Efficiency Characteristics Of Tractor-Semitrailers

Edward S.K. Fekpe
Centre for Surface Transportation Technology, National Research Council, Canada

John H.F. Woodrooffe
Roaduser Research International, Canada

Peter F. Sweatman
Roaduser Research International, Australia

ABSTRACT

Tractor-semitrailer is the most common truck configuration in many countries accounting for more than 70% of truck traffic in North America. The types and number available are dictated by the regulatory setting of the particular jurisdiction. This paper presents the efficiency characteristics of some tractor-semitrailer trucks with five or more axles using a proposed concept of efficiency measure. The relative efficiencies are measured in terms of the productivity, infrastructure impacts, vehicle stability and control characteristics. It is shown that the six-axle tractor-semitrailer with close-spaced tridem axle unit on the semitrailer is the most efficient truck among those investigated. The semitrailer with a belly single axle is less efficient compared to one with close-spaced tridem in terms of both dynamic and operational performance. Using wide spaced single axles on the semitrailer to maximize payload does not improve operational efficiency and stability and control properties.

BACKGROUND

The types of trucks operating on the highways are primarily determined by the regulations governing the sizes and weights. These regulations are developed taking into account the highway infrastructure provisions and capacities. The regulations are intended to balance the costs that these trucks impose in terms of road deterioration, bridge damage, against the benefits of truck operations. The criteria for determining the size and weight limits may be driven by considerations for consumption of pavements and bridges. In the latter, this is guided by a bridge formula. Bridge formulae are designed such that the gross weight of a vehicle using a bridge structure at any time does not cause undue stresses which may lead to collapse. Bridge formulae usually control the axle spread and interaxle spacings of axle units on a vehicle configuration. In Ontario Canada, a wide

variety of heavy vehicle configurations are in evidence because manufacturers and truck operators tend to exploit the open-endedness of the regulations and configure the axles to maximize the weight allowances as long as the requirements of the bridge formula are satisfied. In jurisdictions where the bridge formula is not the primary criterion for determining allowable weights, a tighter control on the types of possible configurations is observed where only specific types are permitted.

This study investigates the efficiency characteristics of some tractor semitrailer configurations in terms of dynamic and operating performance attributes namely: vehicle stability and control properties; productivity, and infrastructure impact. The investigation compares the relative efficiencies of the less common configurations with axle arrangements that satisfy the provisions of the Ontario Bridge formula, with the conventional five axle tractor semitrailer as the baseline configuration. The paper is also directed at providing insights into possible indicators that can be used to formulate regulatory policies for these trucks.

TRACTOR-SEMITRAILERS

In Canada, about 32% of domestic freight is moved by trucks with rail accounting for 53%. About 80% of Canada's imports to and over 60% of exports from the USA by value are transported by trucks. Over 65% of all trucks in Canada are tractor-semitrailers (Statistics, 1994). Tractor semitrailers are responsible for about 68% of annual heavy truck distance travelled with an average of 127000 km in Canada. In the USA, tractor-semitrailers account for 30% of all registered vehicles and are responsible for approximately 70% of heavy truck mileage (Blower et al. 1988).

As noted earlier, a wide variety of tractor-semitrailer configurations are found in Ontario because truck operators tend to exploit the less restrictive weight limits by maximizing payloads to improve productivity. The configurations used in this study are shown in Fig. 1 with

Configuration	Code	Maximum Weights (tones)	
		Gross	Axle
	3-S2 *	39.5	5.5 / 17.0 / 17.0
	3-S2	43.5	5.5 / 19.1 / 19.1
	3-S11	43.5	5.5 / 19.1 / 10 / 10
	3-S3	49.0	5.5 / 19.1 / 24.0
	3-S12	52.5	5.5 / 19.1 / 10 / 19.1
	3-S111	52.5	5.5 / 19.1 / 10 / 10 / 10
	3-S1111	57.8	5.5 / 19.1 / 10 / 10 / 10 / 10
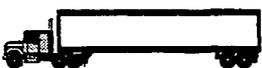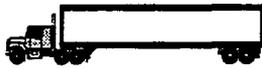
* - interprovincial limit'

Fig. 1 Configurations investigated

the allowable gross vehicle weights (GVW) and axle weights indicated. Typical heavy truck fleet composition in Canada indicate that over 65% of tractor semitrailers are the 5-axle configuration with semitrailer tandem axle spread in the range 1.2 - 2.4 m.

