Pavement loads and weight limits: Canadian experience

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A predictive model of the equivalent standard axle loads for the five axle tractor-semitrailer configuration (3-S2) as a function of the gross vehicle weight limit is presented. The model accounts for the effects of enforcement intensity and the weight split between the two tandem axle groups. The model facilitates evaluation of pavement loads and impacts and allows important trade-off questions to be explored.

1. INTRODUCTION

Increases in truck size and weight limits are usually justified on the basis of economic efficiency. The justification requires demonstrating a positive trade-off between improvements in truck productivity (i.e., the benefit) and increases in infrastructure requirements (i.e., the cost) resulting from the less restrictive regulations. Analyzing this trade-off requires making assumptions about how the trucking industry exploits less restrictive regulations to increase payloads, and how these increased payloads translate into changes in pavement loadings. Both of these considerations require estimating how truck weights vary as a function of truck weight limits.

Various research efforts have attempted to develop objective approaches to predicting and evaluating the effects of alternative size and weight limits on productivity improvements and pavement loadings. Limitations regarding the results of these efforts (including problems in conceptual formulations, inability to produce adequate predictions, assumptions, and methodologies) are discussed in (refs 1-3).

This paper: (a) presents a model for predicting the distributions of the gross vehicle weight (GVW) of 5-axle (3-S2) tractor-semitrailers as a function of weight limits for the so-called "complete compliance" condition. (The 3-S2 configuration dominates trucking in North America, and many other countries); (b) converts this complete compliance model into a weight-limit-dependent model of truck load equivalency factors (TLFs), based on the fourth power load rule; (c) examines how different enforcement levels influence TLF; (d) examines how variations in weight split between axles affects TLF; (e) examines the ratio between TLF and payload for 3-S2s, as a function of weight limit, enforcement and weight split; (f) discusses limitations and implications of the model.

2. THE HYPOTHESIS AND MODEL CONCEPT

The hypothesis behind this work is that the distributions of GVW's of laden trucks can be related to and expressed as a function of governing GVW legal limits, and the enforcement of those limits. This hypothesis emerged from observing two recurring attributes in Canadian truck weight data (ref. 4). The first is that the truck weight distributions of a particular truck type are reasonably stable for a given weight limit, enforcement environment, and demand condition. The second, which is intuitively appealing, is that when the GVW limit for a particular truck type is relaxed, then a proportion of that type of truck's operations will increase payloads. This in turn leads to a new, shifted GVW distribution curve for this truck type.

Fig. 1 illustrates the interaction of circumstances which give rise to the hypothesis and modelling concept, summarized as follows. At any point in time, given a reasonably stable state of demand and supply for the movement of freight by truck [1], and a specified set of rules governing vehicle sizes and weights [2], truckers select an optimum mix of trucks and operating conditions to serve their traffic [3]. Of specific interest for this paper are those vehicles in the fleet of the 3-S2 tractor-semitrailer configuration.

Within the 3-S2 configuration, a variety of body types, dimensional features, and load-carrying structural capabilities are chosen to serve the required demand [4]. Generally, truckers select a variety of 3-S2s which permit them to maximize payloads, subject to the limitations imposed on doing so by the characteristics of the demand for freight movement by the given truck type, the regulations limiting that truck type's size and weight, and the extent to which these limits are enforced. Some loads "weight-out"; some "cube-out"; and some move at less than their maximum possible weight or cubic potential to meet other demands or market considerations. Given a stable demand situation, fixed size and weight limits, and consistent enforcement of them, a "steady-state" hauling situation emerges, exhibiting regularity in truck weight distributions for each given truck type [5]. This distribution can be expressed as a function of the governing limit and the enforcement condition.

