different analysis periods on the failure of existing pavement and overlay life.

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Heavy Trucks on Texas Highways: An Economic Evaluation

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A study undertaken to assess the effects of projected truck traffic on the highway system of Texas is described. The study included the evaluation of costs and benefits for a 20-year planning horizon. Alternative scenarios of future truck traffic were assessed. The study considered only an increase in gross vehicle weights and axle loads and not the effects of changes in the size of trucks or the effects of heavy trucks on county roads and city streets. The major approach to the study involved estimating the comparative pavement maintenance and rehabilitation costs of perpetuating the state highway system under current weight limitations and of future use under different weight conditions. It is concluded that, if changes in weight laws are undertaken, further analysis will be needed to select those routes that would carry relatively large freight tonnages and cost relatively less to upgrade.

The objective of this study was to assess the effects of projected truck traffic on the Texas highway system for a 20-year analysis period. Selected costs and benefits were calculated to show some of the measurable effects of increasing the legal weight limits for trucks that operate on the state network.

The study included the evaluation of costs and benefits for a 20-year planning horizon. Alternative scenarios of future truck traffic were assessed. The study did not consider the effects of changes in the size of trucks, only an increase in gross weights and axle loads. The study did not evaluate the effects that heavy trucks would have on county roads or city streets.

SELECTION OF SCENARIOS

The identification of alternative scenarios was accomplished through analysis, discussion, and evaluation of

Figure 1. Selected truck configurations for scenarios A and B.

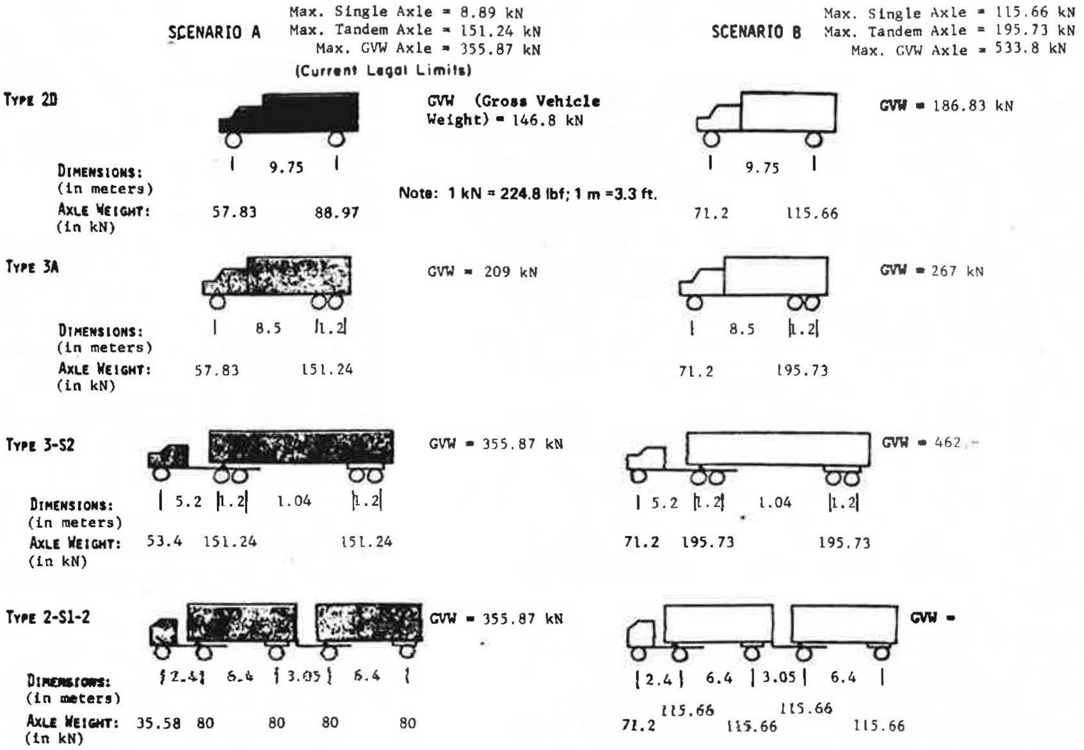
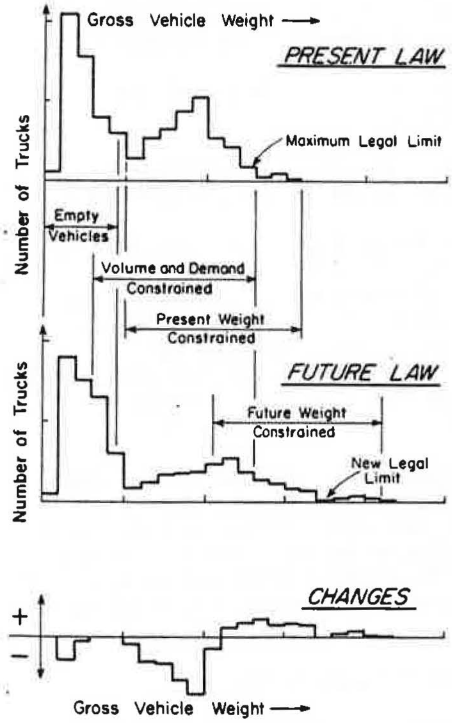


