widespread use of liftable axles, and creative configuration for maximum allowable gross weight has resulted in trucks that fail not only many of the performance standards that form the basis of Canada's Memorandum of Understanding, but even the axle and bridge load limits too [4,8]. If a performance-based regulatory system would be tried, then a designers objective might become development of concepts or devices that were not defined, hence not prevented by that system. Once outside the rules, there is no mechanism to curb innovation. Of course, innovation is healthy and should be encouraged. However, the thrust of innovation in this environment would be directed to producing trucks outside the rules, and over a period of years, there would grow up a large group of trucks outside those rules. It appears necessary that any set of performance standards be complete, and have associated with them sufficient controls on equipment, that creative designers cannot achieve goals outside the objectives of the regulation. By complete, it means that all characteristics of the truck are constrained by the system of performance requirements.

The second is simply that at this time, industry is not in a position to assess the performance of trucks. This may be only a passing difficulty, which will be overcome as use of computers in design increases, and the necessary software becomes available.

Finally, truck configurations would become more diverse, and on-highway inspection staff would have no way of assessing whether a particular truck meets or fails a particular performance standard.

The conclusion is that regulation by performance measures would neither control truck configuration, nor allow them to be evaluated. Performance standards remain an invaluable means of developing regulations in the design specification format used by Canada's Memorandum of Understanding. This sets direct configuration rules that ensure that all trucks meet all the performance standards [7]. This may be unduly conservative for many trucks, and may inhibit the maximum of productivity, but it provides a consistency and simplicity that seems appropriate to the industry at this time.

3.2/ Permits

It has long been the practice for special permits for indivisible over-dimensional or over-weight loads to be based on performance standards set for roadway geometrics or roadway and bridge strength. Some jurisdictions operate special permit programs that allow trucks to operate beyond the legal dimension or weight limits, usually for economic development reasons, and often with strict commodity, route and operating restrictions. There may be good reason to base conditions of this type of permit on performance standards. The vehicles may serve as a means to demonstrate or evaluate standards and equipment. In addition, some vehicles may not be able to meet all performance standards, so it may be necessary to impose additional operating restrictions, such as speed or route limitations. Special permits are a privilege, usually conferring significant benefit to their holders, so the issuing agency can usually retain fairly strong control over permit holders as it retains the right to cancel the permit at any time.

4/ PERFORMANCE STANDARDS

Since a truck operates on the highway system, a logical starting point is to define the various manoeuvres it may be called upon to perform, then to develop performance standards relevant to those manoeuvres. The following manoeuvres are identified :

1/ Acceleration from a stopped condition;
2/ Driving on a straight level road;
3/ Driving on a grade;
4/ Low-speed turn;
5/ High-speed turn;
6/ High-speed obstacle avoidance; and
7/ Braking.

Performance standards should be set by considerations of safety and capacity of the highway system, based upon limiting conditions associated with each manoeuvre. Since the truck must perform within the constraints of the highway system, there will be a feedback relationship between truck and highway characteristics, as shown in Figure 1. It is difficult to set out all these relationships, as they are very numerous and closely inter-related. What follows is necessarily incomplete.

Table 1 identifies performance measures associated with each of the above manoeuvres, then extends this to identify truck and highway factors that may affect the magnitude or constrain the range of that performance measure. There may be more than one performance measure for each manoeuvre, and there are usually a number of truck and highway factors that are important. The same truck or highway factor may occur in different places. Factors like "design standard" and "signing policy" are included as separate items, as it appears that these are not always the same thing, so both would need to be considered. Table 1 is certainly far from complete, but may simply serve as a model that expands upon recent work in this area [6,8,11]. It does not address operator and driver qualifications, economic and operational regulation, the environment, productivity, operating costs and maintenance, all of which are also of great importance to the industry.

Table 1 identifies seventeen performance measures, a number which may well be far from complete. The truck factors contain elements that may be subject partially to federal new vehicle standards; are under provincial weight and dimension regulations; may be under provincial in-service standards regulation; are specified by the truck purchaser; or may be determined by the truck operators maintenance and operational practice. The

