# Quantifying Incremental Pavement Damage Caused by Overweight Trucks

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# ABSTRACT

Significant increases in commercial truck loadings across the Saskatchewan road network have resulted in accelerated damage to the provincial highway system. This accelerated damage has decreased the expected performance life of many of these roads and also increased maintenance and rehabilitation requirements and costs. Although provincial highways have maximum commercial legal load limits and most commercial carriers are compliant, it is inevitable that some trucks will exceed legal load limits.

In the past, difficulties have been encountered in efforts to quantitatively account for incremental pavement damage due to overweight vehicles. This is due to the fact that road agencies typically employ empirical methods to design and assess roadway performance. With its aged state, the performance prediction of incremental damage on Saskatchewan highways resulting from commercial vehicle overloading is difficult to quantify using empirical highway design methods and pavement surface distress surveys.

This study employed a mechanistic-based pavement analysis framework. Using Saskatchewan primary and secondary highway structural asset management data based on heavy weight deflectometer (HWD) network deflection data, the incremental damage from typical trucks operating on Saskatchewan highways was determined. In total, overloading the Saskatchewan highway network by 15 percent trucks (assuming 30,000 truck trips per day) province wide results in an overall daily cost of $621 per km per day and an overall annual cost of $226,677 per km per year. Based on the impact analysis carried out in this study, reducing the number of overweight trucks on Saskatchewan's highway network could significantly reduce road damage costs. Savings will not only be seen in terms of preservation and rehabilitation costs, but also in overall structural performance of the road.

## INTRODUCTION

It is well known that overweight vehicle loading on roads result in increased damage to both pavement structures and bridges (1,2,3,4,5,6,7,8,9). Repetitive loadings have been shown to directly drive pavement fatigue, rutting, and accelerated substructure wetting-up. Overweight vehicles accelerate pavement damage, increasing the cost to agencies that oversee the maintenance of road infrastructure assets (5,6). Overweight vehicles damage pavements more than compliant vehicles and it has been shown that pavement damage relationship to loading can follow a fourth order relationship (5,6,10,11). However, given Saskatchewan's severe field state conditions, reliance on the empirical pavement damage relationships found in the American Association of State Highway Officials (AASHO) Road Test may be considered misleading for predicting pavement damage determination in Saskatchewan.

Given the rising costs of road construction, maintenance, and rehabilitation, overweight vehicles contribute significantly to increased road preservation costs (6). It is estimated by the Transportation Research Board National Research Council that overweight trucks cost between $160M and $670M annually in national pavement costs (11). In addition to the economic concerns of increased maintenance costs, the damage caused by overweight vehicles also pose safety risks due to rutting, potholes, and other distresses to the pavement as a result of increased loading (3,12). Other agencies have analyzed the costs associated with incremental damage created by overweight vehicles and have found the costs to be substantial enough to warrant an evaluation of increasing financial resources allocated for weight enforcement measures (6,9,12).

The Arizona Department of Transportation (ADOT) found that overweight vehicles are responsible for millions of dollars worth of damage that relate to the life span and maintenance of state highways (6). In ADOT's research, it was found that overweight vehicles drive a cost between $12M and $53M per year in uncompensated damages. Based on the ADOT Simplified Highway Cost Allocation Model, $6M to $27M per year would be saved by avoiding the pavement damage caused by overweight trucks if the mobile enforcement budget were doubled and was 50 percent effective at eliminating non-compliant overweight vehicles. The higher end of this estimate would result in a four or five to one benefit/cost ratio for doubling the mobile enforcement (6).

In examining public expenditures on roadways, including the costs of construction, operation, and maintenance, the Victoria Transport Policy Institute also investigated how these costs are associated with vehicle types (9). The results of their research found that the damage costs due to overloaded trucks ranged from $0.08 to $2.50 per ton-mile, which depended on the weight of the overweight vehicle. It was estimated that heavy, overweight trucks compose approximately nine percent of Canadian vehicle traffic yet are responsible for 25 percent of all roadway costs (9).

In Saskatchewan, policies and regulations are put in place by the Ministry's Saskatchewan Transport Compliance to enforce the province's weight restrictions (13,14). Enforcement methods include highway weigh scale locations and roaming highway patrol. Eleven weigh scales located on Saskatchewan primary highways provide weight enforcement, however they do not generate a high degree of commercial truck compliance due to weigh scale evasion and route selection (1,2,3,4,5).

Incremental pavement damage due to overweight vehicles has not been quantitatively determined in Saskatchewan due to the fact that empirical methods are used to design and assess roadway performance. A mechanistic based methodology using non-destructive road deflection measurements provides an actual *in situ* evaluation of structural road integrity and directly quantifies road response simulative of actual truck loading in Saskatchewan field state conditions.

## Background

Saskatchewan's economy is dependent on bulk commodity export including agriculture, livestock, oil, and mined mineral resources. Over the years, the shift from rail transportation to road transportation has increased truck traffic on Saskatchewan highways (2,7). Saskatchewan's economy predominantly depends on interprovincial and international trucking transportation, relying on Saskatchewan highways which are vital to the movement of goods. SMHI is responsible for approximately 14,400 centerline kilometers of primary highways and approximately 11,000 centerline kilometers of secondary highways (13). Primary highways are full structural pavements and are legislated to allow heavier vehicle weights relative to secondary highways.

