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Heavy Duty Vehicle 6x2 Simulation Model Development

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16. Abstract

National Research Council Canada (NRC) was commissioned by Transport Canada (TC) to compare the performance of 6x2 and 6x4 truck tractors when used in a tractor-semitrailer application in Canada. A model was created in Simpack for each of these configurations where the main difference was the load carried by axles in the tractor's tandem axle group, and the axles that were specified as "driven". In addition to this, the 6x2 model could shift load from the non-driven tractor axle to the driven one. These configurations were run through several different manoeuvres using simulation, including various curves, a lane change, and a hill with an ascending grade. Different combinations of truck loads, speeds, tires, and tire-road coefficients of friction were used to compare the performance of the configurations.
It was concluded that the configurations performed very similarly on flat roads, but once an ascending grade was introduced, there was a significant difference in performance. In many cases, the 6x4 truck was able to ascend a hill with a higher grade than the 6x2 truck. Additionally, the more load that was added to the truck, the more the 6x4 truck would outperform the 6x2 trucks in terms of the maximum ascendable grade. Furthermore, the results obtained from the 6x2 configurations were shown to depend on which of the axles were driven, but only under lower loading conditions. In these cases, it was shown that the 6x2 configuration performed better if the front axle in the tractor's tandem axle group were the driven one as opposed to the rear axle being the driven one. It was also found that if the load on the 6x2 truck was shifted to the drive axle when it was performing a turn on a flat surface, the performance was not decreased by a large amount. It was also concluded that the 6x4 truck could outperform the 6x2 truck if the trucks were going down a hill while taking a curve. However, this would only occur in the event that the 6x2 had just performed a manoeuvre that required the load to shift to the drive axle and some or all of this load shifting was still present when the truck started to go down the hill.

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ABSTRACT

National Research Council Canada (NRC) was commissioned by Transport Canada (TC) to compare the performance of truck tractors with 6x2 and 6x4 configurations when used in a tractor-semitrailer application in Canada.

A model was created in Simpack for each of these configurations where the main difference was in which axles were driven and the weight of the axles. In addition to this, the 6x2 model could shift load from the non-driven axle in the tractor's tandem axle group to the driven one. The purpose of this load shifting was to increase the traction. These simulation models were run through several different vehicle manoeuvres including various radii of curvature, a lane change, ascending and descending grades, and a descending curve.

Some of the manoeuvres corresponded to ones used to assess the performance of trucks in previous studies. The other cases were made to evaluate the limits of the two configurations in terms of the minimum radius of curvature or maximum ascendable grade. In addition to this, there were several combinations of truck payloads, speeds, tires, and tire-road coefficients of friction that were used to compare the performance of the two configurations.

It was concluded that the two tractor-semitrailer configurations performed very similarly on flat roads, but once an ascending grade was introduced, there was a significant difference in performance. The 6x4 truck was typically able to ascend a hill with a higher grade than the 6x2 trucks if it was carrying a significant payload. Additionally, the more load that was added to the truck, the more the 6x4 truck would outperform the 6x2 truck in terms of the maximum ascendable grade. The maximum payload that could be carried by the 6x4 truck while staying within allowable weight limits was 26300 kg. With this payload, the 6x4 truck was able to ascend a grade of 2.9%, whereas the 6x2 truck was only able to ascend a grade of 1.4% when the tire-road coefficient of friction was set to a value representative of operation on an icy surface.

Additionally, the results showed that a 6x2 pusher-tag configuration was sometimes outperformed by a 6x2 tag-tandem configuration. This was the case for all coefficients of friction, but not all loading cases. When the payload was 1300 kg or 10300 kg, the 6x2 pusher-tag (with the rear axle of the tractor's tandem axle group driven) was outperformed by the 6x2 tag-tandem (with the front axle in the tractor's tandem axle group driven), but the two configurations performed the same under higher loads.

It was also found that if the load on the 6x2 tag-tandem was shifted to the drive axle when it was performing a turn on a flat surface, the performance criteria were not shown to be consistently affected in either a positive or a negative way, and the difference in the performance criteria was not large. The greatest difference measured was a 5% difference in the rear outswing during a low-speed corner at 8.8 km/h, but in this case the 6x2 with the load shifted actually outperformed the 6x2 without the load shifted. This was not always the case, but the results were seen to not be overly dependent on whether the load was shifted.

There was also a difference in performance between the 6x2 and 6x4 configurations when the truck was descending a downhill curve. Under the circumstances tested in this scenario, which included accelerating, decelerating, and maintaining speed, the 6x2 truck required a higher coefficient of friction in order to be able to perform this manoeuvre than did the 6x4 truck if the 6x2 truck had shifted load to the drive axle. Although a load shift would be unlikely to occur from this manoeuvre alone, there are many situations where this could happen due to a previous manoeuvre that caused the 6x2 tractor to detect a slip event and shift additional load onto the

drive wheels. This shift in load from a previous manoeuvre could exist for some time before the load is equalized again. Even with the load shift, it was determined that the 6x2 truck was able to come very close to the performance of the 6x4 truck if the 6x2 truck used tires with greater traction.