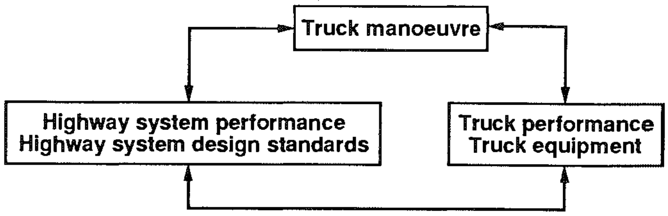


Figure 1/ Relationship Between Highway Factors and Truck Factors

Table 1/ Performance and Design Relationships

Truck manoeuvre	Performance Measure	Truck Factors	Highway Factors
Acceleration from a stopped condition	Startability	Overall length Gross weight Power, gearing	Roadway friction Grade Traffic light timing Intersection sight distance
Driving on a straight level road	Bridge loading	Gross weight Load distribution Axle unit spacings Sliding bogies, fifth wheels and kingpins Liftable axles	Design standards Evaluation procedures Bridge strength Bridge fatigue Designated routes Load compliance Load enforcement
	Pavement loading	Load distribution Sliding bogies, fifth wheels, kingpins Liftable axles Tire type, size, pressure Suspension dynamics	Pavement design Load equivalency Traffic volume Designated routes Load compliance Load enforcement
	Truck ride	Suspension design Cab suspension Hitch slack Component life, reliability, maintenance Trailer length	Roadway roughness Pavement maintenance standards, procedures
	Overall length	Acceleration Gross weight Braking Eye height	Passing, intersection sight distances Local obstructions Traffic light timing Roadway friction Design standard Striping, signing policies
	Spray control	Trailer length, gaps Aerodynamics	Roadway surface texture
Driving on a grade	Gradeability	Gross weight Losses Power, gearing	Grade Grade length Climbing lane warrants
Driving on a grade	Speed control while descending	Gross weight Axle loads Brake distribution, thermal capacity	Grade Grade length Escape ramp warrants
Low-speed turn	Offtracking	Number of units Wheelbase Hitch offset	Intersection geometrics, capacity Designated routes Lane widening
	Outswing	Front, Rear overhang	Lane width Setbacks
	Friction demand	Wheelbase Axle spacings, loads Self-steering axles	Intersection geometrics Roadway friction

Truck manoeuvre	Performance Measure	Truck Factors	Highway Factors
High-speed turn	Static rollover	Gross weight Bed length Load height Suspension design Number of axles Liftable axles Hitch type	Curve and ramp geometrics Advisory speed posting policy
	High-speed offtracking	Number of units Wheelbase Hitch type, offset Self-steering axles Tire properties Axle loads, distribution	Advisory speed posting policy Lane widening Curbs on ramps
	Understeer coefficient	Tire properties Power unit wheelbase Hitch type, offset Liftable axles	Curve and ramp geometrics Advisory speed posting policy
Evasive manoeuvre	Load transfer ratio Transient high-speed offtracking	Number of units Wheelbase Hitch type, offset Tire properties Load distribution	Lane width Designated routes Speed limit
Braking	Braking efficiency	Gross weight Load height Axle loads, distribution Brake torques, distribution Wheelbase	Roadway friction Stopping, intersection sight distance Design standard Signing policy Traffic light timing

highway factors are largely design and construction standards, and operations and maintenance policies and procedures. Some, like roadway friction, may also be dependent upon weather. Note that both truck and highway factors contain items that may be considered either "causes" or "effects".

This section simply identifies the various performance measures that are currently in use or might be considered as part of the system for configuring and regulating heavy vehicles. It does not define them, or present performance standards, as there are now in some cases different approaches being used for different measures.

The pavement loading and bridge loading performance measures are usually automatically satisfied by any vehicle allowed to operate on the highway, as they are part of the law. However, it needs to be recognized that these are important performance measures whose standards can be adjusted from time to time.

The low-speed offtracking and rear outswing performance measures limit truck dimensions to the available space at roadway intersections where turns must be made [6]. The rear outswing, limited in Canada's Memorandum of Understanding to 35% of semitrailer wheelbase, should actually be calculated directly as a performance measure [8]. Former limitations based simply on overall or trailer length limits are ineffective.

Static roll threshold, high-speed offtracking and understeer coefficient are all performance measures of a truck in a high-speed turn. The first two are fairly well understood, while the significance of the third seems to be difficult to come to grips with; it may not be the only way, or the best way, to address truck handling [6].

Load transfer ratio and transient high-speed offtracking are performance measures related to the inherent lateral-directional and rollover stability of the truck in a high-speed evasive manoeuvre. Both are manifestations of the rearward amplification phenomenon, expressing this concept in terms meaningful for highway safety [6].

Friction demand is a measure of the resistance of multiple trailer axles to travel around a tight-radius turn such as at an intersection, and describes the minimum level of tire-pavement friction necessary at the tractor drive axles for the vehicle to make a turn without tractor jackknife [6].

Braking efficiency is a measure of how efficiently the braking system can use available roadway friction to prevent wheels locking, which is the onset of loss-of-control [6].

Startability and gradeability are performance measures generally addressed during the equipment specification stage, rather than by regulation. Truck ride is determined primarily by suspension choices made by the manufacturer, and by roadway roughness. Spray generation is determined by aerodynamic details of the truck, and road surface texture. Speed control while descending grades is determined primarily by brake system standards. Overall length is closely related to a number of aspects of truck interaction with traffic. These are all aspects of heavy truck performance that are closely related to many of the truck factors that control the other, "accepted" performance measures, and also have some important relationships with highway design factors, many of which are also closely related to the "accepted" performance measures too. No attempt is made to define these additional performance measures at this time, or to set standards for their values.

The principal observation that arises from Table 1 is that vehicle engineers and vehicle regulators are setting performance standards for heavy trucks, and highway engineers are setting performance and design standards for highways. There are evidently some very close relationships between the truck factors and the highway factors involved in vehicle performance on the highway system. It is quite unfair to suggest that these are not recognized by vehicle and highway engineers. What is clear that there is not always a close relationship between development of vehicle regulations and highway standards. Truck configuration and design initially consumes the maximum resource allocated by the highway system, and thereafter demands more, so the highway standard invariably tends to be trying to prevent further growth, or catch up to past growth.