Saskatchewan's highway network was designed based on the Association of State Highway and Transportation Officials (AASHTO) Guide for Design of Pavement Structures. This design method uses the cumulative number of 18,000 lb equivalent single axle loads (ESALs) for the design life of the pavement structure and is based on load equivalency factors that were determined during the AASHO Road Test in Ottawa, Illinois in the 1960s (10). Equivalent single axle load factors (ESALFs) across load spectra were determined for single, tandem, and tridem axles and estimated to increase as a function of the ratio of load by 18,000 lb raised to the fourth power. Consequently, it was determined that pavement damage increases exponentially with increasing truck loads (10).

When applied to Saskatchewan field state conditions, several limitations of the ESAL based pavement design and performance prediction method exist. Firstly, Saskatchewan's commercial traffic loading, pavement structures, and environmental conditions are significantly different from those used in the AASHO Road Test. Secondly, the values established in the AASHTO Guide for Design of Pavement Structures were considered to be the best available technical approach to pavement design at the time – over 50 years ago (10). Also, at the time of the AASHO Road Test, limited knowledge existed regarding the long term performance of pavement structures, particularly with regards to ageing road structures and the relationships between damage loading and climatic conditions. Finally, given Saskatchewan's severe climatic conditions and ageing infrastructure, the reliance on AASHO ESAL formulations alone can be misleading for pavement structure life cycle performance prediction in Saskatchewan.

The pavement structures built in Saskatchewan are constructed for varying vehicle weights projected over the road's design life. Vehicle weights are accounted for in the design process using both ESALs and design life. Maximum axle weights for different vehicle configurations are provided in the Ministry's *Vehicle Weight and Dimensions Regulations* for both primary and secondary highways (14).

Saskatchewan's primary highways are constructed of flexible pavement structures typically comprised of a hot mix asphalt concrete (HMAC) surface, granular base layer, and granular subbase layer placed as an integrated surfacing structure on the *in situ* subgrade. The pavement structures of Saskatchewan's secondary highways can vary significantly ranging from full depth flexible pavement structures comprised of a HMAC surface, base layer, and subbase layer to thin granular pavement structures including a seal coat surface and non-structural roads that include a seal coat with little or no granular layers. Generally, secondary highways have thinner overall structures relative to primary highways and are designed and built for lower weight limits.

Although pavement deterioration over years of service is unpredictable, it is known to be primarily a factor of traffic loading, pavement structure thickness, material quality, and environmental and climatic conditions (1,2,7,10). If a pavement structure is subjected to one or a combination of increased traffic loads, poor initial construction, degradation of road materials, or severe environmental conditions over time, it is at risk of further pavement deterioration or pavement failure (1,2,7,10). Climatic effects, particularly in jurisdictions with severe freeze-thaw conditions, have a significant impact on the performance of a pavement structure. The Ministry recognizes that pavement structures weaken during the spring thaw period and restrict the allowable weights of truck traffic on its secondary road network. Typically spring weight restrictions start in the first week of March and are in place for up to six weeks (13).

The Ministry of Highways and Infrastructure have assembled both network level and project level structural road condition data measured using non-destructive heavy weight deflection (HWD) testing over the past ten years. Non-destructive structural road condition data can identify roads that are more susceptible to damage due to overweight loads and/or climatic effects (7). HWD data can be used to assess incremental damage as a result of overweight loads. Past projects utilizing non-destructive testing have demonstrated the ability to assess critical road structural measures, enabling road managers to better optimize limited infrastructure preservation and structural rehabilitation budgets.

### Objective

The objective of this study was to use existing Saskatchewan primary and secondary highways structural asset management deflection data based on heavy weight deflectometer (HWD) network deflection data to quantify the incremental damage from typical trucks operating in Saskatchewan carrying loads that exceed the allowed vehicle weights.

## SCOPE AND METHODOLOGY

Varying structural conditions, load spectra and allowable vehicle weights were considered in this analysis. This study made conservative assumptions to model the incremental load damage effects of overweight trucks to Saskatchewan pavement structures. This study used existing Saskatchewan highways HWD deflection data to determine mechanistic based load equivalency factors. These deflection-based factors, in combination with truck weight sensitivity analysis and preservation life-cycle costing, provided case study examples and a network level sensitivity analysis.

The scope of this study included assumptions to assure the analysis was conservative. This study assumed pavement deterioration due to commercial vehicle loading can be related to pavement deflections. A deflection ratio was calculated to estimate the load response of roads in various condition states using the average deflection under primary loads for primary highways as a baseline. HWD measurements were taken at a minimum of 200 meters across the full width of the road in the inner wheelpath and outer wheelpath, using the heavy weight deflectometer shown in Figure 1.

A sample of 56.51 kilometers of primary highways and a sample of 402.70 kilometers of secondary highways were chosen for this analysis. Peak surface deflections were used to assess the current condition state of the road. Since primary and secondary highways are subject to different weight restrictions and often different pavement structures, the peak surface deflection condition rating scales used to calculate the deflection ratios used in this analysis are listed in Table 1.

Saskatchewan highways are typically designed using the *AASHTO Guide for Design of Pavement Structures.* The equivalent single axle load factor (ESALF) for tandem and tridem axle groups were calculated for axle loads converted from pounds to kilograms. Based on a typical Ministry design, a structural number of two was used.

Damage incurred by overweight trucks was assessed using actual axle weights and assumed overloading of a 5 axle semi-trailer truck and an 8 axle B-train truck. When estimating the amount a truck is overweight, it was assumed that the truck would be overweight on all axles by the same amount, with the exception of the steering axle. The steering axle was left out of scope when determining the incremental damage of overweight trucks.