EFFICIENCY CONCEPT

A fundamental definition of efficiency is the ratio of effective work to energy expended. In trucking, this may translate into net payload moved as a ratio of cost involved in doing so where amount of payload is an indication of the effective work accomplished. The energy expended, measured by the cost involved in moving a given amount of payload, has two main components: (i) the trucking costs or the vehicle operating costs (VOC); and (ii) infrastructure costs. The former is cost to the truck operator. The latter is incurred or charged to the truck through principles of highway cost allocation and expressed in various forms of taxes. A significant component of infrastructure costs is the level of load associated damage that can be directly attributed to the truck operations. This is measured indirectly by the equivalent standard axle loads. This parameter also provides a common basis for comparing the

damaging effects of different truck types, configurations and loading spectra.

Recent developments in heavy vehicle size and weight issues are directed at developing performance based standards that could be incorporated in the regulations. Even though, a number of performance parameters have been identified, the mechanism for including these in size and weight regulations is not yet formalised. It is also observed that performance, from the standpoint of productivity and infrastructure impacts, has not been a mainstay of considerations in developing the regulations. For example, whereas threshold values for vehicle stability and control measures may be well established and documented, there is currently no acceptable measure and level that can be directly related to vehicle-highway infrastructure interaction effects. An indirect product of this investigation is to identify what those levels are likely to be on account of the payload capacity and potential infrastructure damage.

Efficiency as used in this paper is defined as how well the balance between: (i) the benefits or outputs of operating a given truck configuration under a given set of weight limits and rules and their enforcement on one hand, and (ii) the infrastructure costs on the other, is achieved at acceptable levels of safety and adequate dynamic stability and handling capabilities. These parameters and their inter-relationships

Primary Variable   **Identifiers**   **Ranking**   **Second order Efficiency Index**   **First order Efficiency Index**
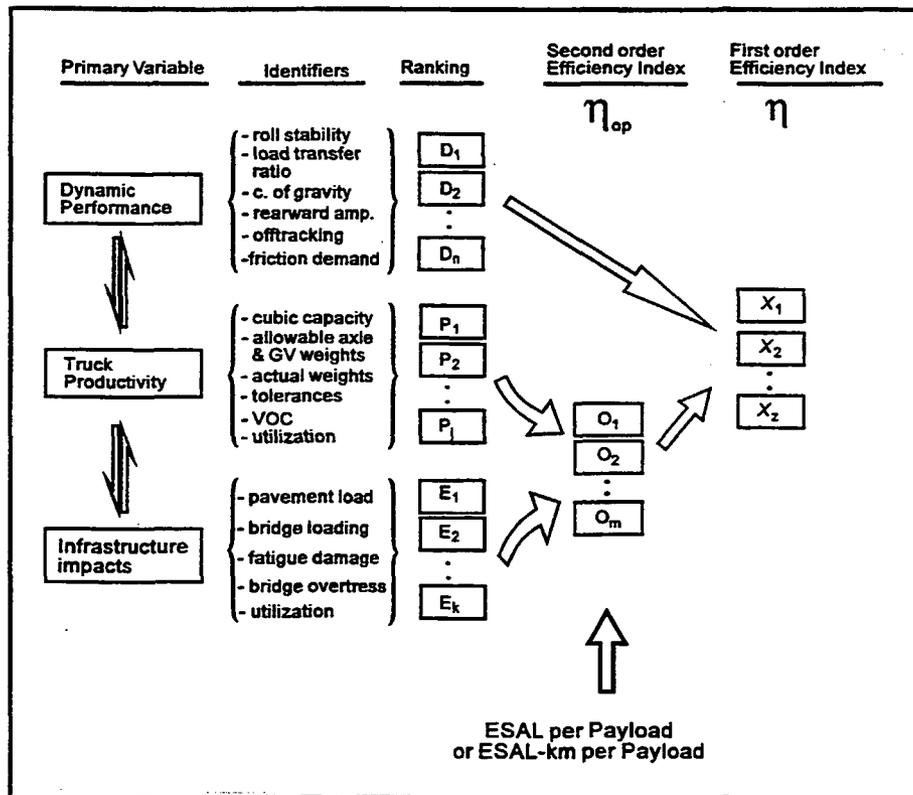
Fig. 2. Efficiency concept