Figure 2. Truck populations and changes resulting from an increase in maximum legal GVW.



both existing weight limits and those that might be likely candidates for the near future. It was decided that two scenarios would be considered. Scenario A would include the continued application of existing law on truck weights and sizes. Scenario B would include increasing the maximum allowable truck weights to those studied by the federal government (1) but would retain current restrictions on the size of vehicles.

Four different types of trucks were selected as [illegible] representative of the fleets of trucks that now operate and will be operating in the future on Texas highways. Diagrams of these vehicles, and the maximum legal gross vehicle weight (GVW) and axle loads considered for each of the two scenarios, are shown in Figure 1.

The following restrictions on vehicle dimensions were considered applicable for both scenarios and are based on existing law: (a) maximum length of 13.72 m (45 ft) for single-unit trucks and 19.81 m (65 ft) for trailer and semitrailer combinations and (b) maximum width of 244 cm (96 in).

A bridge formula that limits truck axle loads and configurations to protect bridges from excessive [illegible] was considered in both scenarios (2).

PROJECTED TON KILOMETERS OF TRUCK TRAVEL

To facilitate the forecast of truck types and their assignment to highway classes, a projection of future ton kilometers of truck travel in the state of Texas from 1977 to 1997 was required. The total projection was divided into two major categories: intercity and urban. Intercity ton kilometers were allocated to three functional highway classes: Interstate highways, farm-to-market roads, and all other state highways. The urban figures were also allocated to three functional highway classes: Interstate highways, other state freeways and arterials, and collectors.

The total projected Texas ton kilometers ranged from 65.7 billion t-km (45 billion ton miles) in 1977 to 131.4 billion t-km (90 billion ton miles) in 1997. Of the total 131.4 billion t-km projected, only 17.52 billion t-km (12 billion ton miles) was forecast for urban travel, whereas 113.88 billion t-km (78 billion ton miles) was forecast for intercity traffic. This intercity figure was then allocated as follows: 47 percent to Interstate highways, 8 percent to farm-to-market roads, and 45 percent to all other state highways. The forecast ton kilometers was assumed to remain constant in both scenarios.

To illustrate the basic procedure, Figure 2 shows how the truck population is likely to be affected by a change in the maximum legal GVW. First of all, more trucks will operate above the current legal limit, and these will replace some that had been operating near and below the old limit. This means that there will be an overall reduction in the number of loaded vehicle trips and, correspondingly, a decrease in the number of empty trips. At the same time, a portion of the truck population will be unaffected by the change in maximum legal GVW. The loads on these trucks are either low-density commodities (volume constrained) or partial loads (demand constrained).

The procedure used data collected by the Texas State Department of Highways and Public Transportation (TSDHPT) over the past 20 years (3). The data represent vehicle (empty and loaded) weight intervals sampled at designated highway locations around the state. The distribution of gross weights for specific classes of trucks under existing legal limits was established from these data.

The process required the development of a technique for computing average empty-vehicle weights, average payload carried, and 80-kN [18 000-lbf (18-kip)] single-axle load (SAL) for each vehicle type and each highway system. The number of 80-kN SALs, truck operating costs, and fuel consumption for each highway class for each year over the forecast period (20 years) are calculated by using the truck-freight ton-kilometer allocation for each class, the average payload per kilometer of a system for each year, and the total number of vehicles required to carry the freight allocated to that vehicle type. The actual procedure used in the computations was obtained from a National Cooperative Highway Research Program (NCHRP) study of truck sizes and weights (4). The NCHRP model was modified and adapted for use in this study.

