Evaluating Pavement Impacts of Truck Weight Limits and Enforcement Levels

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Efforts to compare truck productivity and pavement loading impacts of alternative truck weight limits have met with limited success because of the uncertainty surrounding the important inputs. In addition, the effects of enforcement on the resulting vehicle weights have not been adequately addressed. Parameters for evaluating pavement loading impacts of alternative truck weight limits and enforcement levels are presented. It is indicated that enforcement is a critical factor in assessing pavement impacts of alternative weight limits. For a given weight limit, the effects of enforcement on pavement loading for flexible and rigid pavements differ, with rigid pavements being more sensitive. Parameters measuring total pavement loading and taking into account the amount of payload provide a more objective assessment than the average load per truck alone. In terms of pavement costs resulting solely from axle loads, substantial savings are achievable if strict enforcement schedules are implemented.

Freight movement by trucks has important economic implications in terms of both transport costs and highway infrastructure. The physical and operating characteristics of trucks are governed primarily by the regulations limiting their sizes and weights. Very often governments are confronted with decisions that ultimately require a revision of the regulations governing vehicle weights and dimensions. Reasons for revisions of the regulatory limits include

- Promotion of commerce and economic activity;
- Improvement of operating efficiency in the trucking industry; and
- Achievement of technical harmony and promotion of trade in a geographic region (e.g., provinces of Canada, U.S. states, the countries of the North American Free Trade Agreement, European Community countries).

With increasing need for efficiency in the management of transport infrastructure and objectivity in evaluating the consequences of alternative regulations, reliable methods to forecast traffic information for direct input into pavement design, evaluation of management policies, alternative maintenance and rehabilitation strategies, and pavement performance modeling are important. Pavement impact analyses in recent studies have relied on educated estimates of pavement loadings for given regulatory and enforcement regimes (*1,2*). Uncertainties surrounding these estimates place limitations on the results. Reliable prediction procedures to assist in the management of infrastructure facilities are required.

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The purpose of this paper is to describe a method for estimating pavement loading impacts to assist in evaluating alternative weight limits. The procedure is based on a new methodology that predicts gross vehicle weight (GVW) distributions of a given truck as a function of the weight limit and the intensity or level of enforcement. The paper is also directed to the importance and quantification of the enforcement factor in pavement loading and, indeed, the overall pavement impact analysis of regulatory changes. Enforcement effect as distinct from compliance is addressed. Finally, economic consequences of different enforcement schedules are discussed.

ENFORCEMENT FACTOR

Enforcement of vehicle weight and dimension (VWD) regulations is intended to protect the highway infrastructure from premature deterioration by keeping overweight trucks off the highway system. Illegally overweight trucks rob the system of its life without reimbursing the public and compete unfairly with other trucks. The VWD regulations are meaningless unless they are enforced. The effects of nonenforcement can give rise to potentially important effects respecting public safety, fairness and equity in operations, and efficient use of public funds. These are reflected in increased pavement maintenance and rehabilitation costs due to increased pavement damage. Strict enforcement of the regulations is a step toward reducing violations, heavy-truck accidents, and highway maintenance and rehabilitation expenditures.

A truck weight study in the United States observed that estimating the effects of illegally overweight trucks on pavement costs is difficult because reliable estimates of the magnitude and frequency of illegal overloads are not available (*1*). Although the benefits of enforcing the regulations in terms of reduced pavement damage and subsequent maintenance and rehabilitation expenditures are identified, they have not been expressed objectively and quantitatively. In particular, the relationship between level of enforcement and pavement implications is not well established. Studies have shown that a high level of enforcement is associated with a high probability of noncompliance detection perceived by truckers, and consequent high compliance rates; and that truck weight distributions can be related to and expressed in terms of the weight limit and level of enforcement of the weight regulations (*3*). In addressing pertinent technical and policy issues regarding highway infrastructure management, it is therefore important to account for the enforcement effect in loading impact analyses. The level of enforcement is defined as the inspection rate or inspection capacity, that is, the number of trucks inspected as a percentage of all trucks using a highway facility.