ACRONYMS

6x2 tractor	A tractor with a front steer axle that is not driven, and a tandem axle group at the rear where one of the two axles in the group is driven
6x2 pusher-tandem tractor	A 6x2 drivetrain where the rear axle of the tractor's tandem axle group is driven, and the front axle of the tandem group is not driven
6x2 tag-tandem tractor	A 6x2 drivetrain where the front axle of the tractor's tandem axle group is driven, and the rear axle of the tandem group is not driven
6x4 tractor	A tractor with a front steer axle that is not driven, and a tandem axle group at the rear where both of the axles in the group are driven
ABS	Anti-lock braking system
CCMTA	Canadian Council of Motor Transportation Administrators
CG	Centre of gravity
Combination vehicle	A truck or truck tractor used in combination with a trailer or semitrailer
Effective wheelbase	Distance between the centre of the front axle of the tractor and the load centre of the tandem axle on the tractor when the weight has been shifted
g	Unit of acceleration. 1 g = 9.81 m/s^2
GHG	Greenhouse gasses
Gross combination weight	The weight of a combination vehicle, including its payload
HDV	Heavy-duty vehicle
NRC	National Research Council Canada
Pacejka similarity	Method of determining slip between the tyre and road surfaces
RTAC	Roads and Transportation Association of Canada (now Transportation Association of Canada)
Semitrailer	A freight trailer that is supported at its forward end by a fifth wheel device on a tractor
Simpack	A multi-body dynamics simulation package
Slip event	An event such as an increase in grade, or encountering a low-friction surface, that causes high levels of longitudinal slip between the drive axle tires and the road surface, and limits the vehicle's ability to accelerate or climb hills
Tandem axle	Two or more axles that are close to each other
TC	Transport Canada
Tractor	A truck tractor
Truck tractor	A motor vehicle designed and used primarily for drawing other vehicles, and not designed to carry a load other than as a part of the weight of the vehicle and load that is drawn
Wheelbase	Distance between the centre of the front axle of the tractor and the point that is equidistant between the centres of the tandem axles on the tractor

EXECUTIVE SUMMARY

Introduction

National Research Council Canada (NRC) was commissioned by Transport Canada (TC) to evaluate heavy-duty vehicles (HDVs) equipped with 6x2 axle technology in comparison to HDVs with conventional 6x4 axles. The scope of this study is to compare the different drivetrain types using a tractor-semitrailer application in Canada in order to determine which would perform better and more safely when performing certain dynamic manoeuvres and while driving on different road configurations (e.g., hills and curves).

The use of 6x2 drivetrains could be advantageous in terms of a decreased production of greenhouse gasses (GHGs) and increased fuel efficiency [1]. For this reason, the use of a 6x2 drivetrain could be preferred. However, the 6x2 drivetrains do not necessarily perform as well as the 6x4 drivetrains under all conditions since they do not have as much traction, and this is especially of concern when climbing a hill. This is the reason 6x2 axle technology adds a lifting axle. If load can be transferred off the lifting axle and onto the drive axle, then traction should increase.

Currently, the use of 6x2 drivetrains with a lifting axle violates regulations in some provinces, because of concerns that axle loading during slip events (i.e., events such as an increase in the grade, or encountering a low-friction surface, that cause high levels of longitudinal slip between the drive axle tires and the road surface, and limit the vehicle’s ability to accelerate or climb hills) could exceed provincial weight limitations. For example, B.C. prohibits the use of 6x2 drive tractors [1], while in Ontario, the load on each tandem axle must be equalized within 1000 kg of each other under all conditions of loading and there can be no load shifting traction-control technology [2]. Other provinces implicitly restrict their potential utility with regulations that restrict the axle loads [1].

A 6x2 drivetrain has three axles, but only one is driven, whereas a 6x4 drivetrain also has three axles but two are driven. This study will compare the 6x4 drivetrain with the 6x2 drivetrain technology. The 6x2 can either be driven by the front axle of the tandem axle group on the tractor (called a tag-tandem configuration), or by the rear axle in the tandem axle group on the tractor (called a pusher-tag configuration). Additionally, the tandem axle that is not driven can be either a lifting axle or a non-lifting axle. In this study, most comparisons were done between a 6x4 tractor-semitrailer and a 6x2 tag-tandem tractor-semitrailer. However, the 6x2 pusher-tag tractor-semitrailer was also investigated in some cases.

Dynamic Simulations

Analytical work was conducted to study how a 6x2 tractor-semitrailer and a 6x4 tractor-semitrailer performed in a variety of dynamic driving scenarios. These driving manoeuvres included combinations of hills, curves, truck weights, coefficients of friction, tires, and speeds.

A general model of a truck was built in Simpack based on some real measurements and some assumptions. Major dimensions such as the wheelbase and length of the tractor were measured on a real truck. However, there were other dimensions that were simply assumed. In addition, the masses and moments of inertia of each of the different components of the tractor and trailer were given assumed values. This means that some of the vehicle performance parameters may not align exactly with what the results of a real vehicle would produce. However, both the 6x2 and 6x4 configurations that were tested in this study used the same tractor and semitrailer models. This means that while the results may not be as accurate as possible, the comparison between the two configurations is likely still reasonable.

Summary and Recommendations

It was found that, in most cases, when the tractor-semitrailer was negotiating turns or lane change manoeuvres on a flat surface, the performance of the truck was not affected much by whether the 6x2 tag-tandem tractor or 6x4 tractor was used. In fact, the difference in the various performance criteria in all but one of these cases was below 5%. In addition to this, it was not consistent which tractor configuration would outperform the other. This small difference was likely due to the fact that the 6x2 tractor has one axle in its tandem axle group that is lighter than the axle in the corresponding position on the 6x4 tractor. This is because the 6x4 tractor has two driven axles, which are heavier than non-driven axles, and the 6x2 tractor only has one driven axle. This change in mass of the axle has an effect on the empty weight of the tractor and on the location of the tractor CG.