SMHI provided a typical maintenance and rehabilitation strategy over a pavement life of 25 years that would be conducted, at a minimum, for secondary and primary highways, in addition to estimated costs. This study did not account for initial construction costs as the majority of Saskatchewan highways are already in existence and are in need of maintenance and rehabilitation treatments. The equivalent uniform annual cost for both secondary and primary highways was determined based on an initial pavement life of 25 years, a five percent discount rate, and the preservation costs provided by the Ministry.

It was assumed that incremental pavement damage due to overloaded trucks can occur in winter months as well as other seasons, even though the road structure itself is structurally sound from a vertical deflection state perspective. Recent development in damage mechanics applied to pavement performance prediction show damage due to overloaded trucks occurs year round (13,14). Therefore, in order to factor out the pavement damage costs related to climatic effects, the incremental damage costs derived from the analysis were reduced by 50 percent. Therefore climatic effects are out of the scope of this study.

## STUDY RESULTS

### Mechanistic ESALs

Using traffic data provided by the Ministry, both conventional ESALs and mechanistic ESALs (M.ESALs) were calculated for comparison purposes, for a design life of 15 years. To calculate the mechanistic equivalent axle load (M.EAL), SMHI's equivalent axle load (EAL) for each highway segment was multiplied by the deflection ratio. The load response of each road in terms of its mean peak surface deflection (mm) under primary loads was measured using the HWD. The deflection ratio, as mentioned in the scope, compared the measured primary deflection values to the average HWD deflection under primary loads for primary highways as a baseline.

Figure 2 presents the calculated conventional ESALs and the M.ESALs for each primary and secondary highway road segment. Primary highways carry primary weight traffic and often are designed with higher ESALs. Therefore, primary highway ESALs are greater than secondary highways ESALs, as seen in Figure 2.

As seen in Figure 2, in cases such as primary highway Control Section (C.S.) 1-10B and secondary highway C.S. 55-14, the calculated M.ESALs are greater than the conventional design ESALs. This demonstrates that the road segment is in good condition and has not reached the end of its performance life. In cases such as primary highway C.S. 11-08 and secondary highway C.S. 51-05, the calculated M.ESALs are less than the conventional design ESALs. This demonstrates that the road segment is in poor condition. Comparing conventional and mechanistic ESALs shows that conventional EALs do not adequately reflect the actual damage of the pavement structure. The use of conventional ESALs is a fit-all solution whereas the use of mechanistic ESALs reflects the performance of the road structure as M.ESALs are calculated using mechanistic-based HWD peak surface deflections.

### Analysing Truck Sensitivity

Analysing the impact truck axle weights have on Saskatchewan roads was conducted using two typical trucks common on Saskatchewan primary and secondary highways: the 5 axle semi-trailer truck and the 8 axle B-train truck. Damage incurred by overweight trucks was assessed using actual axle weights and assumed overloading. The 5 axle truck consists of a steering axle and two tandem axle groups and is commonly used for grain and freight haul. The 8 axle truck consists of a steering axle, two tandem axle groups, and one tridem axle group and is commonly used for bulk resource haul. Table 2 lists typical amounts that trucks will typically be overweight and the corresponding ESAL factor (ESALF). It was estimated that trucks would typically be overweight by two percent; five percent; ten percent; 20 percent; and 30 percent over legal loads.

Figure 3 presents the mechanistic equivalent axle loads (M.EALs) for typical 5 axle and 8 axle trucks overloaded on both tandem axle groups by two to 30 percent on primary highway road segments. Truck M.EALs were calculated using the deflection factor for each road segment. Figure 4 presents the M.EALs for a typical 5 axle truck and 8 axle truck overloaded on both tandem axle groups by 2 to 30 percent on secondary highway road segments. Truck M.EALs were calculated using the deflection factor for each road segment.

The truck sensitivity analysis presented in Figure 3 and Figure 4 demonstrated the following conclusions:

- Overloading trucks increases the M.EAL for both primary and secondary highways.
- The M.EAL depends on the amount a truck is overloaded, the type of truck that is overloaded, and the present field state condition of the road structure.
- An overloaded 8 axle truck does more incremental damage to the pavement structure than an overloaded 5 axle truck.

**Cost of Overloading**

The equivalent uniform annual cost (EUAC) for both secondary and primary highways was determined based on an initial pavement life of 25 years, a five percent discount rate, and typical preservation costs determined by SMHI. Although the design life is 15 years, Saskatchewan highways are typically maintained and rehabilitated over a pavement life period of 25 years. The EUAC was applied as it is useful when budgets are established on an annual basis; such is the case for the Ministry of Highways and Infrastructure.

To quantify the cost of overweight trucks' incremental damage on Saskatchewan highways, both primary and secondary highways in various condition states were analyzed. The condition states include good, fair, and poor, and were assessed using the peak surface deflections determined by the HWD survey, as previously listed in Table 1. To determine the cost of damage created by overweight 5 axle and 8 axle trucks, the reduction in life from SMHI's Design ESALs pavement life to the overweight pavement life was determined. The cost of overloading primary and secondary highways was calculated per truck per kilometer (km) travelled. These costs were reduced by 50 percent to omit the cost of damage due to climatic effects.

Table 3 and Figure 5 present the cost of overloading (per truck per km) for both primary and secondary highways omitting the cost of climatic effects to pavement damage (assumed to be 50 percent of total costs). As seen in Table 3 and Figure 5, the cost of overloading is greatest on roads in poor condition with 8 axle trucks that are overweight, as expected. As also seen in Table 3 and Figure 5, the cost of overloading is greater on secondary highways when compared to primary highways.