are explored for some tractor-semitrailer truck configurations with a view to identifying possible indicators for comparing the relative efficiencies of different truck types.

The efficiency equation is defined by three primary variables: dynamic performance measures; truck productivity measures; and infrastructure impacts. Each of these is measured by a number of identifiers or attributes. Fig. 2 illustrates the linkages between these variables and how they illustrates the linkages between these variables and how they determine the overall efficiency of a truck. It shows the framework for determining the relative efficiencies of various truck types. The primary variables are generally functions of the regulatory setting governing the sizes and weights and the enforcement practices. The ranking may be based on the aggregate effect of the relevant attributes meeting pre-defined threshold values or how these values compare with a defined baseline configuration. The first order efficiency index considers both dynamic and operational performance and represents the overall ranking. Given n arbitrary qualitative levels of dynamic performance and m levels of second order efficiency index ranking, there are $n \times m$ possible levels of first order efficiency index. The operational performance efficiency measure is considered a second order efficiency index because it measures the efficiency given that the stability and control properties of that truck are adequate.

VEHICLE OPERATING COSTS

It could be argued that vehicle operating cost (VOC) is a primary variable that defines efficiency of a vehicle. This parameter is not included in the definition of efficiency because (i) there is a wide variation in the parameters that determine the VOC of a vehicle. This includes, types of freight, geometric features of highways, horse power ratings, unit costs of labour, delay costs etc. The values for these items could be very different even for the same truck operating under different conditions; (ii) relevant statistics on these parameters for the various configurations are not readily available; and (iii) the definition of efficiency sought is one that is based on variables that are common to all configurations and directly related to the size and weight regulations.

A snapshot of the VOCs for 3-S2 operating at 39.5t GVW limit in Manitoba, western Canada and in Ontario at 47.2t for different levels of utilization and commodity types are shown in Table 1. The values represent VOC expressed in cents per kilometre and derived from TRIMAC model (TRIMAC, 1993) at 1993 prices. The values show that VOCs are 12-14% higher in Ontario for dry freight and 16-20 higher for bulk freight depending on the utilization. Since these differences are attributable to a number of factors other than vehicle capacity, it cannot be concluded that the lower the VOC the more efficient the truck for identical utilization rates.

25

Table 1. VOC for 5-axle Tractor-semitrailer
Paved roads

Utiliza-tion '000 km	VOC in cents per kilometre			
	Dry freight		Bulk freight	
	Ont.	Man.	Ont.	Man.
80	154.3	138.3	149.2	128.9
160	135.1	119.3	125.7	105.5
240	128.6	112.8	117.7	97.7

Notes:
Ont. - Ontario, GVW limit = 47.2 tonnes
Man. - Manitoba, GVW limit = 39.5 tonnes
Source: TRIMAC, 1993.

ANALYTICAL FRAMEWORK

In analyzing efficiency, performance is discussed under two main headings, dynamic performance (i.e. stability and control properties) and operational performance (i.e. productivity and infrastructure impact performance). The analysis is based on the following assumptions:
- all trucks are equipped with the same suspension type;
- the dimensions are identical except for the arrangement of the axles on the semitrailer being the only variable;
- pavement types on which these trucks are operated are designed, constructed and maintained to identical standards;
- enforcement practices are identical in jurisdictions in which these trucks are operated;
- freight characteristics are identical for all truck types.
- annual average vehicle miles travelled (VMT) or utilization is comparable for all configurations considered. Strictly, this may not be true but it is assumed to be for the purposes of the analysis.