If a higher GVW limit is permitted for any particular

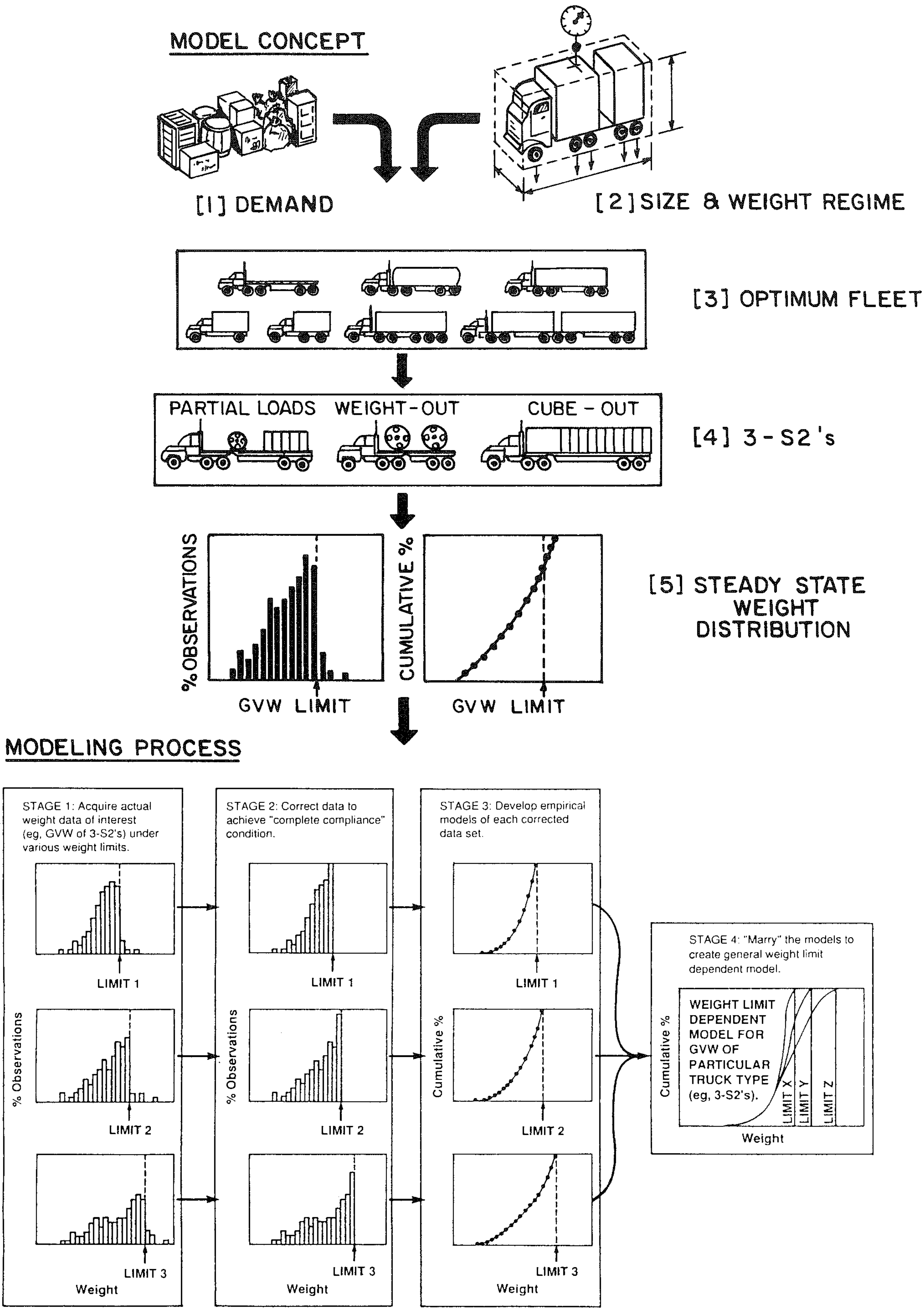

FIG. 1 Model Concept and Modeling Process

vehicle type (and in this case, the 3-S2), increases in the shipment sizes of some weight-out movements handled in these trucks take place, up to a level constrained by the new limit. Cube-out movements, on the other hand, must continue to be handled in their original cube-out quantities at their original GVW levels. The weight limit, per se, does nothing to alter the incidence of partial loads. After some period of adjustment, a new steady state characterized by new weight distribution functions emerges. An equivalent cause and effect response also occurs with a relaxation of dimensional limits, or a combined relaxation of both weight and size limits.