MODIFICATIONS OF NCHRP METHODOLOGY

Initial efforts in this study used the methodology contained in NCHRP Report 141 with only minor modifications. However, an examination of the preliminary estimates of costs and benefits led to a more extensive critique and modification.

The NCHRP researchers examined historical GVW distributions before and after changes in size and weight laws. There is a pattern in these data that shows a shift to heavier trucks and a small shift on the empty weight portion of the distribution. A shift that is approximately proportional to the ratio of the practical maximum gross weight under the new law to the practical maximum gross weight under the old law exists on the loaded weight portion of the distribution.

The results of applying this type of shift to scenario A for one hundred 3-S2 trucks on a representative 1.6 km (1 mile) of Interstate highway are shown in Figure 3. Figure 3(a) shows a large decrease in 80-kN SALs for trucks that are operating near the current legal limit. This decrease is negated by the increase caused by the new heavy trucks. Figure 3(b) is similar except that a large savings in truck operating costs is indicated for empty and lightly loaded vehicles. Such data caused us to reexamine the shifting procedure.

If weight laws (only) were changed, certain consequences might be expected. Those trucks that operate near the legal axle or GVW limit would increase their loads, and this would result in fewer loaded and empty trips. Vehicles that carry low-density cargo and are constrained by vehicle volume (size) would be unaffected. A significant number of partially loaded vehicle trips are made. Some of these are delivery trips in which vehicle weight decreases or increases along the route. Segments of these trips could be affected by the change in the weight laws, whereas the less-loaded trips, which are made because the demand is only for a partial load, would be unaffected.

It was concluded that a shifting procedure would be used that would have the following characteristics: (a) heavily loaded vehicle trips would shift to a larger GVW in proportion to the previously mentioned ratio of practical maximum gross weights, (b) lightly loaded vehicles would be unaffected by the change in the law, and (c) empty-vehicle trips would be reduced in proportion to the reduction of loaded-vehicle trips.

It is postulated that the historical changes in GVW distributions that were used as a basis for the NCHRP shift were the result of factors other than changes in weight laws. To explore this phenomenon, a sensitivity study was conducted to examine the effects of several possible shifts on the computed savings in truck operating costs and increased 80-kN SALs. In general, truck operating cost savings are more sensitive than 80-kN SAL to shifts that increase the weight of lightly loaded trucks. Furthermore, for shifts that primarily affect heavily loaded vehicles, neither output is extremely sensitive to the shifting procedure.

The results obtained by using the shifts are shown in Figures 4-7. Results for the NCHRP procedure are based on one hundred 3-S2 trucks in scenario A and 61.7 trucks with the same payload in scenario B on a representative 1.6 km (1 mile) of Interstate highway. Results for the Texas procedure are based on one hundred 3-S2 trucks in scenario A and 85.7 trucks with the same payload in scenario B.

Note that for the adopted (TSDHPT) shift the following results were obtained:

1. Fewer empty trips resulted in savings.
2. Some partially loaded or lightly loaded trucks were unaffected.
3. The number of trucks possibly constrained by axle or GVW laws was reduced.
4. The number of trucks that exceed the present law (but are constrained by the future law) was increased. This resulted in increased savings.
5. Net savings in truck operating costs were affected much more than was the net increase in 80-kN SALs by the adopted shift versus the NCHRP shift.

Figure 8 shows the NCHRP and TSDHPT shifting factors. The TSDHPT shift is considered a "most likely" outcome; it must be pointed out, however, that the basis for its selection lacks precision. For much cargo, the point of diminishing returns as far as gross- or axle-weight limitations are concerned may already have been reached.

IMPLEMENTATION OF SCENARIOS

Currently, many farm-to-market roads and bridges are load-zoned for less than the vehicle weights considered for scenario A. But it was considered more reasonable to implement scenario A as if no restrictions existed since enforcement is difficult.

It was found that a significant number of existing bridges would require restrictive load zoning until replacement if the load limits were eased as in scenario B. In this study, it was assumed that the scenario B increase in the legal limit would be effective in 1980.