The one case where the performance criteria of the two tractor-semitrailer configurations varied by more than 5% while performing a manoeuvre on a flat surface was when the tractor-semitrailers were going through the high-speed curve manoeuvre. In this case, the transient high-speed offtracking value with the vehicles loaded to the maximum payload studied of 26300 kg was 10.8% higher for the 6x2 tag-tandem configuration than for the 6x4 configuration. However, the 6x2 tractor-semitrailer was observed to be unstable during this simulation in that it would begin to rock back and forth. The transient high-speed offtracking value throughout the curve was seen to oscillate. The maximum value is what was taken and recorded in this study, but the average was closer to the value for the 6x4 tractor-semitrailer. This was the only simulation result where an instability of this type was observed, and it is possible that the side-to-side rocking of the truck was caused by a problem with the computer simulation model rather an inherent problem with the 6x2 tractor-semitrailer when it carries a payload of 26300 kg. This should be investigated further in any future work that may be done with these 6x2 and 6x4 tractor-semitrailer simulation models.

Additionally, it was determined that the performance of the 6x2 tag-tandem tractor-semitrailer configuration in the low-speed corner and tight turn manoeuvres was not too adversely affected by an unexpected load shift. As described previously, there could be some unexpected load shift still present from a previous manoeuvre where load shifting was required, and it has been shown that it can take some time for the load to equalize again [1]. It was shown that, when close to the maximum possible difference in axle load occurred between the driven and non-driven axles on the tandem axle of the 6x2 tractor, there was almost no difference in performance. The low-speed offtracking and outswing values changed by a maximum of 5% and the differences are explained by the change in effective wheelbase. Also, the minimum radius remained the same on the high-friction surface, but decreased from 128 m to 127 m on the low-friction surface. These differences are not large, and for the low-speed offtracking and rear outswing values in the low-speed corner manoeuvre, the performance was actually improved slightly when the unexpected load shift was considered. Therefore, it was determined that an unexpected load shift would be unlikely to cause any performance issues while performing this manoeuvre.

Once a hill was introduced with the steep hill manoeuvre, there was a much greater difference in performance between the 6x4 and 6x2 tag-tandem tractor-semitrailers. On a high friction surface, both configurations could climb grades that were in excess of 15%. However, on a low friction surface, the 6x4 outperformed the 6x2 tractor-semitrailer under many loading conditions.

This was because the 6x2 tractor could not have as much load supported by the driven wheels, which meant that the traction was often lower. If the total mass of the tractor-semitrailer was low, then a higher percentage of the load could be shifted to the driven axle on the 6x2 tractor without exceeding the axle load limit. As the total mass of the tractor-semitrailer increased, the gap in performance would become larger since the 6x2 tractor could not shift much of the load to the driven axle without exceeding the axle load limit. In the end, the maximum difference in performance was observed when the payload was set to 26300 kg, which resulted in a gross combination weight of 39500 kg on the 6x4 configuration. Carrying this load, the 6x4 tractor-semitrailer could ascend a 2.9% grade at 50 km/h on a low-friction surface, corresponding to an extremely icy surface with a coefficient of friction of 0.1, whereas the 6x2 tag-tandem tractor-semitrailer could only ascend a 1.4% grade under the same conditions.

Additionally, the 6x2 pusher-tag tractor (i.e., the tractor with the rear axle in the tractor's tandem axle group being driven, and the front axle in the group not being driven) was seen to perform worse in the steep hill manoeuvre than the standard 6x2 tag-tandem tractor under lower loading conditions. With the payload set to 1300 kg or 10300 kg, the 6x2 pusher-tag tractor-semitrailer was outperformed by the standard 6x2 tag-tandem tractor-semitrailer by a difference of up to 16%. However, once the load was increased to 20300 kg, there was little to no difference between the results of the standard 6x2 tag-tandem tractor and the 6x2 pusher-tag tractor when used in the tractor-semitrailer applications examined here.

It was also concluded that the use of better tires could significantly increase the performance of both 6x4 and 6x2 tag-tandem tractor-semitrailers. However, in the worst-case steep hill manoeuvre on ice, where the payload was 26300 kg and the coefficient of friction was 0.1, the 6x2 tag-tandem configuration with the high-traction tires still only yielded a maximum ascendable grade of 2.2%. This is lower than the corresponding value of 2.9% for the 6x4 tractor under the same conditions using the standard tires. Therefore, although under some conditions the 6x2 tag-tandem tractor with the high-traction tires can outperform the 6x4 tractor with the standard tires, the 6x2 tractor with high-traction tires still cannot fully match the performance of the 6x4 tractor with standard tires under all conditions, when used in this tractor-semitrailer application.

The gap in maximum ascendable grade between the 6x4 tractor-semitrailer and the 6x2 tag-tandem tractor-semitrailers is significant and is a serious limitation of the 6x2 configuration. For this reason one recommendation is that 6x2 tractor-semitrailers would be limited in where they are allowed to be used to routes or regions with only lower grades of hills. Alternatively, the recommendation could be to limit the allowable payload that a 6x2 tractor-semitrailer can carry to values that allow most of the load on the tandem axle of the 6x2 tractor to be shifted to the driven axle. In this study, that load was 8300 kg for the standard 6x2 tag-tandem tractor and 11800 kg for the 6x2 pusher-tag tractor, but the weights and dimensions used in this study were approximations, so further study would be needed to determine this weight limit for each tractor-semitrailer application.