To illustrate the overall cost implication of overweight trucks on Saskatchewan's highway network using the costs presented in Table 3 and Figure 5, a scenario of overloading trucks in Saskatchewan is presented in Figure 6. This scenario was determined based on input from both Ministry preservation and Traffic Compliance staff and made various educated assumptions:

- It was assumed that there are an estimated 30,000 truck trips per day on the highway network and an estimated 15 percent of those trucks are overweight.
- Assuming an 80/20 split of the overweight trucks on the primary and secondary highway networks: 3,600 truck trips per day were assumed overweight on the primary highway network and 900 truck trips per day were assumed overweight on the secondary highway network.
- The road condition of each primary and secondary highway network was assumed to be the sample population split of good, fair, and poor road conditions (50% good, 38% fair, and 12% poor for the primary network, and 60% good, 33% fair, and 7% poor on the secondary network).

- It was also assumed that a 50/50 split of the overweight trucks are overweight 5 axle and 8 axle trucks, on each road condition of each primary and secondary highway networks.

As seen in Figure 6, overweight trucks on primary highways result in an overloading cost of $381 per km of average haul length per day. Also seen in Figure 6, overweight trucks on secondary highways result in an overloading cost of $240 per km of average haul length per day. Based on the assumptions made, overloading the Saskatchewan highway network by 15 percent trucks results in an overall daily cost of $621 per km per day and an overall annual cost of $226,677 per km per year.

Based on the cost of overloading Saskatchewan highways network determined in the flowchart in Figure 6, the cost of overloading was calculated for varying average haul lengths. As seen in Table 4, the total cost per day and cost per year were determined for average haul lengths of 100 km, 250 km, and 500 km. When considering the effect of average haul length on the overall cost of overloading on primary and secondary highways, the cost of overloading per kilometer increases with average haul length. Therefore, overweight trucks that haul further distance cause more incremental damage. In summary, the cost of overloading increases with average haul length.

## DISCUSSION AND RECOMMENDATIONS

This study used existing Saskatchewan primary and secondary highways structural asset management deflection data based on heavy weight deflectometer (HWD) network deflection data to quantify the incremental damage from typical trucks operating in Saskatchewan. The focus of this study was on overweight trucks carrying loads that exceed the allowed vehicle weights. This study showed pavement deterioration due to commercial vehicle loading is related to pavement deflections.

Comparing conventional and mechanistic ESALs showed that conventional ESALs do not adequately reflect the actual damage of the pavement structure when formulated using empirical-based performance models. The use of conventional ESALs is a fit-all solution whereas the use of mechanistic ESALs reflect the actual structural capacity of the road structure. An analysis of overloading 5 axle and 8 axle trucks showed that overloading trucks increases the M.EAL for both primary and secondary highways. Also, an overloaded 8 axle truck does more incremental damage to the pavement structure than an overloaded 5 axle truck.

It was calculated that overloading the Saskatchewan highway network by 15 percent trucks (assuming 30,000 truck trips per day) results in an overall daily cost of $621 per km per day and an overall annual cost of $226,677 per km per year. When considering the effect of average haul length on the overall cost of overloading on primary and secondary highways, the cost of overloading per kilometer increases with average haul length. Therefore, overweight trucks that haul further distance cause more incremental damage to the roads.

Based on the impact analysis carried out in this study, reducing the number of overweight trucks on Saskatchewan's highway network could significantly reduce road damage costs. Savings will not only be seen in terms of preservation and rehabilitation costs, but also in overall structural performance of the road. Effective vehicle weight management is essential all year round to ensure optimized pavement preservation and life cycle economic utility

This research used mechanistic-based HWD peak surface deflections to quantify the incremental damage from typical trucks carrying loads that exceed the allowed vehicle weights in Saskatchewan. This study demonstrate that there is a significant financial impact if roads deteriorate sooner than predicted due to increased loads. Future research may include mechanistic-based pavement damage prediction models to estimate road deterioration.

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**Table 1 Peak Surface Deflection Condition Rating Scale**

| Rating | Primary Highways | Secondary Highways |
|---|---|---|
| Good | < 0.65 mm | < 0.75 mm |
| Fair | 0.65 mm to 1.00 mm | 0.75 mm to 1.50 mm |
| Poor | > 1.00 mm | > 1.50 mm |

**Table 2 Typical Overweight Truck Weights, Amount Overweight, and ESALF**

| Axle | Primary Highway | | | Secondary Highway | | |
|---|---|---|---|---|---|---|
| | Actual Weight (kg) | Amount Overweight (kg) | ESALF | Actual Weight (kg) | Amount Overweight (kg) | ESALF |
| **Tandem** | **17,000** | - | **1.750** | **14,500** | - | **0.823** |
| **Tandem +2%** | 17,340 | +340 | 1.900 | 14,790 | +290 | 0.950 |
| **Tandem +5%** | 17,850 | +850 | 2.150 | 15,225 | +725 | 1.200 |
| **Tandem +10%** | 18,700 | +1,700 | 2.500 | 15,950 | +1,450 | 1.350 |
| **Tandem +20%** | 20,400 | +3,400 | 3.700 | 17,400 | +2,900 | 1.950 |
| **Tandem +30%** | 22,100 | +5,100 | 5.100 | 18,850 | +4,350 | 2.650 |
| **Tridem** | **24,000** | - | **1.660** | **21,000** | - | **0.825** |
| **Tridem +2%** | 24,480 | +3,480 | 1.800 | 21,420 | +420 | 0.900 |
| **Tridem +5** | 25,200 | +4,200 | 2.000 | 22,050 | +1,050 | 1.000 |
| **Tridem +10%** | 26,400 | +5,400 | 2.400 | 23,100 | +2,100 | 1.400 |
| **Tridem + 20%** | 28,800 | +7,800 | 3.450 | 25,200 | +4,200 | 2.000 |
| **Tridem +30%** | 31,200 | +10,200 | 4.700 | 27,300 | +6,300 | 2.700 |