These actual weight distributions will also be affected by enforcement policies. Substantial overweight trucking can be expected where the weight limits are not enforced at all; some overweight trucking if partially enforced; and none if totally enforced. This latter condition is referred to as complete compliance.

3. THE 3-S2 COMPLETE COMPLIANCE GVW DISTRIBUTION MODEL

The modelling requires relating measured truck weights to governing weight limits for a particular truck type, and developing empirical models of these relationships. This is done in four stages as illustrated in the "modelling process" component of Fig. 1. Stage 1 is the acquisition of the truck weight information of interest for each truck type (e.g., the GVW's of laden 3-S2 tractor-semitrailers) under a series of weight limits (e.g., LIMIT 1, LIMIT 2, etc.). Stage 2 rids these raw data sets of overweight observations, thereby creating the complete compliance condition. Stage 3 develops empirical models of a common form designed to reproduce the resulting corrected weight distributions for each of the governing limit cases. Stage 4 "marries" these models so as to permit their generalization as a function of the governing limit. The resulting generalized model permits estimating weight distribution curves given the governing weight limit.

Development of the 3-S2 complete compliance GVW distribution model is detailed in (ref. 5). It has been developed to estimate the GVW distributions of "laden" trucks handling "all-commodity" freight (i.e., where no one commodity or small number of commodities dominates). It is based on the observation of the actual gross weights of 25,879 laden 3-S2 trucks operating under three different "effective" GVW limits (EGVW), of 33.6 t, 37.3 t and 40.5 t. The effective GVW limit is the lesser of: (i) the legislated GVW limit; or (ii) the sum of the axle weight limits, with the steering axle limit being set at the "effective steering axle limit". The effective steering axle limit for each truck type is set at the mean weight of that truck type's steering axles observed in the field, plus twice the standard deviation of the sample of steering axle weights from which the mean is derived, or (0.08 [Tandem Axle Limit in kg] + 4000) in kg for the 3-S2's modelled here.

The model is:

$$P(x) = [\gamma(x - 40)^{\beta} + 31] \quad \ldots \text{ for } x > 40 \quad (1a)$$

$$P(x) = 13 + 0.75x - 0.0075x^2 \quad \ldots \text{ for } x \leq 40 \quad (1b)$$

where:

$P(x)$ = GVW at which x% or less trucks operate (in t)
x = % less than or equal to on a cumulative curve
$\gamma = 3.663908 - 0.18422(EGVW) + 0.002495(EGVW)^2$
$\beta = -9.30265 + 0.498098(EGVW) - 0.00611(EGVW)^2$

4. TRUCK LOAD FACTORS FOR COMPLETE COMPLIANCE CONDITION (3-S2)

This section examines how truck load factors (TLFs) for 3-S2s vary as a function of governing weight limits for the complete compliance condition.

The analysis involves the following. First, complete compliance GVW distributions were calculated from the model presented in Section 3, for GVW limits of 33.6, 35.0, 37.3, 39.0 and 40.5t. Second, these GVW distribution curves were converted into equivalent standard axle load distributions. This was done by assuming that the GVW of a 3-S2 is split such that the steering axle load is the lesser of 4.0t or {4.0 + (GVW - 30.0) /10}t, with the remaining load allocated equally between the drive and tailer tandem axles. The resulting axle load distributions were then converted into equivalent axle load distributions using the fourth power rule and an exponent of 3.8. Third, for each GVW limit, the TLF was calculated by taking the weighted mean of the sum of these equivalent standard axle load distributions.

Fig. 2 shows the resulting TLFs as a function of the GVW limit. The relationship can be represented by a power function of the following form:

$$y_{(50/50:CC)} = 1.4(1.05)^x \quad (2)$$

where:

$y_{(50/50:CC)}$ = truck load factor given equal loads on the two tandem axle groups and complete compliance
$x = [GVW_{limit} - 33.0]$ (in t)

The relationship applies across a GVW limit range of 33 to 41t inclusive.