Figure 3. Results of use of NCHRP shift: (a) decrease in 80-kN SAL and (b) savings in truck operating costs.

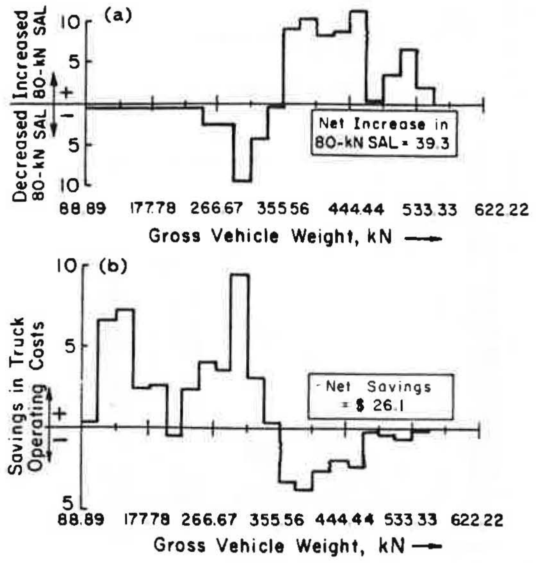
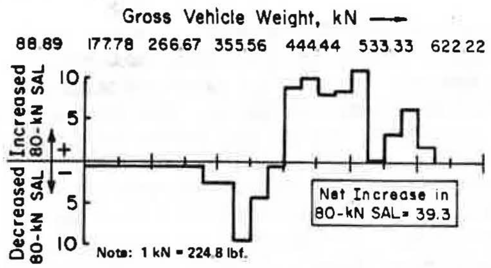
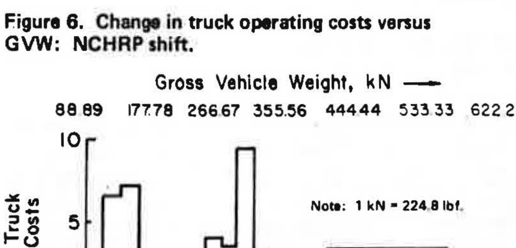


Figure 4. Change in 80-kN SAL versus GVW: NCHRP shift.



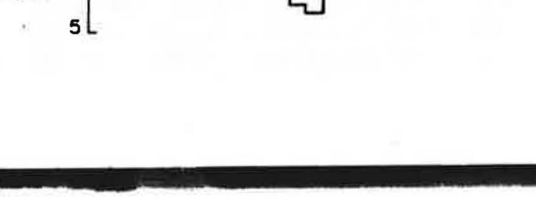
Note: 1 kN = 224.8 lbf.

Figure 5. Change in 80-kN SAL versus GVW: TSDHPT shift.



Note: 1 kN = 224.8 lbf.

Figure 6. Change in truck operating costs versus GVW: NCHRP shift.



Note: 1 kN = 224.8 lbf.

As a result of the load restriction on bridges, it was estimated that a 14-year program of bridge replacements would be necessary to fully implement scenario B.

HIGHWAY COSTS

Costs to maintain the existing network of pavements in good condition for the next 20 years were first estimated for scenario A. A second estimate was made for scenario B that considered only those items of highway maintenance and construction that would be affected by an increase in gross weight and axle loads. Included in the pavement costs were the costs of routine pavement maintenance, seal coats, and pavement rehabilitation. Also included were the estimated costs of upgrading structurally deficient bridges to carry the loadings of the two scenarios. Because pavement deterioration is caused by both truck loading and environmental stresses, the routine maintenance and seal-coat costs were assumed to remain constant in both scenarios. This assumption implies that routine maintenance and seal coats are sufficient to handle the environmental deterioration. Pavement rehabilitation costs were estimated to increase with the heavier trucks.

The resulting annual and cumulative cost estimates are shown in Figures 9 and 10. No data were available to estimate the costs of roads and streets off the state system. Table 1 gives the costs accumulated for the analysis period.

Other smaller but still significant increases in highway construction costs will be incurred. These costs have not been estimated because of either time limitations or lack of data.

BASIS FOR ESTIMATES OF PAVEMENT COST

A computer program entitled REHAB, originally developed in the McKinsey study (5), was improved and used to estimate the costs of pavement rehabilitation. Inputs to this program include the number of lane kilometers of pavement, their age, unit costs for rehabilitation, and survivor curves that portray the expected life of the pavements.