TRUCK WEIGHT PREDICTION

In evaluating the impacts of alternative regulatory scenarios, knowledge of the probable weight distributions is required. Whereas it is easy to obtain truck weight data under the prevailing limits, weight prediction models are required to forecast the probable weights that are expected under proposed limits. New GVW distribution prediction models have been developed as a function of the GVW limit and the level of enforcement (*3*). The procedure overcomes major shortcomings of previous methods by recognizing and accounting for the effects of enforcement, establishing stability (transferability) of the models in time and space, and converting GVW distributions to axle weight distributions in an objective manner on the basis of truck weight split characteristics. The procedure and formulation of the models have been detailed by Fekpe and Clayton (*3,4*).

In this procedure, two distinctive GVW distribution "families" are identified and each represented by the most common or dominant configuration that reflects the characteristics of that family. The first family comprises configurations that are used for hauling "all-commodity" freight, where no one commodity or small number of commodities dominates. Trucks in this family are used to transport the full range of commodities (volume based and weight based), in both truckload and less-than-truckload quantities. This family is termed the "all-commodity" family and is typified by the tractor-semitrailer and straight trucks. The second family comprises truck configurations that are operated at GVWs very close to the weight limit. The probability density distributions of such configurations have a strong positive skew. This family is characterized by the double-trailer configurations. These trucks are generally used for hauling dense products (i.e., heavy weight-based commodities) in truckload quantities. This family is termed the "weight-based" family. The five-axle tractor semitrailer truck (3-S2) and the eight-axle tractor-semitrailer-semitrailer truck (eight-axle B-train, i.e., three-axle tractor plus tridem-axle semitrailer plus a second tandem-axle semitrailer) are considered the reference configurations for the "all-commodity" and "weight-based" families, respectively.

Essentially, the GVW predictive models are cumulative functions that determine the probability of the number of trucks operating at a given GVW in terms of the governing limit and the intensity of enforcement of the weight limit. The predictive models are developed for "steady state" conditions for loaded trucks, expressing the weight distributions that could be expected under particular weight limits. The steady state condition represents the situation that would exist if any change in the limits had been in effect long enough for the trucking industry to have fully adjusted the fleet to optimize operation under the new limits. For a given stable demand situation, fixed weight and dimension limits, and consistent enforcement, a "steady state" hauling situation emerges, exhibiting regularity in truck weight distributions for each given truck type (*4*). In reality due to system dynamics, a full steady state condition can be approached only in the limit.

Predicted GVW distributions of the reference trucks are translated into those of other truck types in the same GVW family based on a concept of truck substitution ratios (*3,5*). The rationale behind the development of the substitution ratio is that the GVW distributions for different vehicles in the same family are very similarly distinguished, primarily by the differences in the legal GVW limits. These ratios are factors that convert the GVW distribution of the reference truck to that of the target configuration in the same family. It is calculated as ratio of the effective GVW limit of the target truck to the effective GVW limit of the reference truck. The effective GVW limit is defined as the lesser of (a) the legislated GVW limit or (b) the sum of the axle weight limits.

Model Formulation

The parametric form of the GVW predictive model is given in Equation 1 where, for a given GVW limit and level of enforcement, the GVW distribution can be predicted. The level of enforcement is measured by the violation rate (i.e., number of trucks in violation as a percentage of all trucks inspected). This paper presents the model for the five-axle tractor-semitrailer truck (3-S2) representing the "all-commodity" GVW distribution family. This truck is the most common type in Canada and the United States, accounting for about 70 percent of all trucks. The model is given in Equation 2 as obtained from nonlinear regression analysis on truck weight data using the modified Gauss-Newton numerical search method in the SAS statistical package (*6*). The coefficient of correlation is 0.995 with a mean squared error of 0.00223. The *t*-test statistic was used to assess the goodness of fit, which indicated that at the 95 percent confidence limit, the quadratic function is sufficiently accurate in relating the variables. The model was validated with new independent data not used in its development and found to be accurate at the 95 percent confidence limit. Statistical tests used in assessing the predictive capability of the fitted model include the nonparametric two-sided Kolmogorov-Smirnov test statistic (*3,4*).

$$F(x) = \left[\frac{1}{1 + f(z)}\right] P_r(x) \tag{1}$$

$$\text{F}(x) = \left[\frac{1}{100 + f(z)}\right]\left[23 - 1.43x + 0.022x^2\right] \text{ for } x > 35 \tag{2}$$

where

$F(x)$ = proportion of trucks operating at GVW less than or equal to x;
$P_r(x)$ = proportion of trucks operating at GVW less than or equal to x under complete compliance condition;
x = operating GVW as a percentage of GVW limit (35 percent being the average tare weight as a percentage of the GVW limit for 3-S2);
$f(z)$ = violation rate (i.e., percentage of trucks inspected that are in violation) = f (inspection rate); and
$1 + f(z)$ = violation factor.