5/ PROBABILISTIC ASSESSMENT OF PERFORMANCE

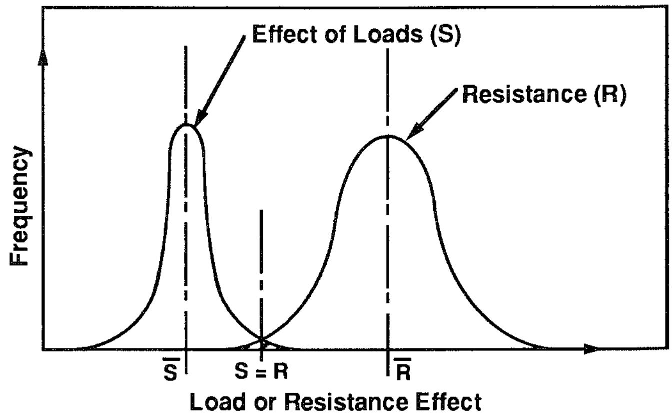
The Ontario Highway Bridge Design Code introduced probabilistic concepts to design of structures [12]. The concept is that the nominal resistance to load of the structure, multiplied by a factor that represents the variability in its construction, should always exceed the force effects on the structure of a combination of loads, each multiplied by a factor that represents the variation of load over the design life of the bridge. Simply put, the expected return period of a load that exceeds the resistance of the structure should be greater than the design life of the bridge. This is illustrated in Figure 2. A similar concept is used, for example, to ensure the structural integrity of aircraft designed for flight through turbulent air.

A probabilistic analysis has recently been developed as a means to evaluate the relative likelihood that vehicles can come to a stop in the time and distance provided by the highway [13]. A parallel of this, looking at the probability of wheel lockup during braking of cars [14], could be extended to assess the probability of tractor jackknife due to drive axle lockup as a function of brake application pressure and roadway friction

A recent study of vehicle operations on two-lane, two-way roads has assessed the passing manoeuvre at the critical passing sight distance as a function of vehicle speeds, acceleration and braking performance [15].

These approaches could be extended to encompass many of the vehicle and roadway interactions identified in Table 1. For example, an interesting application would be evaluation of rollover on a freeway ramp. Rollover is perhaps the best understood of the performance standards. The suspension of the truck provides the resistance side of the equation, and has a statistical variation across the population of trucks. The load is due to the combination of payload weight, its centre of gravity height, vehicle speed, and path curvature. On any particular curve, the first three have statistical distributions, and may also not be strongly correlated. It should be possible to assess the probability that the overturning moment exceeds the resistance, which would give rise to a rollover. The ultimate objective would be to provide all ramps with a uniform probability of rollover occurrence. Another example is the probability of the rear of a multi-unit truck striking a vehicle in the adjacent lane due to rearward amplification from an evasive manoeuvre. The fact that it may be difficult to get data for such analyses is merely a conceptual hindrance at this time.

This concept is simply advanced as a matter of interest at this time. It is likely to be no less difficult to get the kind of data needed to develop and calibrate modes as it is for calibration of a bridge code, or to do credible statistical accident analysis.



$$\emptyset R \geq \sum_i \propto_i L_i$$

Figure 2/ The Limit States Concept

6/ CONCLUSIONS

This paper has attempted to extend the concept of heavy truck performance measures beyond the intrinsic properties of the truck to its interaction with the highway system as a whole. It provides three definitions :

Truck manoeuvre means any action that a truck might be required to perform.

Performance measure means an objective quantity used to evaluate the performance of a truck on the highway system that is derived by a specified method of analysis from a specified truck manoeuvre.

Performance standard means a numerical limit assigned to a performance measure.

The performance measure is an abstract quantity, whereas the performance standard is numeric and limits the performance measure in some way related (usually) to the capacity or safety of the highway system, and the truck manoeuvre. The paper has identified a large number of heavy truck performance measures, which are not necessarily either a complete set, or adequately defined at this time.

If trucks are to be configured using performance standards, then a complete set of standards will be necessary to ensure truck design does not diverge in directions where the set is incomplete. It may always be necessary to supplement performance standards with equipment standards. It is difficult at this time to see how performance standards could be used as the sole basis for configuration of trucks, as neither industry nor enforcement officers have the means to assess trucks in terms of such standards at this time. A format like that adopted for Canada's Memorandum of Understanding on Vehicle Weights and Dimensions seems appropriate, as it is simple and clear and automatically ensures all trucks meet the performance standards.

There is an intimate relationship between vehicle factors, highway factors, and vehicle performance on the highway system. Vehicle and highway engineers need to understand these factors more closely, so that the heavy truck can "fit" better into the highway system.

A statistical approach similar to that used in limit states structure codes is suggested for consideration as a means to address the interaction of heavy trucks with highways. It might be used to identify areas where compromises in highway or truck design standards need to be made, or perhaps specific sites where design changes are necessary.

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