Data on lane kilometers and age (the time elapsed since construction, reconstruction, or rehabilitation) were obtained from files maintained by TSDHPT. The greatest number of recently constructed pavements has been on the Interstate system. Many non-Interstate lane kilometers have not been rehabilitated or reconstructed in the past 20 years. A proportionate mix of minor and major rehabilitations was used as input to REHAB to represent the rehabilitations that are most likely to occur.

Survivor curves that show the percentage of each pavement type that is expected to survive to a certain age were estimated by a panel of experienced pavement

Figure 7. Change in truck operating cost versus GVW: TSDHPT shift.

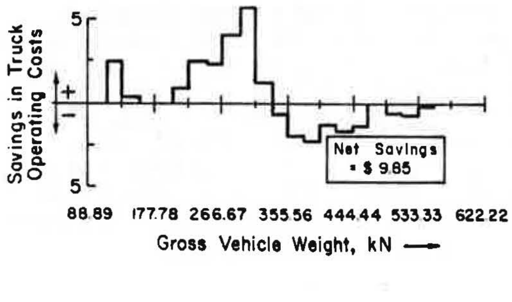


Figure 8. Multipliers adopted for shifting GVW distributions from scenario A to scenario B.

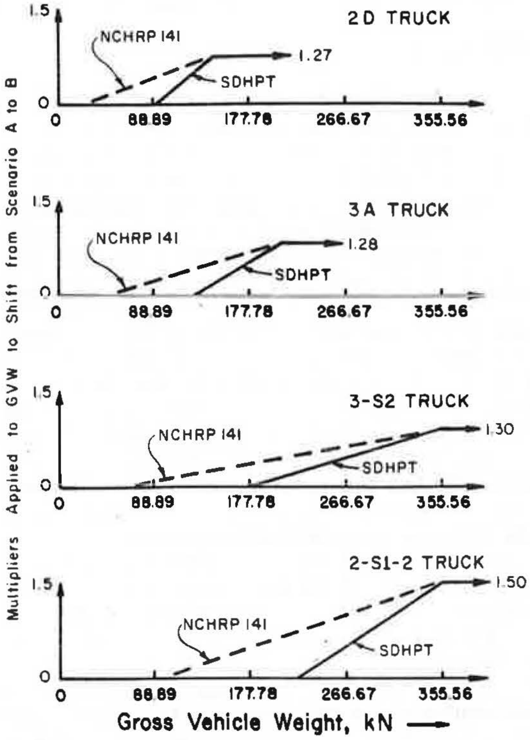


Figure 9. Cost to maintain existing pavement system, including maintenance, replacement, and rehabilitation.

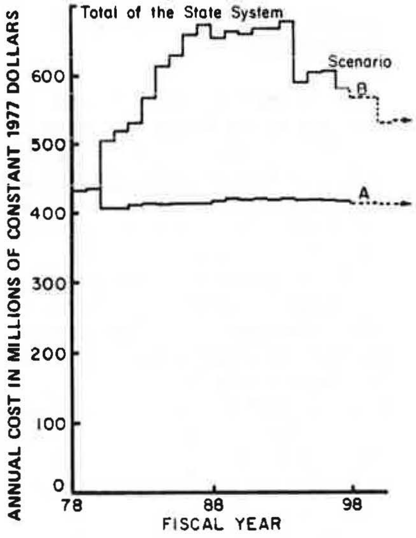
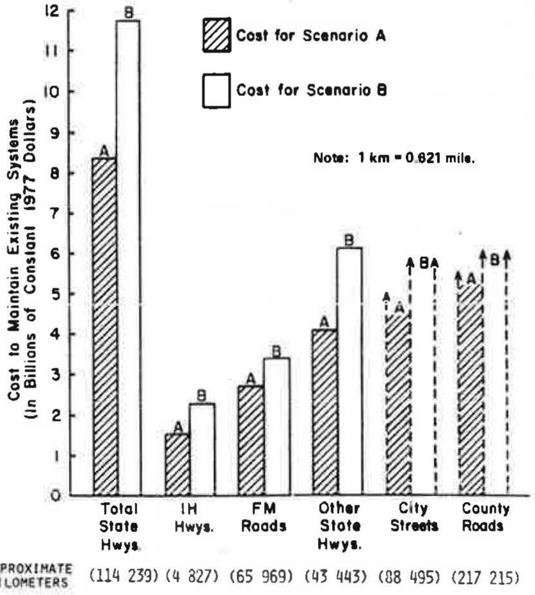


Figure 10. Cost to maintain existing pavement systems over 1977-1997 analysis period.



engineers for use by McKinsey and Company when the original REHAB model was developed. These curves were updated for this study by using unpublished information made available to the panel after the original estimate.