The relationship between level of enforcement and violation rate (VR) is described elsewhere (*7*). The VR is a reflection of the level of enforcement and depends on the method of enforcement (e.g., permanent weigh scale or mobile inspection teams). Since a given VR corresponds to different levels of enforcement for different methods of enforcement, VR is used as a proxy of the level of enforcement. It should also be noted that the definition of what constitutes violation varies among jurisdictions (e.g., whereas a charge laid against an operator may be considered a violation in one jurisdiction, only a successful prosecution of an operator is counted as a violation in the other).

In applying the models for different levels of enforcement, except for the complete compliance condition, a 20 percent maximum degree of overweight (amount by which weight limits are exceeded) is assumed. This accounts for (a) tolerances above the weight limit exercised by enforcement personnel, (b) extra loading from overweight trucks operating under special permits, and (c) wide variability in the degree of overweight as evidenced in available data.

PAVEMENT IMPACT ANALYSIS

This section illustrates the application of the model in pavement loading impact analysis of alternative GVW limits for the 3-S2 truck. In the following sections, parameters that can be used in comparing pavement loading of a given truck (e.g., 3-S2 truck) operated under alternative weight limits are discussed. The weight limits considered are the current U.S. federal weight limit with the grandfather clause and the Canadian interprovincial weight limit. It is assumed that pavement design, construction, and maintenance standards are identical in all cases.

Equivalent Pavement Loading

GVW distributions are first predicted under the two weight limits and converted into axle load distributions on the basis of the weight split characteristics on the axle units of this truck type. Equivalent standard axle loads (ESALs) are then calculated using the AASHTO load equivalency factors (*8*). Truck load factors (TLFs), or average ESALs per truck, are obtained as the weighted sum of the ESAL factors.

Flexible and rigid pavements are treated separately, but a terminal serviceability index, p_t, of 2.5 is used for each type. Flexible pavements with a structural number (SN) of 5 and rigid pavements with a slab thickness of 10 in. are used as representative structures. For each weight limit and pavement type, four levels of enforcement reflected in the VR are considered, namely 0 percent ("complete compliance"), 5 percent, 10 percent, and 15 percent. These values reflect typical VRs experienced at permanent weigh scales and by mobile inspection teams and are used to illustrate the effect of level of enforcement. Typical maximum VR for permanent weigh scales is in the region of 5 percent corresponding to an inspection rate of 3 percent or less; the corresponding value for mobile inspection teams is about 15 percent corresponding to an inspection rate of about 10 percent.

Truck Load Factor (Average ESAL per Truck)

Figure 1 indicates the percentage increase in TLF above the complete compliance situation as a function of the level of enforcement measured by the VR. The figure is derived from models that are demonstrated to be accurate in predicting average pavement loading at the 95 percent confidence level; therefore, these values are also deemed to have the same level of accuracy. The figure indicates that TLF generally increases with VR but at rates that depend on pavement type and the weight limit. For a given truck type, the consequences of nonenforcement of the regulations are more pronounced at higher weight limits. For example, under U.S. limits, a 1 percent increase in VR is accompanied by an approximately 2 percent increase in TLF on average for both flexible and rigid pavements. For the Canadian limit, which is about 18 percent higher than the U.S. limit, the corresponding increases are 2.7 percent for flexible pavements and 4.3 percent for rigid pavements.

Table 1 contains the relative changes in TLF at different levels of enforcement for two pavement types when the Canadian limit is compared to the U.S. federal limit. For the truck under consideration, 3-S2, TLFs under the Canadian limits are at least 32 percent greater than the U.S. equivalent, suggesting that load-associated pavement deterioration will be increased. The increase is likely to be minimized by exercising tight weight control strategies.

Figure 2 depicts the general relation between TLF, GVW limit, and level of enforcement for the 3-S2 truck. This relationship is developed from an ESAL calculated assuming the "fourth power" rule, with an exponent of 3.8 and no distinction between pavement types. The figure illustrates the effect of enforcement on the equivalent pavement loading for different GVW limits for the same truck.