There was also a gap in performance when the tractor-semitrailer was performing the downhill curve manoeuvre. When descending a hill with a 12% grade and a radius of curvature of 333 m and while carrying a payload of 10300 kg, there was a difference in performance between the 6x4 tractor-semitrailer and the 6x2 tag-tandem tractor-semitrailer when there was an unexpected load shift on the 6x2 tractor. Although this load shift would not usually happen just from descending a grade, there could be some unexpected load shift still present from a previous manoeuvre such as having just climbed a hill. It has been shown that it could take some time for the load to equalize again [1]. Therefore, under the worst-case conditions when almost all of the load is shifted from the rear axle in the tractor's tandem axle group to the front axle in the group, as could be the case when a 10300 kg payload is carried by the 6x2 tag-tandem tractor-semitrailer, the 6x4 configuration can outperform the 6x2 configuration in terms of the minimum required coefficient of friction by about 23%. This was also true when the tractor-semitrailer was decelerating or accelerating down the hill. Furthermore, it was found that, with the use of high-performance tires, the 6x2 tag-tandem tractor-semitrailer can come much closer to matching the performance of the 6x4 tractor-semitrailer using the original tires; in fact, the minimum required coefficient of friction only varies by 0.01 between these two cases.

This study was limited in that the simulation models made use of generic information to describe the various model components based on a few measurements that were made, since more precise information from various manufacturers was not available. The simulation model included estimates of tractor and semitrailer component weights, many dimensions, centre of gravity positions, and moments of inertia. It also included estimates of brake system performance, ABS brake system performance, and a simplified powertrain model. An engine traction control system was not included. Furthermore, the method by which the 6x2 tractor detects slip events and adjusts the 6x2 tag-tandem and 6x2 pusher-tag tractor axle loads in response to slip were not available, and a simplified representation of this was included in the simulation model. Due to the limitations in this study, it is recommended that further investigative work and analysis be done on more accurate models and on a wider variety of manoeuvres to fully and more accurately assess the difference in performance between the 6x2 and 6x4 tractors in this tractor-semitrailer application.

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1 INTRODUCTION

1.1 Purpose

National Research Council Canada (NRC) was commissioned by Transport Canada (TC) to evaluate heavy-duty vehicle (HDV) 6x2 drive technology in comparison to 6x4 technology, when the tractor is used in a tractor-semitrailer application in Canada. The scope of this study is to compare the different drivetrain types in order to determine which would perform better and more safely when performing certain manoeuvres and following certain tracks that implement various hills and curves.

The use of 6x2 drivetrains could be advantageous in terms of a decreased production of greenhouse gasses (GHGs) and increased fuel efficiency [1]. For this reason, the use of a 6x2 drivetrain could be preferred. However, the 6x2 drivetrains do not necessarily perform as well as the 6x4 drivetrains under all conditions since they do not have as much traction, especially when climbing a hill. This is the reason for adding a lifting axle. If load can be transferred off the lifting axle and onto the drive axle, then traction should increase.

Currently, the use of 6x2 drivetrains with a lifting axle violates regulations in some provinces, because of concerns that axle loading during slip events (i.e., events such as an increase in the grade, or encountering a low-friction surface, that cause high levels of longitudinal slip between the drive axle tires and the road surface, and limit the vehicle's ability to accelerate or climb hills) could exceed provincial weight limitations. For example, B.C. prohibits the use of 6x2 drive tractors [1], while in Ontario the load on each tandem axle must be within 1000 kg of each other under all conditions of loading and there can be no load shifting traction-control technology [2]. Other provinces implicitly restrict their potential utility with regulations that restrict the axle loads [1].

1.2 Scope

A tractor with a 6x2 drivetrain has three axles, but only one is driven, whereas a 6x4 drivetrain also has three axles but two are driven. This study will compare the conventional 6x4 drivetrain with the 6x2 drivetrain technology, when used in a tractor-semitrailer application. The 6x2 can either be driven by the front axle of the tractor's tandem axle group (tag-tandem configuration), or by the rear axle of the tractor's tandem group (pusher-tag configuration). Additionally, the axle in the tandem group that is not driven can be either a lifting axle or a non-lifting axle. In this study, most comparisons were done between a 6x4 tractor and a 6x2 tag-tandem tractor. However, the pusher-tag configuration was also investigated in some cases. For the purposes of this evaluation, it was assumed that load-shifting could occur at speeds up to 70 km/h; above that speed, load shifting does not take place.

1.3 Limitations

In this study, a general truck model of the tractor-semitrailer combination was used and was not made to match any particular truck. This means that the dimensions of the 6x4 and 6x2 tractor-semitrailer model will not match any real tractor-semitrailer combination in operation. The vehicle model also did not include sub-models of the engine, transmission, differentials and other portions of the drivetrain, but instead applied a torque directly to the wheels of the driven axles. This torque was either a specified value or was made to be whatever was required to match a certain velocity profile. Additionally, the model did not include an accurate system for representing ABS brakes or any engine traction control.

These limitations mean the results are not precise representations of the performance of real tractor-semitrailers, but the main goal of this study was to compare the 6x4 and 6x2 technologies. This is still possible in the manoeuvres analyzed in this study, since the same limitations were present on both models and the only differences between the models were in whether the tractor had a 6x2 or 6x4 axle configuration, and whether or not the load could be shifted from one axle to another in order to increase traction.

Another limitation is that no information was obtained on how the tractors with 6x2 technology shift the load in response to a slip event. To account for this, in simulations of 6x2 configurations that encounter a slip event, load is shifted from the non-driven axle of the tractor's tandem axle group to the driven axle.