5. THE ENFORCEMENT EFFECT

The complete compliance condition exists only where limits are enforced in a manner where no trucks operate at GVW levels beyond them. At the opposite extreme from the complete compliance condition is the "complete ignorance" condition. This happens where a weight limit exists, but truckers ignore it. The amount of overweightness experienced here is limited by technological factors (e.g., cubic capacity, rated weight limits) and demand considerations (e.g., shipment size restrictions originating with shippers and/or consignees). Whether or not the complete ignorance condition is ever

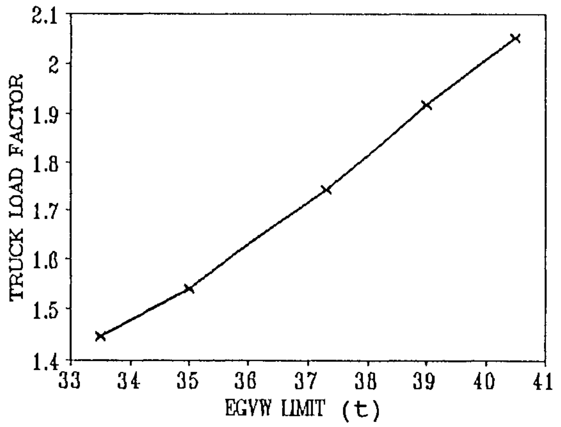

Fig. 2. Truck Load Factor as Function of GVW Limit

really present in practice, at least in North America, is a matter of conjecture. Presumably in most situations where a GVW limit is imposed, at least some effort is made to encourage compliance, with some effect.

Between the complete compliance and complete ignorance conditions is the most common of operating circumstances, where weight limits exist and some attempt is made to enforce them. This Section presents a methodology for modifying the model developed in Section 4 to account for the effect of varying levels of enforcement.

The methodology considers two factors: (i) the (typical) maximum magnitude of overweightness observed under the complete ignorance condition; (ii) the effect of the level of enforcement on the incidence of non-compliance. The methodology uses field data regarding overweight trucking, and overweight trucking and enforcement.

Overweight trucking was present in the original, uncorrected data used in development of the model presented in Section 3. This was because the data was collected in on-road truck weight surveys designed to obtain pavement load data, and not enforcement data. In its collection, efforts were made to weigh trucks operating in their normal states rather than in states designed to appease enforcement personnel. While some enforcement effect would be present, the resulting weight distributions represent conditions which would be about as close to the complete ignorance condition as one could expect to obtain using static weighing. Based on this data, the following observations provide boundary conditions for the extent of overweight (i.e., over-GVW) activity for 3-S2 "all-commodity" operations on Canadian highways assuming the complete ignorance condition: (1) the maximum observed GVW is 50.0t; (2) the percentage of overweight trucks was never observed to be greater than 17%; (3) the percentage of overweight trucks decreases as the GVW limit increases, from 17% at a limit of 33.6t to (about) 10% at a limit of 40.5t.

In a study of weigh scale operations in Saskatchewan over a 2-year period, (ref. 6) developed a relationship between the "violation rate" experienced at a weigh scale (i.e., the percentage of inspections found "in-violation", where an in-violation involves the issuance of a written warning or a ticket) and the "inspection rate" (i.e., the percentage of trucks passing a point weighed for enforcement purposes), as follows:

INSPECTION RATE	VIOLATION RATE
2 - 6%	< 3%
6 - 10%	< 2%
> 10%	< 1%

Based on this relationship and the maximum 50.0t GVW boundary condition discussed previously, Fig. 3 presents the approach used for modifying the GVW cumulative distributions developed from the model to account for a relaxed enforcement effort. Specifically, it illustrates how the GVW distribution function is assumed to change as the violation rate increases from the lowest level (i.e., the complete compliance condition, associated with the highest level of enforcement) to the highest level (i.e., the complete ignorance condition, associated with zero enforcement).