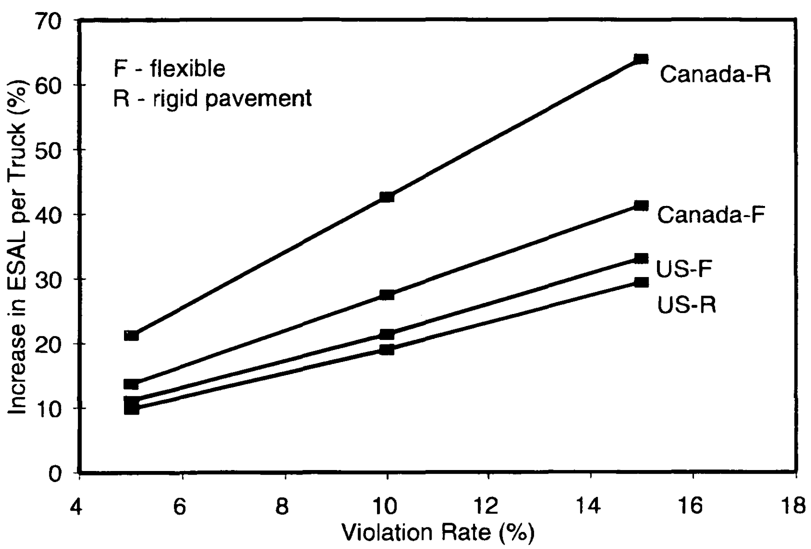

FIGURE 1 Enforcement effect on ESAL per truck (3-S2).

TABLE 1 Summary of Evaluation Parameters

Violation Rate (%)	Flexible Pavement[a]			Rigid Pavement[b]		
	US	Canada	Δ(%)[c]	US	Canada	Δ(%)[c]
			(a) Truck Load Factor			
0	1.102	1.495	+35.6	0.731	0.965	+32.1
5	1.256	1.700	+38.7	0.803	1.170	+45.7
10	1.338	1.905	+42.4	0.869	1.376	+58.2
15	1.466	2.111	+43.9	0.945	1.581	+67.3
			(b) ESAL per Payload			
0	0.081	0.098	+20.5	0.054	0.063	+17.4
5	0.087	0.107	+23.4	0.057	0.074	+29.6
10	0.091	0.115	+27.0	0.059	0.084	+41.1
15	0.096	0.124	+28.7	0.062	0.093	+49.6
			(c) ESAL-km			
0	153.7	131.0	-14.8	101.8	84.6	-17.0
5	170.9	149.0	-12.8	112.0	102.6	-8.4
10	186.5	167.0	-10.4	121.2	120.6	-0.5
15	204.5	185.0	-9.5	131.8	138.6	+5.2
			(d) ESAL-km per Payload			
0	11.33	8.58	-24.2	7.51	8.54	-26.2
5	12.10	9.39	-22.4	7.93	6.46	-18.5
10	12.72	10.16	-20.1	8.27	7.33	-11.3
15	13.45	10.89	-19.1	8.67	8.15	-5.9

[a] - SN = 5.0; ρ_t = 2.5. [b] - D = 10"; ρ_t = 2.5.
[c] - changes relative to the US equivalent.
GVW Limit (tons): US = 36.3; Canada = 39.5
VMT (billions, 1995): US = 139.42 km; RTAC = 87.66 km Source: TRB, 1990a.