It was necessary to devise a method for adjusting pavement life when truck volume increases or heavier trucks are operated over a road segment. This adjustment procedure was based on the results of the AASHO Road Test (6). The expected pavement lives, i.e., the survivor curves, were shortened in proportion to the increase in equivalent axle loads supplied from the projected traffic discussed previously. It was also necessary to institute this additional aging of the pavements at the expected time of occurrence of the heavier trucks.

Another revision to REHAB was necessary. After the accelerated wearing out of the existing pavements, it would be desirable to redesign pavement structures to handle the heavy trucks properly. The program was revised to accomplish this for that portion of the pavements that receive major rehabilitation. The original survivor curves (those developed under more recent weight standards with longer lives) were then applied to these pavements. The increased cost to accommodate heavier trucks was estimated to be proportional to the ratio of the logarithm of the heavy traffic equivalencies to the logarithm of the original traffic equivalencies. This methodology is also based on the findings of the AASHO Road Test (7).

In summary, the necessary revisions changed the REHAB program so that when heavier trucks are applied the life curves are shortened, which causes the pavements to wear out faster. The "worn-out" pavements are then rehabilitated. Those that receive minor rehabilitation (thin overlays) continue to wear out at the accelerated rate. However, those that receive major rehabilitation are redesigned at an increased cost to handle the heavier trucks. These redesigned pavement structures now begin to wear out at a slower rate. The slower rate is the same rate as the original life curves for these pavements.

BASIS FOR ESTIMATES OF BRIDGE COST

The Federal Highway Administration (FHWA) and the American Association of State Highway and Transportation Officials (AASHTO) have developed a formula for calculating a sufficiency rating for bridges. This formula takes into consideration structural adequacy and safety features, serviceability and functional obsolescence, and essentiality for public use.

By using the above formula and current bridge-inspection data, a sufficiency rating was calculated for all bridges on the state highway system. The bridge-replacement costs for scenario A were developed by applying the same criteria used by FHWA in the National

Table 1. Comparative 20-year costs for scenarios A and B.

Scenario	Cost Category	Cost (millions of constant 1977 dollars) Interstate Highways	Farm-to-Market Roads	Other State Highways	Total State System
A	Pavement maintenance and seal coats	240	1 100	960	2 300
	Pavement rehabilitation	1 334	1 512	3 084	5 930
	Bridge replacements	4	76	50	130
Total		1 578	2 688	4 094	8 360
B	Pavement maintenance and seal coats	240	1 100	960	2 300
	Pavement rehabilitation	1 888	1 953	4 618	8 459
	Bridge replacements	172	376	554	1 102
Total		2 300	3 429	6 132	11 861

Figure 11. Savings in truck operating costs from 1977 to 1997: scenario B over scenario A.

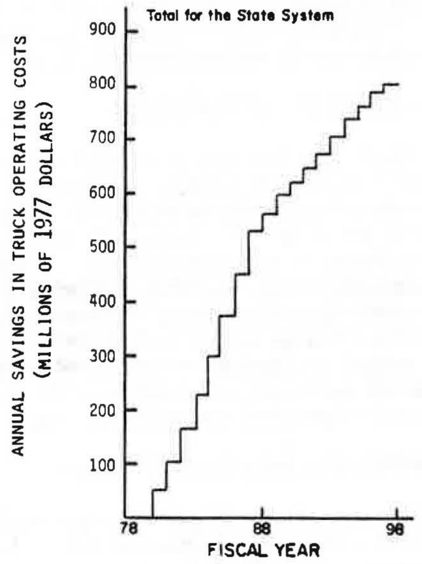
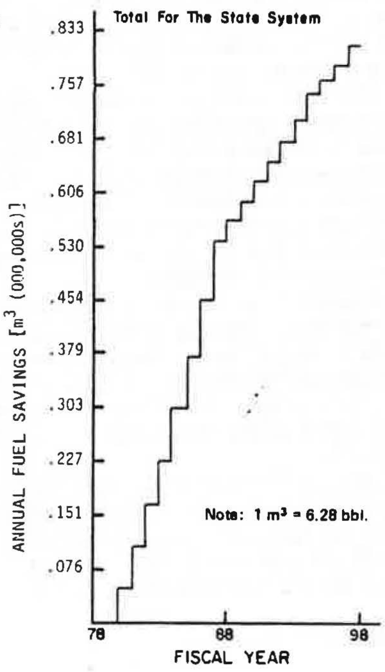