2 6X2 AND 6X4 TRACTORS

Both 6x4 and 6x2 tractors have three axles, one steer axle at the front and a tandem axle set at the back. They both have six possible wheel stations, one on each side of each axle. Additionally, in both cases, the front axle steers and at least one of the axles in the tandem group is driven.

Tractors with 6x2 technology have only one axle driven (i.e., where only two of the six wheel stations are powered), whereas for the 6x4 configuration, two axles are driven (four of the six wheel stations are powered). Figure 1 shows a 6x2 tag-tandem tractor where the front axle in the tandem group is driven and the rear axle in the tandem group is not. Figure 2 shows a 6x2 pusher-tag tractor where the rear axle in the tandem group is driven and the front axle in the tandem group is not. Figure 3 shows a 6x4 tractor where both axles in the tandem group are driven. In the three figures, the driven axles are shown in red, and non-driven axles are shown in green.

Another difference between the two configurations is that the 6x2 tractor can be equipped with technology that allows for load shifting between the axles in the tandem group. This is typically used to shift weight to the driven axle from the non-driven rear axle when a slip event occurs (i.e., events such as an increase in the grade, or encountering a low-friction surface, that cause high levels of longitudinal slip between the drive axle tires and the road surface, and limit the tractor's ability to accelerate or climb hills). This can serve to increase traction. However, for a 6x4 tractor, this would not increase traction since both of the rear axles are driven.

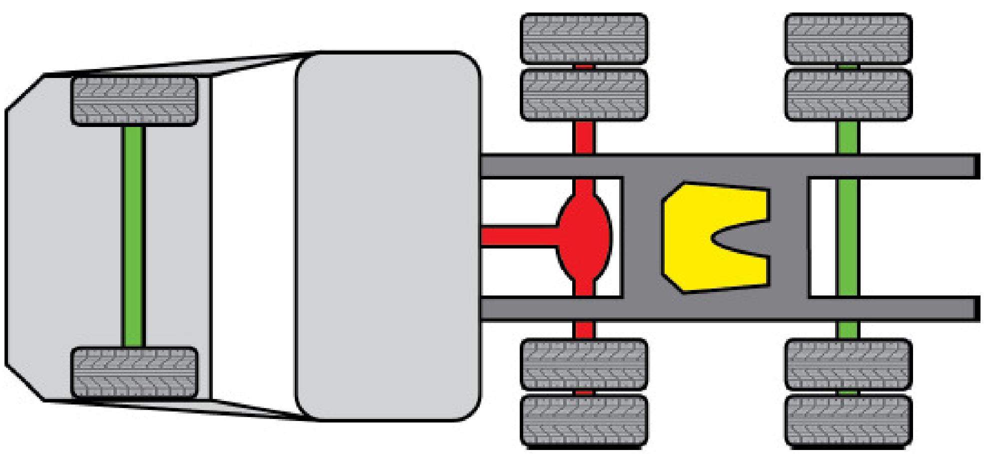

Figure 1: 6x2 tag-tandem tractor (adapted from [3]), where the front axle of the tractor's tandem axle group (shown in red) is driven, and the rear axle of the tandem group (shown in green) is not driven.

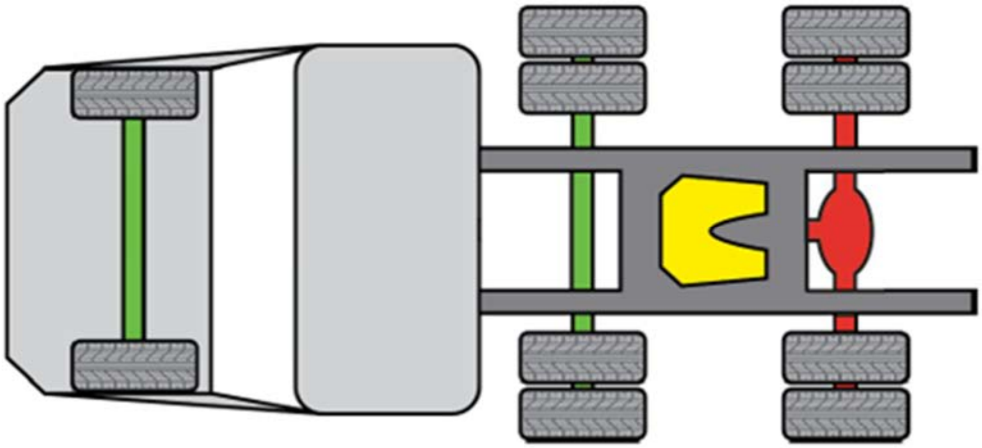

Figure 2: 6x2 pusher-tag tractor (adapted from [3]), where the front axle of the tractor's tandem axle group (shown in green) is not driven, and the rear axle of the tandem group (shown in red) is driven.

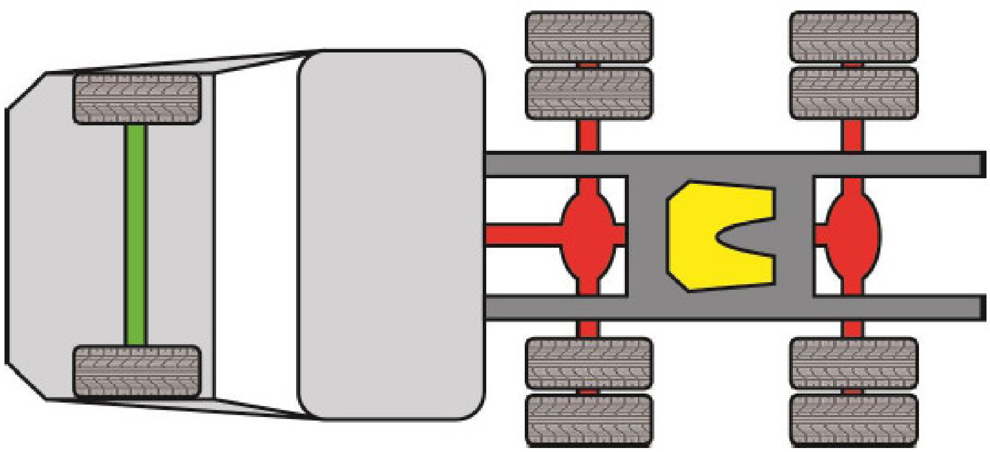

Figure 3: 6x4 tractor (adapted from [3]), where the front and rear axles of the tractor's tandem axle group (shown in red) are both driven.