Using this approach for estimating cumulative GVW distributions as a function of the enforcement level and the GVW limit, and the TLF calculation methodology presented in Section 4, Fig. 4 shows how the TLF - GVW limit relationship changes as a function of the level of enforcement.

Based on this figure, there is a 2.5% increase in the TLF for every 1% increase in the violation rate. This enforcement effect is incorporated into the TLF expression developed in Section 4, as follows:

$$y_{(50/50)} = (1 + m) [1.4 (1.05)^x] \tag{3}$$

where:

$y_{(50/50)}$ = truck load factor given equal loads on the two tandem axle groups

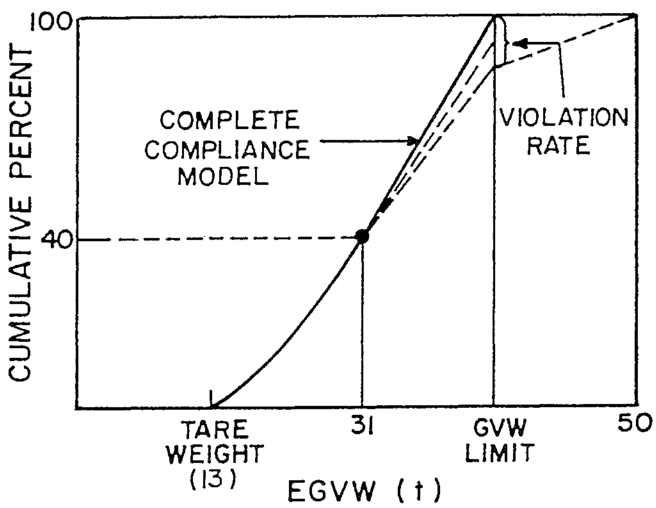

Fig. 3. Adjusting the Model for Non-Compliance

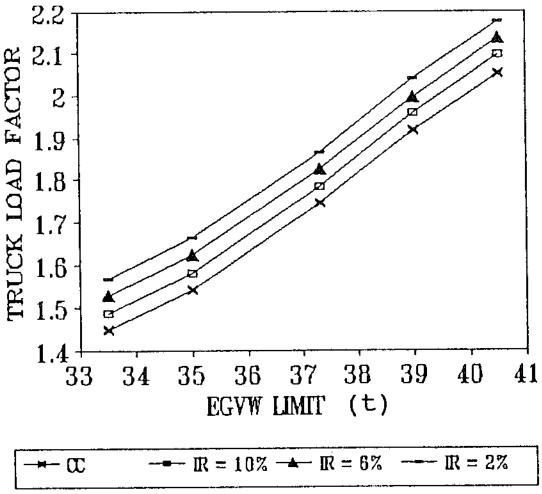

Fig. 4. The Effect of Enforcement

m = enforcement intensity factor,
= 0 when IR = 100% (CC)
= 0.025 when 10% $\leq$ IR < 100%
= 0.050 when 6% $\leq$ IR < 10%
= 0.075 when 2% $\leq$ IR < 6%

6. THE WEIGHT SPLIT EFFECT

Previous analysis has assumed that the weight of any 3-S2 not handled by the front steering axle is spread evenly (i.e., 50/50) between the two tandem axle groups on the unit. This is seldom the case. It has been shown (ref. 7) that in practice, the weight split for the 3-S2 configuration is typically 53/47 (drive tandem/trailer tandem).

The sensitivity of TLFs to weight split between tandem groups was explored by repeating the analysis in the previous Sections assuming 40/60 and 45/55 weight splits. The results are shown in Fig. 5. It is observed that the weight split ratio (WSR) has a significant effect on the TLF irrespective of the GVW limit. The 40/60 and 45/55 splits yield TLFs which are respectively 20% and 5% greater than the TLFs associated with the ideal 50/50 split condition.

This weight split effect extends the expression developed in Section 5, as follows:

$$y = (1 + n)\ (1 + m)\ [1.4(1.05)^{x}] \qquad (4)$$

where: y = truck load factor for a 3-S2
n = weight split factor,
= 0 when WSR = 50/50
= 0.05 when WSR = 45/55
= 0.20 when WSR = 40/60

7. RATIO OF TLF/PAYLOAD AS A FUNCTION OF THE GVW LIMIT (3-S2)

It is useful to consider how the relationship between the actual TLF (a measure of actual pavement loading) and actual average payload (a measure of actual productivity) associated with different limits changes as a function of the limit for the 3-S2 configuration.