**Table 3 Cost of Overloading Omitting Cost of Climatic Effects**

| Road Condition Rating | Primary Highway | | Secondary Highways | |
|---|---|---|---|---|
| | Cost of Overloading (per truck per km) | | | |
| | 5 Axle Trucks | 8 Axle Trucks | 5 Axle Trucks | 8 Axle Trucks |
| **Good** | $ 0.01 | $ 0.02 | $ 0.10 | $ 0.13 |
| **Fair** | $ 0.11 | $ 0.17 | $0.28 | $ 0.42 |
| **Poor** | $ 0.25 | $ 0.50 | $ 0.90 | $ 1.41 |

**Table 4 Cost of Overloading Saskatchewan's Highway Network for Varying Haul Lengths**

| Average Haul Length | Cost per day | | Total Cost per day | Total Cost per year |
|---|---|---|---|---|
| | Primary Highways | Secondary Highways | | |
| **1 km** | $ 381 | $ 240 | $ 621 | $ 226,677 |
| **100 km** | $ 38,139 | $ 23,964 | $ 62,103 | $ 22,667,655 |
| **250 km** | $ 95,437 | $ 59,911 | $ 155,258 | $ 56,669,138 |
| **500 km** | $ 190,695 | $ 119,821 | $ 310,516 | $ 113,338,276 |

## LIST OF FIGURES

Figure 1 Heavy Weight Deflectometer

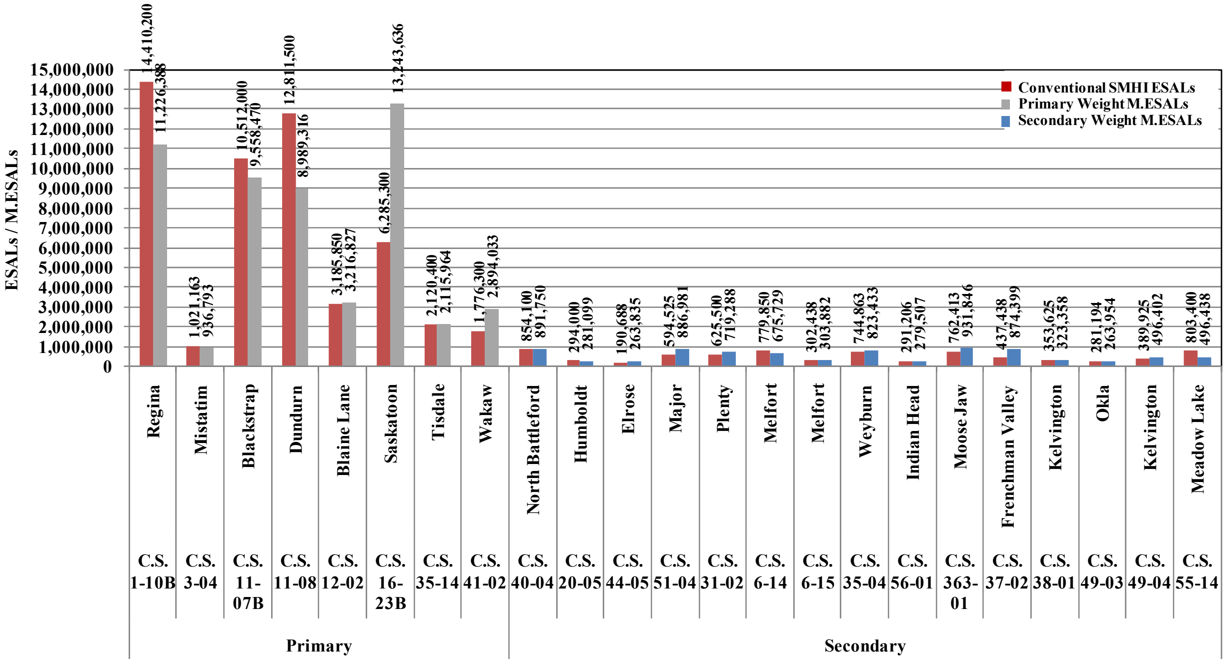
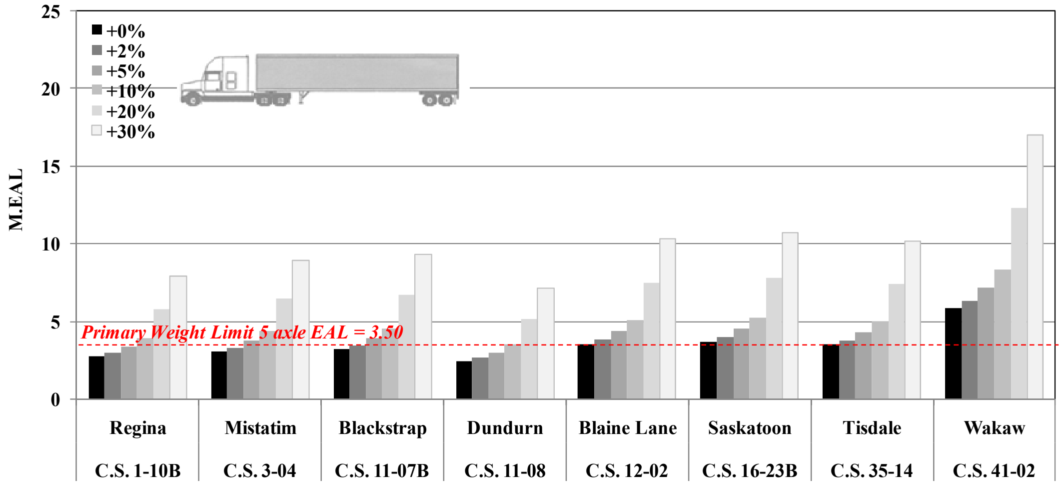
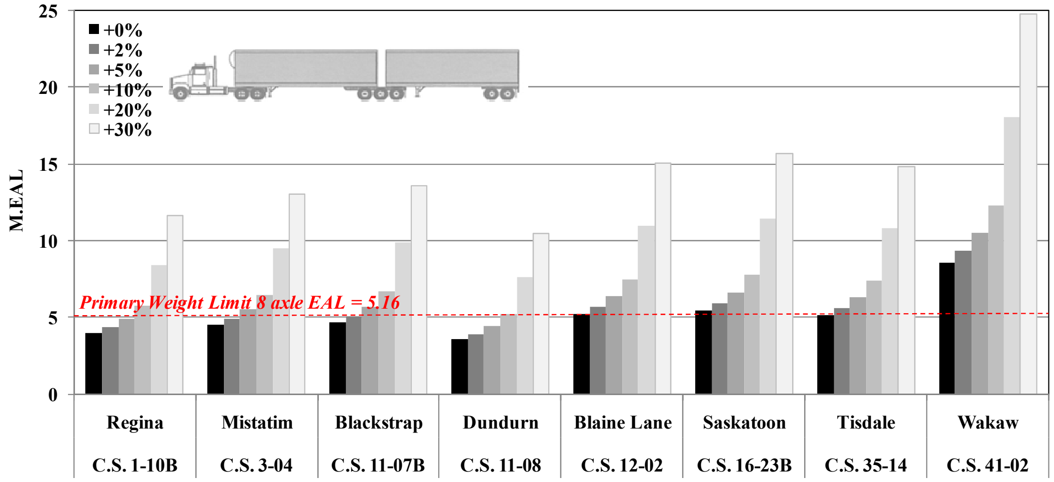