3 DYNAMIC SIMULATION MODEL AND SCENARIOS

3.1 Introduction

Analytical work was conducted to study how 6x2 and a 6x4 tractor configurations performed when used in a tractor-semitrailer application in Canada in a variety of driving scenarios. These driving scenarios included combinations of hills, curves, truck weights, coefficients of friction between the tires and the road surface, tire types, and speeds.

A general model of a tractor-semitrailer was built in Simpack based on some real measurements and some assumptions. Major dimensions such as the wheelbase and length of the tractor were measured on a real truck. However, a number of other dimensions and parameters included in the model were simply assumed. In addition, the masses and moments of inertia of each of the different components of the tractor and trailer were given assumed values. This means the simulation results are not precise representations of the performance of a real vehicle. However, both the 6x2 and 6x4 configurations that were evaluated in this study used the same basic tractor and trailer models. This means that the results should be useful for comparing the general performance of the 6x2 and 6x4 configurations.

3.2 Dynamic Simulation Model

The components of the tractor-semitrailer were modelled in Simpack as rigid bodies and were assembled together to make the model. However, the engine, transmission, differentials and other portions of the tractor powertrain were not modelled directly. Instead, the tractor model incorporated a torque that was applied directly to each of the powered wheels on the drive axle(s). The torque was sometimes applied as a specified value, and sometimes a torque was applied that caused the tractor-semitrailer to match a specific speed profile.

Since there was no detailed powertrain in the model, there was no attempt to introduce engine traction control into the model. In addition, ABS brakes were not modelled in a way that matched any real ABS system. When a braking scenario was considered, the ABS brakes were implemented by applying levels of torque that corresponded to levels of longitudinal tire slip consistent with maximum possible braking on the wheels, while avoiding high levels of slip that correspond to incipient wheel lock-up. These simplifications allowed the model to be developed in a cost-effective way that was suitable for comparing the performance of the 6x2 and 6x4 configurations in the manoeuvres analyzed in this study.

Another important aspect of the model is how the tires were connected to the road. In this model a Pacejka similarity model was used. This is simply a method of calculating the amount of lateral and longitudinal slip that would take place between the tire and the road based on several parameters including the friction coefficient, material of the tire, width of the tire, etc.

The suspension on the 6x2 and 6x4 models had the same basic design. In both cases the two trailer axles used leaf springs. Coil springs were used on the steer axle of the tractor. Leaf springs were used on the tandem axle group at the rear of the tractor, regardless of whether the axles in the tandem group were driven or not.

For the 6x2 simulations the distribution of load between the two axles in the tandem group of the tractor was very important. Since information was not available on how current 6x2 drivetrain technologies determine when and how much load to transfer from the non-driven axle in the tractor tandem axle group to the driven axle, in response to a slip event, the stiffness of the springs in the simulation model were altered in a way that transferred the load and caused a resulting increase in the maximum possible tractive effort. For the purposes of the simulations described here, the amount of load shifting was limited so that no single axle load exceeded the limit of 9100 kg per axle [4], and they were usually kept about 300 kg below this to introduce a small factor of safety.

One of the key differences between the 6x4 and 6x2 tractor models was in the mass of the axles. In both of these models, the steer axle had a mass of 725 kg, and the rest of the non-driven axles had masses of 500 kg. Each driven axle in the model had a mass of 800 kg. This means that for the 6x4 tractor-semitrailer model, there were two axles with a 500 kg mass on the trailer, one steer axle at the front of the tractor with a mass of 725 kg, and two axles at the rear of the tractor with masses of 800 kg. The 6x2 tractor-semitrailer model was the same except that one of the axles on the rear of the tractor had a mass of 500 kg.

There were four main loading cases used in the model where different payloads were evenly distributed in the trailer, and this resulted in the axle loads shown in Figure 4 and Table 1 for the 6x4 tractor-semitrailer configuration. It should also be noted, that the regulations state that the total gross mass of the tractor-semitrailer cannot be more than 39500 kg [4], which corresponded to load case 4 where the payload was 26300 kg. This resulted in a tractor tandem axle load of 15600 kg, which was 1400 kg under the allowable axle group limit of 17000 kg, and a trailer tandem axle load of 19196 kg, which was 2196 kg over the allowable axle group limit of 17000 kg. It is quite possible that a situation like this could occur in practice, and no further attempts were made to reduce or move the payloads to bring the two tandem axle group loads in line with the 17000 kg limit.