Whereas this analysis deals with two performance groups separately, it is recognized that they are interdependent. For a given set of mechanical features, the dynamic performance attributes such as load transfer ratio, friction demand, roll stability depend on the weight carried and the distribution of the load on the axle units of the vehicle configuration. Conversely, the productivity and infrastructure impacts are determined by the number, arrangement and load limitations on the axle units. For example, the level of pavement damage imposed by a given truck depends on its dynamic properties including type of suspension system, load transfer mechanism etc.

DYNAMIC PERFORMANCE

Sweatman and Bruza (1994) identified factors that may influence the dynamic performance of any vehicle configuration to include, weight and dimension limits, suspensions, vehicle stability and braking efficiency. Key attributes for safety related include: (i) steady state roll stability; (ii) rearward amplification; (iii) load transfer ratio (this distinguishes between the dynamic roller tendency of different vehicle configurations subjected to the same manoeuvre); (iv) offtracking at low and high speeds.

The dynamic performance parameters obtained from the Canadian vehicle weight and dimension study using the UMTRI roll/yaw model are summarized in Table 2 (Ervin and Guy, 1986). The values are normalized using the baseline 3-S2 as the reference configuration i.e. all values are expressed as a ratio of the 3-S2 equivalent (Table 3). This allows the relative stability and control properties of the configurations to be studied. There is no distinction between 3-S2 operating at 39.5 tonnes interprovincial GVW limit from that operating under the Ontario bridge formula. Given that a truck has satisfactory dynamic performance, consideration must be given to the operating characteristics.

OPERATIONAL PERFORMANCE

The term operational performance is used in this paper to include highway infrastructure impact and trucking productivity. Productivity can be measured in different ways depending on the system under consideration. It is usually measured by the output per resources consumed i.e. it expresses the cost or resource consumption as a function of the outputs generated. Vehicle capacity being one major variable to which truck productivity is most sensitive, the average payload (a reflection of both cubic and weight capacity) is used as an indication of productivity.

As noted earlier, infrastructure cost is indirectly measured by equivalent pavement loading and in order to normalize the differences in pavement and payload capacities, and use the productivity measure as defined above, the average equivalent standard axle load (ESAL) per unit payloads are compared. This is equivalent to the definition of efficiency. This parameter accounts for the fact that vehicles with higher weights require fewer trips to transport the same amount of freight thereby offsetting part of the additional pavement damage attributed to the increased weight. Fekpe et al. (1995) however, proposed that ESAL-km per payload is more appropriate parameter for comparison because it relaxes the constant payload condition implicit in the ESAL per payload parameter and allows the total pavement loading and hence potential load associated damage by each truck type or weight limit to be compared.

The operational performance efficiency measure therefore is ESAL per payload or ESAL-km per payload. Due to unavailable information on average utilization of the various configurations considered in this study, the analysis

is based on ESAL per payload. GVW distributions, average payloads and resulting pavement loadings of the various configurations are determined using a methodology that predicts the GVW distributions as a function of the

governing weight limit and the intensity of its enforcement expressed in terms of the violation rate (Fekpe and Clayton, 1995). Weight violations are assumed to be negligible i.e. near complete compliance condition. The ESAL is calculated using the fourth power rule with an exponent of 3.8 and the average ESAL per truck is calculated as the weighted sum of the ESAL factors (Fekpe et al. 1995a). Table 4 summarizes the results.

DISCUSSIONS

DYNAMIC PERFORMANCE

Comparison of the dynamic performance characteristics (Table 3) indicate that the baseline 3-S2 exhibits a better performance than the other configurations in all parameters except low speed offtracking. According to the overall ranking (Ervin et al. 1986), the 3-S2 and 3-S3 belong to the same category that is rated as having good dynamic performance properties. This is followed by the 3-S111 having marginal reductions in performance due to higher demand for friction in tight turns. The 3-S12 is the next with the major limitation of apparent excessive demand for friction levels in tight turns. The semitrailer with four single axles (3-S1111) is ranked the least acceptable. Its major stability and control limitations are, excessive demand for friction levels in tight turns and unusually low static rollover threshold.