Figure 12. Truck fuel savings from 1977 to 1997: scenario B over scenario A.



Special Bridge-Replacement Program and adding additional load-restricted bridges.

Scenario B required evaluation of the effect of increased truck loading on bridges. This was performed generally in accordance with the methodology of the NCHRP procedure.

From computer listings that represented all of the bridges on the Texas highway system, 12 bridge types were selected as representative of the entire system of bridges. The usual ratio of dead-load moment to live-load moment was established for each type by calculations and estimates. These vary slightly from those reported in the NCHRP procedure to correspond more nearly to Texas conditions. Spans of each structure type were considered for four design loadings—H10, H15, H20, and HS20—and on each of three types of highway systems—Interstate, farm-to-market, and all others. Live-load moments attributable to one design truck or lane were taken from Appendix A of the AASHTO Bridge Specification for each span. Moments caused by one truck from the proposed legal loading, scenario B, were calculated for each span by using a computer program called BMCOL 43 (8). Trucks represented by scenario B were considered, and the absolute maximum moment for the span was used. The ratio of the scenario B moment to the design-load moment represents the increase in live-load moment for each span of each structure type. To convert this to stresses, the ratio of dead to live load was used. The formula selected for calculating overstress is that used in NCHRP Report 141.

In order to evaluate the effects of the overstress, allowable values for the various types of bridges were established. Whenever the calculated overstress exceeded the allowable overstress, all bridges represented by the type-span loading were considered inadequate for scenario B loads and therefore required replacement. Where the overstress was less than that allowable, the bridges were considered adequate.

The deck area of bridges that are currently load restricted was tabulated and subtracted from the total to provide the bridge deck area that would be affected by the proposed changes for scenario B. The bridge replacement costs calculated are given in Table 1.

DECREASED TRUCK OPERATING COSTS

The primary benefit obtained by the hypothesized change in the weight limit accrues in the form of reduced operating costs in the trucking industry. The projected savings are shown in graphical form in Figure 11. The projected $9.12 billion savings that occurs within the 20-year analysis period was calculated by using a procedure similar to that used in NCHRP Report 141. The data base for operating costs was obtained by updating the cents-per-ton-mile numbers described in the NCHRP report. The components of the total operating costs per ton kilometer are (a) repair and servicing,

Table 2. Twenty-year incremental costs and savings associated with shift to heavier trucks.

Type of Road	Additional Highway Costs (billions of 1977 dollars)	Savings in Truck Operating Costs (billions of 1977 dollars)	Fuel Savings (millions of cubic meters)
Interstate	0.72	4.57	4.58
Farm-to-market	0.74	0.71	0.68
Other state highways	2.04	3.84	3.90
Total for highway systems	3.50	9.12	9.16

Note: 1 m^3 = 6.28 bbl.

(b) tires and tubes, (c) fuel, (d) driver wages and subsistence, (e) overhead and indirect costs, and (f) depreciation and interest.

After several different cost indices were considered, the general consumer price index (CPI) was finally selected as the mechanism for updating 1970 truck operating costs to current 1977 levels. A recent study conducted by the Hertz Corporation suggests that increases in truck operating costs since 1975 were larger than those reflected in the CPI. The Hertz data, however, were not incorporated in this analysis primarily because of time constraints. The savings shown in Figure 11 are probably on the low side because of the relatively more rapid increase in fuel costs, which is not reflected in the estimates.