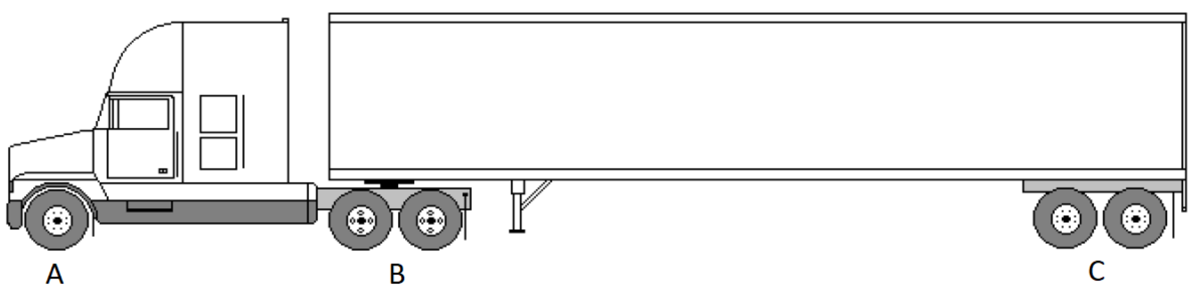

Figure 4: Axle loads on the tractor-semitrailer model

Table 1: Axle loads on the 6x4 tractor-semitrailer corresponding to locations A, B and C in Figure 4.

Load Case	Payload (kg)	Axle Load at A (kg)	Axle Load at B (kg)	Axle Load at C (kg)	Gross Combination Weight, A+B+C (kg)
Empty	0	4829	5489	2882	13200
1	1300	4826	6007	3670	14503
2	10300	4790	9466	9254	23510
3	20300	4736	13300	15475	33511
4	26300	4714	15600	19196	39510
	Allowable Limit [4]	5500	17000	17000	39500

Table 2 is similar to Table 1, except that it shows the axle loads for the 6x2 tractor-semitrailer configurations instead of the axle loads for the 6x4 configurations. As noted above, the non-driven axle in the 6x2 tractor's tandem axle group is 300 kg lighter than the corresponding driven axle in the 6x4 tractor's tandem axle group. This is shown in the Axle Load at B column of the table, and causes the gross combination weight for each of the 6x2 configurations to be 300 kg less than the value for the corresponding 6x4 configurations shown in Table 1.

Table 2: Axle loads on the 6x2 tag-tandem and pusher-tag tractor-semitrailers corresponding to locations A, B and C in Figure 4.

Load Case	Payload (kg)	Axle Load at A (kg)	Axle Load at B (kg)	Axle Load at C (kg)	Gross Combination Weight, A+B+C (kg)
Empty	0	4829	5189	2882	12900
1	1300	4826	5707	3670	14203
2	10300	4790	9166	9254	23210
3	20300	4736	13000	15475	33211
4	26300	4714	15300	19196	39210
	Allowable Limit [4]	5500	17000	17000	39500

Since no data was provided to NRC on the algorithm for shifting load in response to a slip event, the simulations were all done by running the simulation and then checking the measured longitudinal slip that was present on the driven wheels. If excessive levels of slip were occurring, then the simulation was run again with some of the load shifted to the front axles. For some of the test manoeuvres, the amount of load shifted to the drive axle did not have much effect on the results, whereas for other manoeuvres, such as the steep hill, it had a large effect and the ideal amount of load shifted was limited by the amount of available load on the tractor's tandem axle group or by the axle weight limit.

3.3 Test Manoeuvres and Vehicle Performance Parameters

There were six main test manoeuvres that were used in this study to evaluate the performance of the tractor-semitrailer configurations. The first three were manoeuvres that align with the approach used in the CCMTA/RTAC Vehicle Weights and Dimensions Study [5], [6], [7]. These cases included a high-speed lane change manoeuvre for obstacle avoidance, a high-speed curve manoeuvre, and a low-speed corner manoeuvre. It should be noted that there are specified limit values in the RTAC study for various vehicle performance parameters that describe required levels of vehicle performance, but due to the fact that the tractor-semitrailer models were not built with completely accurate weights and dimensions, only the differences between the results for the 6x2 and 6x4 models were considered in this study. In addition to the three manoeuvres described above, three additional manoeuvres were examined. The first was a straight ascending hill manoeuvre, the second was a flat curve manoeuvre, and the last was a downhill curve manoeuvre, all of which involved evaluating the limits of what the tractor-semitrailer configurations could handle in terms of hill grade, curve radius, or coefficient of friction.

For all of these test manoeuvres, except for those involving a hill, it was found that there was not much difference in the results for the 6x4 and 6x2 models when the 6x2 tag-tandem configuration was used (i.e., when the front axle of the tractor's tandem axle group was driven). Therefore, the other 6x2 configuration, the pusher-tag configuration (when the rear axle of the tractor's tandem axle group is driven), was not considered for these cases. This was done to focus effort on what was found to be the area of greatest concern. This was seen to be the scenario of ascending the steep hill, so that is where comparisons were made with both 6x2 configurations, the pusher-tag and the tag-tandem.

3.3.1 High-Speed Lane Change

Both the 6x2 tag-tandem and 6x4 tractor-semitrailers were run through a high-speed lane change manoeuvre to assess the response of the vehicle to a driver suddenly needing to avoid an obstacle. The RTAC study specifies that this be run on a high friction surface to obtain the required vehicle performance parameters [6], and therefore a coefficient of friction of 1.2 was used. The vehicle performance parameters include the load transfer ratio and the transient high-speed offtracking.

The analysis that was done involved different speeds and truck weights. The speeds used included 90, 100, and 110 km/h. The results using these speeds were compared for one tractor-semitrailer weight. After this, the speed was set to 90 km/h and the truck weight was varied to four different load cases by changing the load in the trailer. Additionally, in each case, the steering input for the lane change manoeuvre was modified so that the peak lateral acceleration would be approximately equal to 0.15 g, as this is what is specified in the RTAC study in order to obtain accurate values for transient high-speed offtracking and load transfer ratio [6], [7].