Table 2. Dynamic performance parameters

| Configu-ration | Rollover threshold (g) | Centre of Gravity Height (m) | Load Transfer Ratio | Offtracking (m) | | Friction demand |
				High speed	Low speed	
3-S2	0.437	1.97	0.384	-0.303	5.906	0.031
3-S3	0.418	2.08	0.408	-0.304	5.577	0.051
3-S12	0.376	2.18	0.475	-0.400	4.942	0.217
3-S111	0.399	2.14	0.478	-0.360	5.492	0.303
3-S1111	0.332	2.37	0.625	-0.485	4.166	0.709

Source: Ervin R.D. and Guy Y., 1986

Table 3. Normalized dynamic performance parameters

| Configu-ration | Rollover threshold (g) | Centre of Gravity Height (m) | Load Transfer Ratio | Offtracking (m) | | Friction demand |
				High speed	Low speed	
3-S2	1.000	1.00	1.00	1.00	1.00	1.00
3-S3	0.957	1.06	1.06	1.00	0.94	1.65
3-S12	0.860	1.11	1.24	1.32	0.84	7.00
3-S111	0.913	1.09	1.25	1.19	0.93	9.77
3-S1111	0.760	1.20	1.638	1.60	0.70	22.87

Table 4. Operational performance measures

Configu-ration	GVW Limit (tonnes)	ESAL per Truck	Average GVW (tonnes)	Average Payload (tonnes)	ESAL per Payload
3-S2 †	39.5	1.83	30.8	15.3	0.120
3-S2	43.5	2.70	33.8	18.3	0.147
3-S11	43.5	2.90	33.8	18.2	0.162
3-S3	49.0	2.65	38.1	21.6	0.123
3-S12	52.5	3.30	40.8	24.3	0.136
3-S111	52.5	3.70	40.8	24.3	0.152
3-S1111	57.8	3.34	45.0	27.5	0.122

† - interprovincial weight limit.

OPERATIONAL PERFORMANCE

The discussion is in two parts, namely: (i) 3-S2 under Ontario Bridge formula weight limit is compared with the other configurations; and (ii) the 3-S2 under the interprovincial limit is compared with the 3-S2 operating under Ontario weight limit.

The 5-axle configuration with widely spaced two single axles (3-S11) obviously has higher pavement damage potential than conventional 3-S2. The average ESAL per truck is about 48% higher than for the baseline configuration. The average payload for the 3-S11 is at most 19% greater than that for the baseline 3-S2 depending on the percentage of the potential weight capacity utilized. In terms of ESAL per payload, the 3-S11 has a higher values in the region of 35% above the baseline 3-S2 truck. These suggest that the payload advantage of the 3-S11 is overshadowed by the pavement damaging potential. For every percent payload advantage over the baseline 3-S2, the corresponding pavement damage potential is more than two fold. The dynamic and operational performance attributes clearly indicate that the 3-S11 is less efficient than the baseline 3-S2 configuration.

Except for the 3-S11, the 3-S2 under Ontario bridge formula is operationally less efficient than the other configurations investigated when assessed in terms of ESAL per payload. Relative to the 3-S2, the 3-S3 imposes 16% less ESAL per payload and at an average payload that is at least 15% higher depending on the percent of allowable weight capacity utilized. These values suggest that the 3-S3 is more efficient than the baseline 3-S2 given that these trucks possess identical dynamic performance characteristics.

For the 6-axle tractor-semitrailer configurations considered in this study, the close-spaced tridem axle spread i.e. 3-S3 is operationally more efficient. The following observations are also made:

- even though the average payload capacity of 3-S12 configuration is about 13% more than the 3-S3, the 3-S3 imposes about 10% less ESAL per payload than the 3-S12 configuration;
- the 3-S111 configuration possesses at least 40% more pavement damaging potential and 24% more ESAL per payload than the 3-S3 configuration even though these configurations have identical GVW limits;
- 3-S111 is a less efficient configuration than the 3-S12 measured in terms of the ESAL per payload but has better dynamic performance properties;
- 3-S1111 exhibits operational efficiency comparable to the 3-S3 but this is overshadowed by its relatively poor stability and control properties.