Fig. 6 shows how average payload varies with GVW limit and level of enforcement. Fig. 7 shows how the ratio of TLF to the average payload, (Z), associated with each GVW limit, enforcement level, and weight-split assumption, changes with the limit.

It is observed that the ratio increases approximately linearly across a GVW range of 33 to 41t, irrespective of the enforcement intensity factor or the weight split factor, as follows:

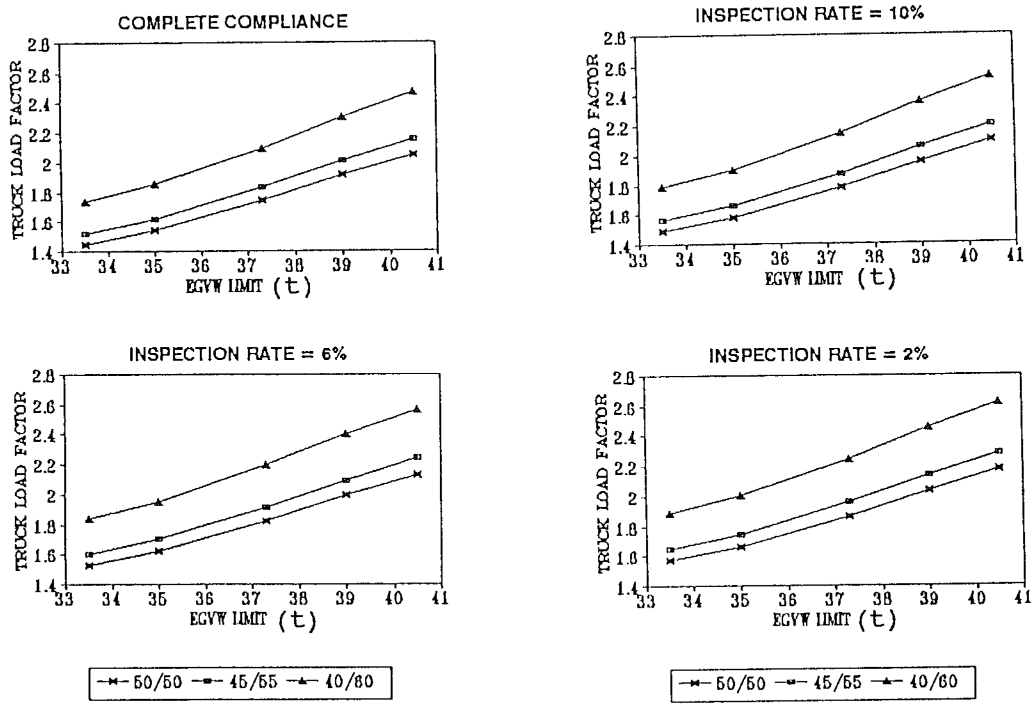

Fig. 5. The Weight Split Effect

$$Z = [(1 + n)(1 + m)(0.0872)] + 0.0034x \tag{5}$$

where: Z = ESAL/payload

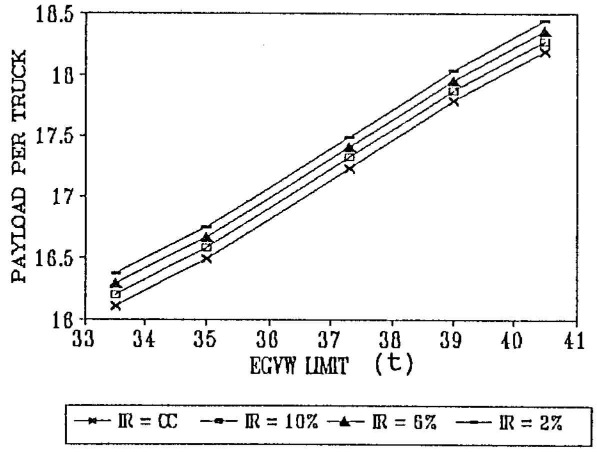

Fig. 6. Average Payload as Function of GVW Limit and Level of Enforcement

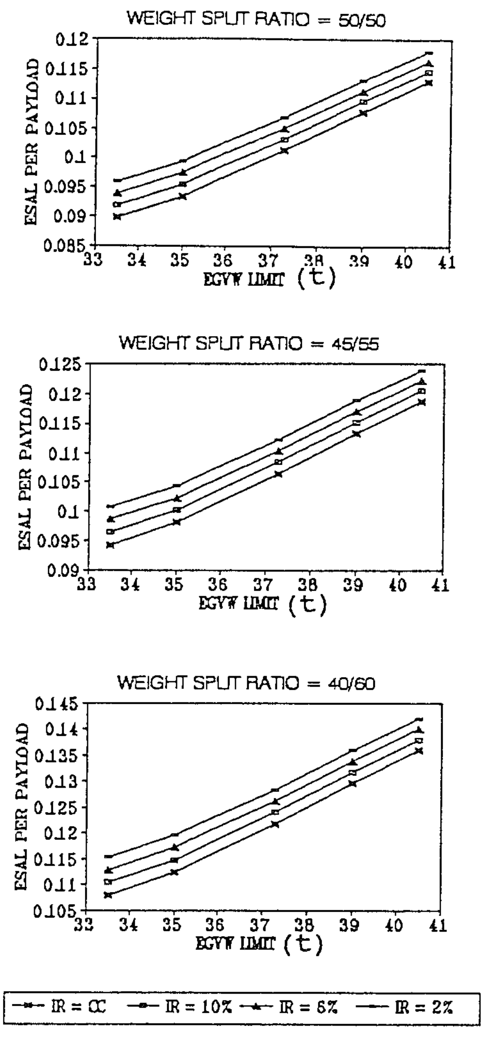

Fig. 7. ESAL per Payload as Function of GVW Limit and Level of Enforcement

The key implication is that for the 3-S2 truck type handling a given quantity of "all-commodity" freight, the higher the GVW limit, the higher the ESALs required to handle the freight.

8. DISCUSSION AND CONCLUDING REMARKS

The paper has developed and calibrated a model for predicting the ESALs generated by each 3-S2 (handling "all-commodity" freight) as a function of the governing GVW limit (for a GVW range of 33 to 41t), enforcement intensity, weight split, and the fourth power rule (exponent = 3.8), of the following general form:

$$y = \rho\eta AB^{x} \tag{6}$$

where: y = ESAL per 3-S2
ρ = weight split effect
η = enforcement effect
A, B = constants
x = $[GVW_{limit} - 33.0]$

The model can be used to:

(1) explore trade-off questions relating to the benefits of enforcement, the advantages of better load distribution practices, and their sensitivity to alternative size and weight policies.

For example, the following observations can be made:

- total pavement loadings associated with moving a given quantity of "all commodity" freight in 3-S2s is lowest at the lowest feasible GVW limit. For a given weight split and enforcement level, a 1t increase in the GVW limit creates a 5% increase in the TLF.
- enforcement programs involving inspection rates of greater than 10% contribute little to lowering TLFs. Complimenting a decrease in enforcement from a high inspection rate of greater than 10% to a low inspection rate of 2-6% with a 1.5t decrease in a GVW limit leads to no change in pavement loading.
- efforts directed at achieving more equal weight distribution between tandem axle groups could prove quite productive in reducing pavement loadings. Achieving a consistent 50/50 weight split on tandems can decrease TLFs by at least 5%.
- large changes in GVW limit are required to effect significant changes in average payloads.

(2) facilitate more objective evaluation of pavement loads and pavement impacts, and productivity improvements, associated with alternative GVW limits, particularly where 3-S2s comprise an important component of a truck fleet (e.g., North America). Calibration to different operating conditions may be necessary.

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