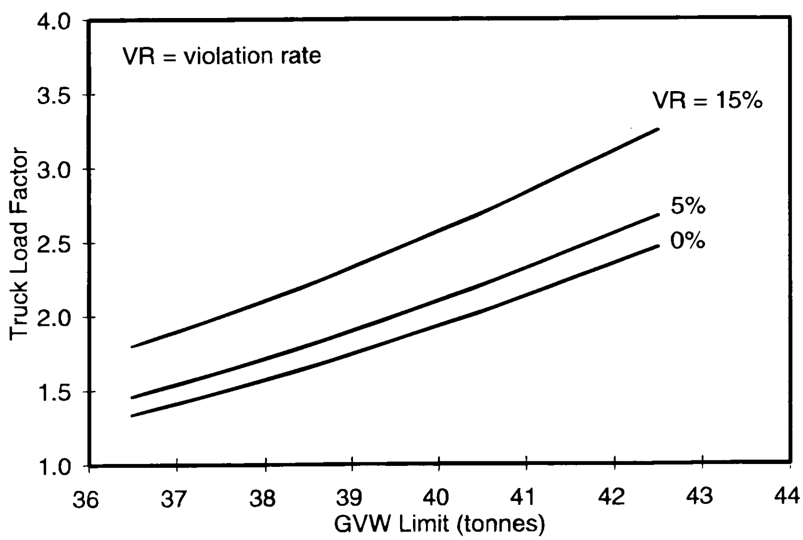

FIGURE 2 TLF-GVW limit relationship (3-S2).

ESAL per Payload

It is normal practice to estimate the damaging effect of a given vehicle on pavements from the ESAL. However, comparison of vehicles in terms of ESAL does not account 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 wear caused by increased weight. To circumvent this problem, vehicles can be compared in terms of the ESALs per unit freight carried (*1*). Furthermore, in evaluating alternative weight limits for different vehicles, it is useful to consider how the relationship between the actual ESALs and the actual average payload associated with different weight limits changes as a function of the weight limit. It has been indicated that a unit change in the GVW limit is accompanied by a change in the ESAL per payload on the order of between 2.3 and 3, and that there is no optimum GVW limit at which the ESAL per payload is a minimum (*9*).

ESAL per payload under the two weight limits are compared in Table 1. Changes in the ESAL per payload at different levels of enforcement indicate that, generally, introducing a higher weight limit (e.g., Canadian limit) results in higher ESALs per payload—20–28 percent on flexible pavements and 17–49 percent on rigid pavements—compared to the U.S. limits. Again, the effect of level of enforcement is very noticeable, emphasizing its importance in evaluating the impacts of alternative weight limits.

ESAL-Kilometer

Even though ESAL per payload takes into account the amount of freight moved, it does not consider the number of repetitions of the loading on the pavement, that is, total loading. Changes in the weight limit are accompanied by changes in the total distance traveled per unit period for the same amount of freight. ESAL total distance traveled can be used as an indication of the total load repetitions imposed. It is noted, however, that highway cost allocation and road user charges or taxes are usually based on the ESAL-km moved. Relative changes in the ESAL-km are therefore studied using a base case forecast of 1995 vehicle miles traveled (VMT) for this truck under the two weight limits (*1*).

Table 1 also shows the percentage changes in ESAL-km. Introducing the Canadian weight limit reduces the ESAL-km of this truck operating on flexible pavements by 9 to 15 percent, relative to the U.S. limit, depending on the level of enforcement. On rigid pavements, the relative change varies from −17 percent at complete compliance, to +5.2 percent at 15 percent VR. The reduction decreases as the level of enforcement is relaxed. The results indicate that, for comparable levels of enforcement and same pavement type, the total pavement loading imposed by the 3-S2 truck, moving the same amount of payload operating under the Canadian limit, is less than under the U.S. limit. It is interesting to note that ESAL-km and ESAL per payload comparisons indicate opposing changes (i.e., the equivalent pavement loading per unit freight moved by this truck type will be substantially increased but the total loading over the given time period will be reduced).

ESAL-km per Payload

Considering that total imposed loading (magnitude and frequency) is determined by the quantity of freight, it is worthwhile to examine how the ESAL-km per payload varies under the alternative weight limits. This parameter relaxes the constant freight condition and allows comparison of the total loading per unit weight of freight moved by each truck type under the alternative weight limits.

Table 1 shows that substantial reductions in ESAL-km per unit payload may result when this truck is operated under the Canadian limit compared to the U.S. limit. The reduction is between 19 percent and 24 percent in ESAL-km per payload on flexible pavements and 6 percent to 26 percent on rigid pavements, depending on the level of enforcement. These results indicate that total pavement loading per unit payload moved under the Canadian limit is less than under the U.S. weight limit for a given level of enforcement. To realize the benefits of reduced ESAL-km per payload indicated by adopting a higher weight limit, it is imperative, therefore, to exercise tighter weight controls on truck operations. This is more critical for rigid pavements than for flexible pavements. However, it should be noted that these comparisons assume that the pavements are designed, constructed, and maintained to identical standards.