Relative to the 3-S2 operating at GVW limit of 39.5 tonnes, two important observations are made from the standpoint operational efficiency: (i) it is more productive to adopt a 3-S3 than increasing the GVW limits for the 3-S2 and/or having wide spaced single axles on the semitrailer (e.g. 3-S11); (ii) irrespective of the allowable GVW limit of the 3-S2 configuration, the 3-S3 is more efficient in terms of ESAL per payload.

EFFICIENCY RATING

The overall efficiency rating of a given truck depends on the dynamic and operational performance properties. The ratings from the individual performance categories are however not additive. Following the efficiency concept proposed and the discussions presented, the following model for efficiency rating is proposed.

Ensure that dynamic performance satisfies a pre-defined level of acceptance; then rate the vehicles according to the operational performance using the second order efficiency

index of ESAL per payload or ESAL-km per payload. In order words, the overall efficiency of a truck can be assessed by the operational efficiency rating given that the dynamic performance satisfies acceptable levels. This can be represented by EQ (1).

$$\eta = \eta_{op} \mid_{DP \geq adequate} \qquad (1)$$

where η stands for efficiency; η_{op} is operational efficiency index; DP and OP are dynamic and operational performance respectively.

The rationale behind this model is that, all configurations stipulated in any size and weight regulations, must have passed the dynamic performance criteria i.e. possess acceptable stability and control properties. These properties are indications of safety therefore, the parameter of interest in assessing efficiency is the operational performance characteristics.

This efficiency measure can be used to compare operational performance of different truck types, weight limits and control measures. It combines the parameter that truck operators strive to maximize (i.e. payloads) and that used by the highway agency to apportion costs to truck operations (i.e. pavement damage potential).

CONCLUSION

The relative efficiencies of some tractor semitrailer configurations are compared using a proposed concept of efficiency measure. The efficiency of a truck can be assessed by operational efficiency index i.e. average ESAL per unit payload, given adequate dynamic performance. The study focused on tractor-semitrailer but the index can be used for other truck types.

It is evident that the 6-axle tractor-semitrailer with close-spaced tridem axle unit on the semitrailer (3-S3) is the most efficient truck among those investigated based on its dynamic and operational performance characteristics. This truck provides improved productivity with identical dynamic performance relative conventional 5-axle equivalent i.e. 3-S2. The semitrailer with a belly single axle (which could be a liftable axle) i.e. 3-S12 configuration, is less efficient than the 3-S3 in terms of both dynamic and operational performance.

It is also found that, from the efficiency standpoint, there is no real advantage in increasing the allowable GVW for 3-S2 beyond the current interprovincial limit of 39.5 t. Also, using wide spaced single axles on the semitrailer in order to maximize payload does not improve operational efficiency and jeopardizes stability and control properties.

REFERENCES

Blower D. and Pettis L.C. 1988. National truck trip information survey. University of Michigan Transportation research report. UMTRI 88-11.

Ervin R.D. and Guy Y. 1986. Vehicle Weights and Dimensions Study Vol. 1. The influence of Weight and Dimensions on the Stability and Control of Heavy Trucks in canada - Part 1. Technical Report. Roads and Transportation Association of Canada. Ottawa, Canada.

Fekpe E.S.K. and Clayton A. 1995. Predicting Gross Vehicle weight Distributions ASCE Transportation Engineering Journal Vol 121 No. 2: 158-168.

Fekpe E. Clayton A. and Haas R.C.G. 1995 Evaluating pavement impacts of truck weight limits and enforcement levels. 74th Annual TRB Meeting. Washington DC. Paper #950167. (in press)

Statistics Canada 1994. Trucking in Canada 1991. Statistics Canada, Ottawa. Canada.

Sweatman P. and Bruza L. 1994. Dynamic Performance of Heavy Vehicles in Australia. Proc. X1 Int. Heavy Vehicle Conference. Budapest, Hungary. pp XIV: 1-13

Trimac Consulting Services. 1993. Operating Costs of Trucks in Canada. Developed for Transport Canada. Ottawa, Canada