The projected ton-kilometer data were allocated to the three highway systems and to the selected vehicle types within each system. The hypothesized change in truck weight limits allowed the heavier vehicles to haul more ton kilometers, which resulted in fewer trips and therefore lower aggregated costs for truck operations in scenario B.

Cost savings by types of systems were calculated on a disaggregated basis. The major finding is that 50 percent of the calculated savings occur on the Interstate system, 43 percent on all other highways, and only 8 percent on the farm-to-market network.

FUEL SAVINGS

A separate analysis was conducted to examine what, if any, fuel savings might result from an increase in truck weights. The following model was selected from a review of the literature (9-13) to relate liters of fuel per kilometer and GVW:

$$L/km = 0.327 + 0.003\,41\ GVW \qquad (1)$$

Intercity ton-kilometer fuel consumption rates were calculated by using the above equation. Projected fuel savings are shown in Figure 12. The fuel saved would be about 1.8 percent of the amount needed without the increase in truck weights. The total 20-year savings—9.16 million m^3 (2.42 billion gal)—represents an amount approximately equal to 28 percent of all the motor fuel used in Texas in 1975.

EFFECTS OF AIR AND NOISE POLLUTION

Some analyses were completed in an attempt to relate pollution from vehicles and changes in vehicle weights. The results are derived from previously developed models (14-16). In the three major Texas metropolitan areas (Dallas-Fort Worth, Houston-Galveston, and San Antonio), a 3-6 percent reduction in air pollution caused by heavy trucks was calculated. This calculated decrease represents a less than 1 percent reduction in transportation-generated pollution.

The available data and research on noise pollution indicated that the hypothesized increase in axle-weight limits should generate only small increases in noise along highways. Estimates of these reductions were not calculated because of the incompleteness of techniques in the state of the art (17-24).

OTHER CONSIDERATIONS

Many significant considerations that are involved in size and weight changes in truck use were not considered explicitly in this study. These include, but are not limited to, geometric redesign of streets and highways to accommodate larger trucks, highway safety considerations, costs of replacing bridges and pavements other than those on major highways, implications of new design trucks and performance, changes in technology, and externalities associated with heavier truck loads and the freight shares of rail pipelines and waterways attributable to the modal shifts.

FINDINGS AND CONCLUSIONS

The major approach used in this study involved estimating the comparative maintenance and rehabilitation costs of perpetuating the state highway system under current limitations on vehicle weights and on future use under different weight conditions. These costs were based on alternative weight limitations on trucks and did not consider alternative vehicle sizes.

The incremental costs for scenarios A and B associated with heavier truck loads and the corresponding savings in truck operating costs for the 20-year analysis period were computed for the three highway classes. Also included was an estimate of fuel savings. These are given in Table 2.

It was determined in the study that, if changes in legal weight limitations were undertaken, further analysis would be justified to select those routes that would carry relatively large freight tonnages and would cost relatively less to upgrade.

It can also be inferred that, once the highways have been upgraded to handle heavier trucks, the additional cost to maintain the system for the heavier trucks will decrease. In other words, annual additional costs beyond 1997 would be less than the annual costs that would occur during upgrading.

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Fatigue Damage to Flexible Pavements Under Heavy Loads

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A modified Chevron N-Layer computer program has the capability of calculating the "work" done on pavements by the total load of various types of trucks. Seven truck groups are examined: two-tire and four-tire single axles, tandems, triaxles, and four-, five-, and six-axle groups. The two-tire (front steering) axle has the most severe damage relationship. Damage factors based on the AASHO Road Test and factors based on the concept of strain energy density are compared in the analyses. Various vehicle configurations and ranges of loads are discussed and evaluated in terms of damage per trip.

In the past, pavement design engineers have generally sought merely to sustain current statutory limits on axle loads—that is, to avoid destructive or catastrophic damage to pavements and premature depletion or ruination of physical assets (premature in this context implies that the damage occurs before the responsible agency is fiscally capable of restoring and maintaining the system under the changed circumstances). If it were feasible and practical to manufacture highway truck-trains that had perfect cornering and guidance capabilities in their trailing axles, bulk raw materials such as ores, coal, logs, and freight could be transported on highways more efficiently than they can by some of the simpler types of trucks, which are currently being overloaded by some owners and operators. These ideas issue from the "centipede concept", which fostered railroads and freight trains. These factors should be, and perhaps are being, considered by automotive designers and