Figure 2 Calculated M.ESALs for Sample of Saskatchewan Highways Network Data for Design Life (N) of 15 Years

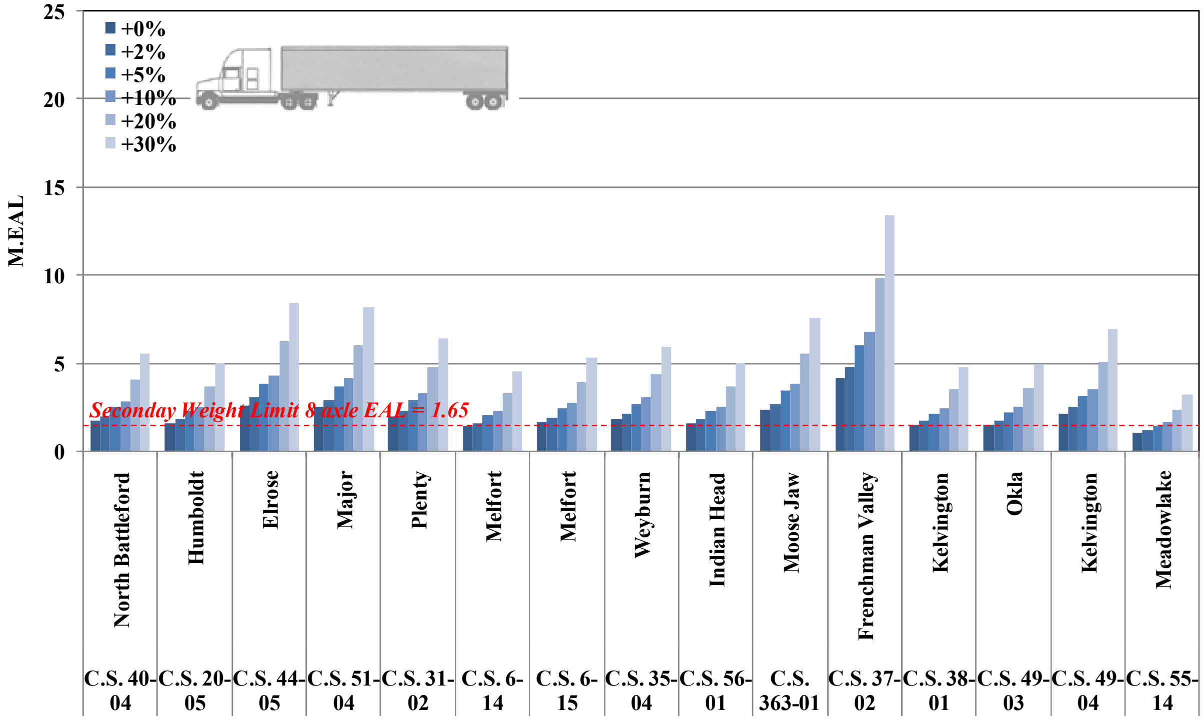


a) Typical 5 Axle Truck Overloaded up to 30 Percent

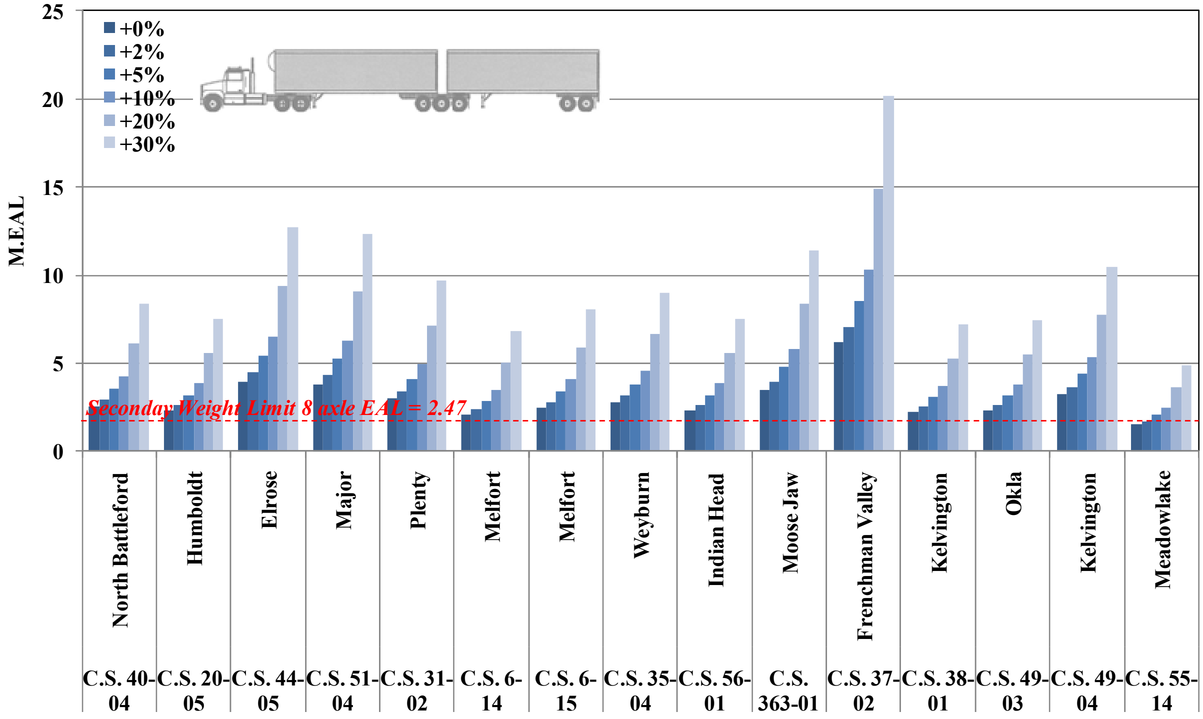


b) Typical 8 Axle Truck Overloaded up to 30 Percent