Discussion

In general, for the levels of enforcement considered, the range of variation of the relative changes in the parameters examined for rigid pavements is about four times that for flexible pavements. The values also indicate that load-associated damaging potential for rigid pavements is more sensitive to the level of enforcement than for flexible pavements. The analyses demonstrate the scope of the models and, in particular, highlight the importance of enforcement in the evaluating alternative pavement loading scenarios.

These comparisons are based purely on pavement loading. The cost of enforcement, cost of upgrading the existing infrastructure to withstand the increased loading (TLF) resulting from a higher weight limit, the maintenance and rehabilitation costs associated with the higher loading per unit payload, and so forth, need to be considered in the total evaluation process. It is worthwhile to note that in situations where pavement deterioration is attributed more to environmental effects than to traffic loading, these parameters may not be very useful from the pavement performance standpoint. However, these parameters may be of value in highway cost allocation and taxation mechanisms since they are based primarily on the pavement loading.

It is observed that the ESAL-km per payload is a more objective and flexible parameter because it is not constrained by the fixed amount of payload under alternative scenarios and takes into account the total amount of pavement loading.

PAVEMENT COST

From the standpoint of highway cost allocation, it is relevant to express the enforcement factor quantitatively in the pavement loading analysis. A study in Canada (*10*) suggested that environmental factors account for most pavement deterioration in Canada. From the perspective of highway cost allocation, this implies that most pavement costs can be treated as a common cost (i.e., costs that cannot be traced to one user—truckers—versus another). There is, however, a broad range of costs attached to ESAL-km, depending on pavement type, truck type, and costing mechanism. To illustrate the pavement cost implications of alternative weight limits and the enforcement levels, estimates by Rilett et al. (*10*) representing typical conditions in Ontario, Canada, are used, that is, 0.6 cents per ESAL-km (high-volume highway) and 2.2 cents per ESAL-km (low-volume high-

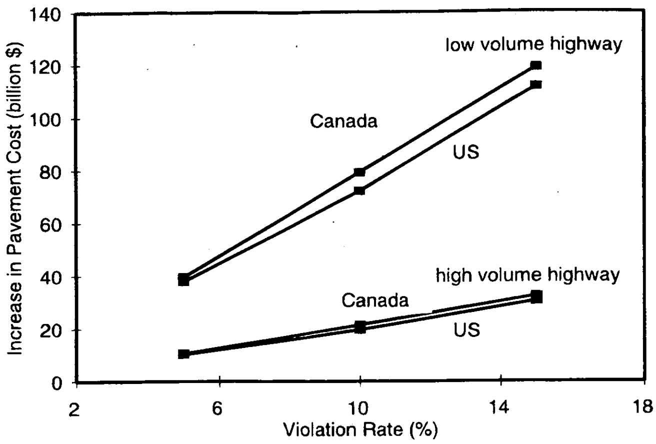

FIGURE 3 Enforcement effect on pavement cost (3-S2).

way). These are pavement costs arising from axle loads only (i.e., pavement costs due to environmental factors are excluded).

Figure 3 illustrates the incremental changes in the pavement cost as a function of the level of enforcement and highway usage. It indicates how the effect of enforcement reflected in the pavement loading translates into pavement costs. It is noted that the values for the higher Canadian weight limit are marginally higher than those for the U.S. limit for the same highway usage and level of enforcement. This suggests that for a given highway type, pavement cost is more dependent on the level of enforcement than weight limit. In other words, pavement costs can be minimized by adopting strict weight enforcement measures. Large differences between the rates of increase on low- and high-volume highways may be partly attributed to the assumption that the VMT on both highway types are the same. This may not necessarily be the case in reality.

CONCLUSION

Parameters for evaluating pavement loading of alternative GVW limits and their enforcement are presented. It is observed that enforcement is a critical factor in pavement loading analysis of alternative weight limits. Equivalent pavement loading on flexible and rigid pavements respond to enforcement levels differently, with rigid pavements being more sensitive to the enforcement level. Consideration of the payload and/or distance traveled together with the ESAL per truck under alternative weight limits provides a more objective assessment of pavement loading impacts than the truck load factor alone. In terms of pavement costs resulting solely from pavement loading, the order of magnitude of savings resulting from implementing tight enforcement schedules is attractive.

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