Figure 3 M.EALs for Network Data – Primary Highways

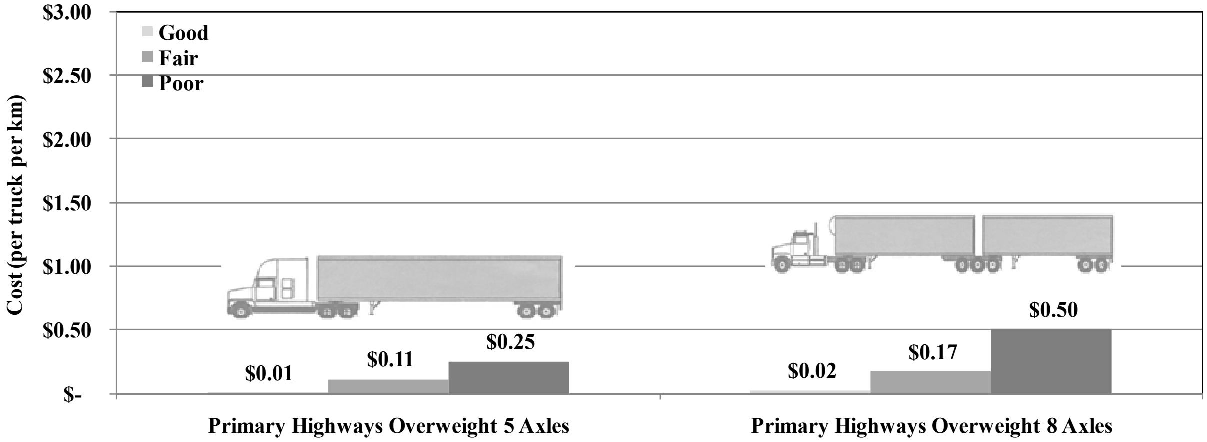


a) Typical 5 Axle Truck Overloaded up to 30 Percent

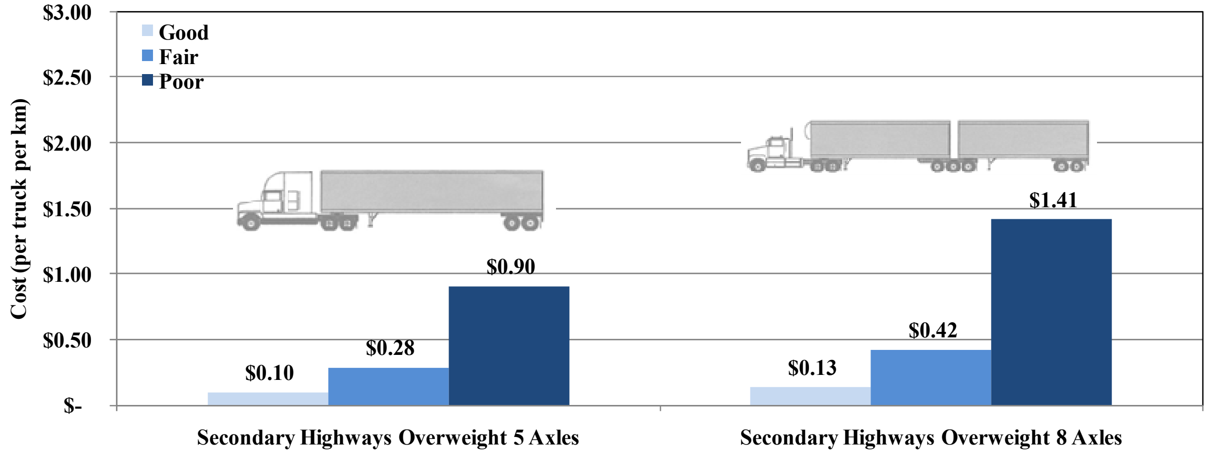


b) Typical 8 Axles Truck Overloaded up to 30 Percent

Figure 4 M.EALs for Network Data – Secondary Highways



a) Primary Highways



b) Secondary Highways

**Figure 5** Cost of Overloading (per truck per km) Omitting Cost of Climatic Effects

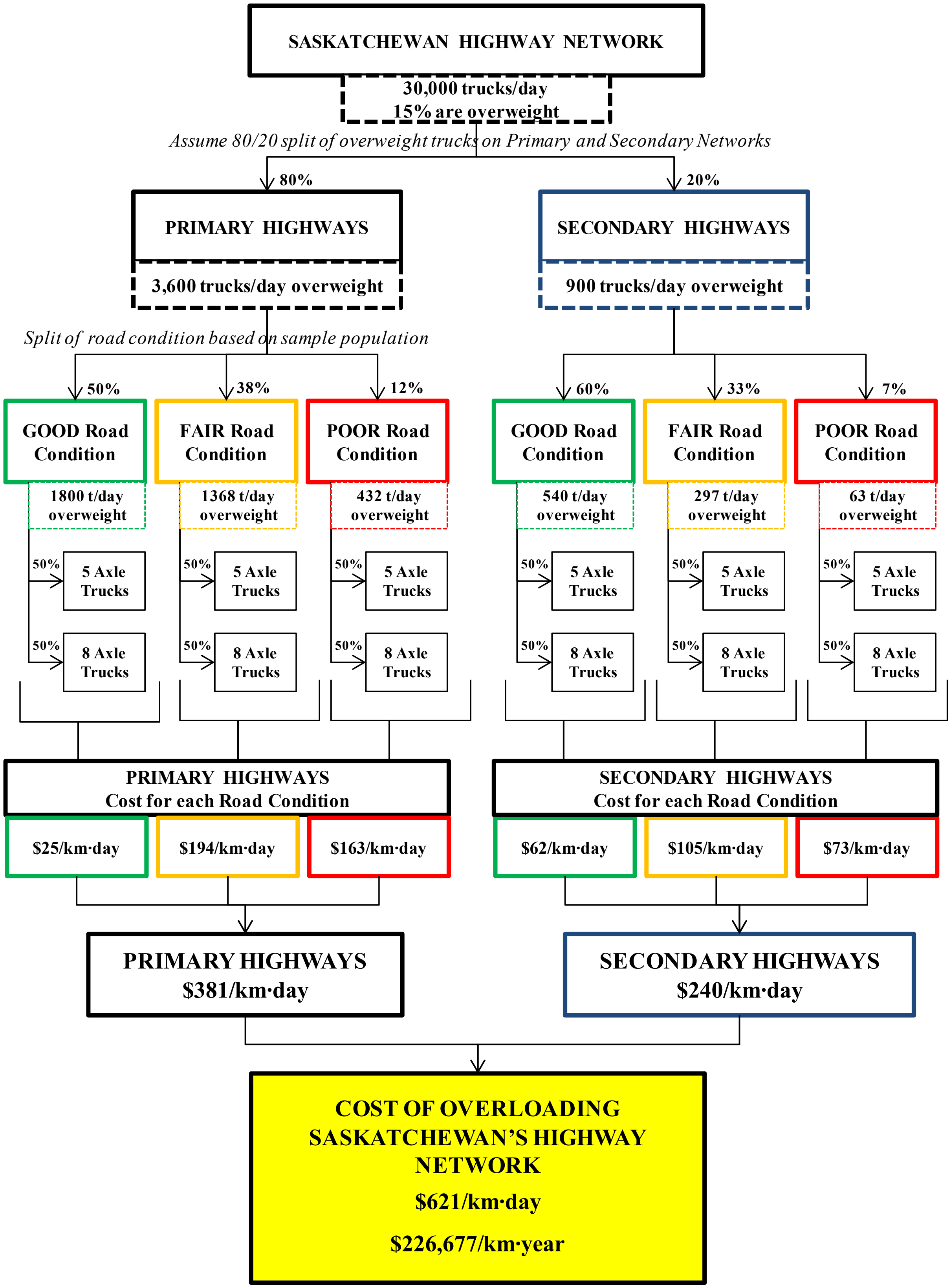


**Figure 6** Flowchart: Daily and Annual Cost of Overloading Saskatchewan's Highway Network Omitting Cost of Climatic Effects