The load transfer ratio is a measure that gives information on how close the tractor-semitrailer is to rolling over. It represents the portion of the original load that shifts from the tires on one side of the truck to the tires on the other side of the truck. If all of the weight were shifted to the tires on one side of the truck, then the load transfer ratio would be 1 and the truck would roll over. Therefore, the closer the value of the load transfer ratio is to zero, the better. As another example, if the load transfer ratio were 0.5, this would mean that half of the original load on the wheels on one side of the truck was transferred to the other side. This would result in one side bearing 25% of the load and the other side bearing 75%. For the purposes of this study, the load transfer ratio was determined by measuring the sum of the wheel forces on the entire left side of the truck and the entire right side of the truck, and calculating a load transfer ratio value for the whole vehicle. This is useful for torsionally stiff (e.g., for some types of tractor relatively rigid tank trailers). In cases where less torsionally stiff trailers are being towed (e.g., flat bed trailers), it is appropriate to calculate separate load transfer ratio values for each axle group.

Figure 5 shows the whole-vehicle load transfer ratio for one specific tractor-semitrailer configuration as it conducts the high-speed lane change manoeuvre. The top-right and bottom-left plots in the figure show time-history plots of left- and right-side wheel forces in the manoeuvre, and the bottom-right plot in the figure shows a time-history plot of the load transfer ratio. A peak of -0.35 is reached first in one direction, and then a second peak of +0.41 is reached in the other direction. The highest absolute value of the load transfer ratio in the entire manoeuvre is the value that was recorded as the load transfer ratio. Thus a value of 0.41 is recorded as the load transfer ratio for this particular tractor-semitrailer configuration.

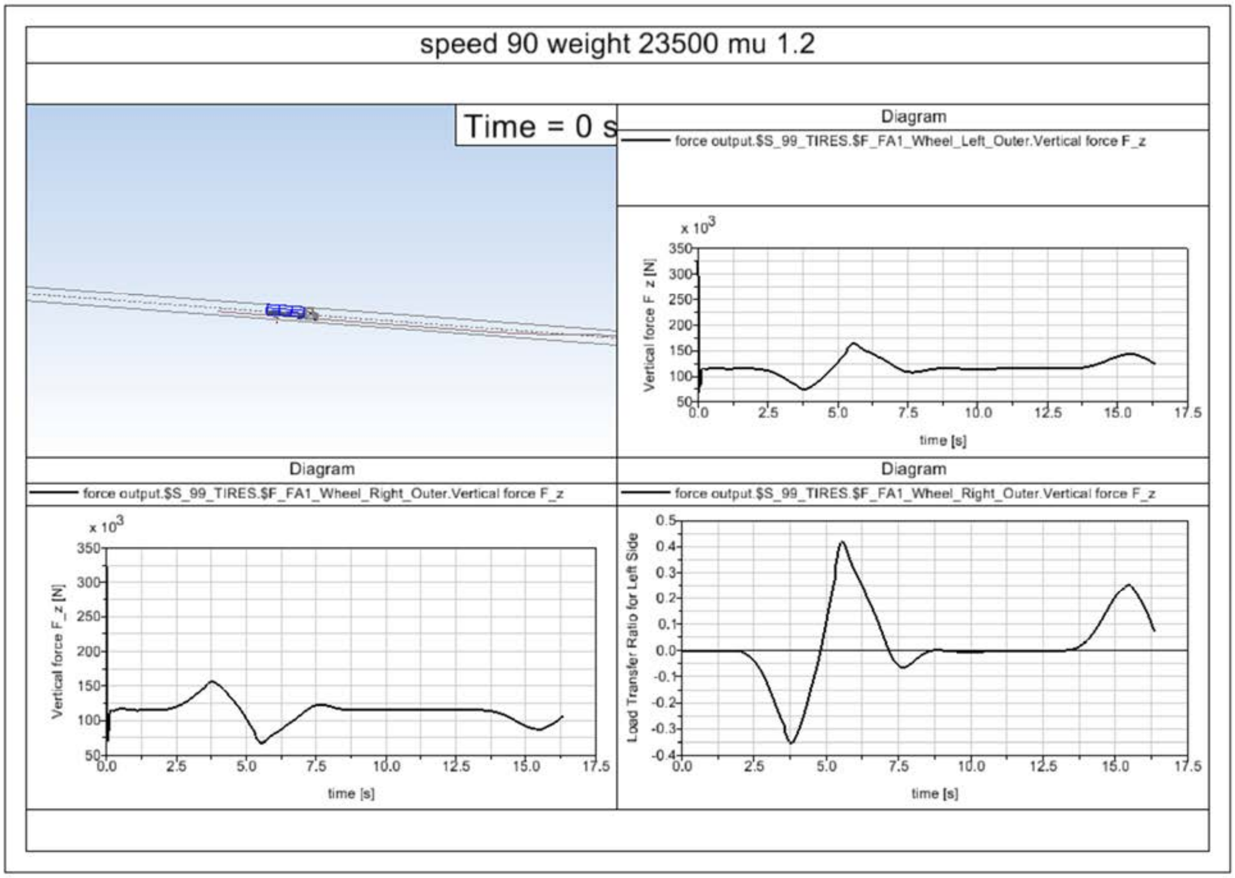

Figure 5: Sample output of load transfer ratio in the high-speed lane change manoeuvre.

Transient high-speed offtracking is a measure of how far the path of the centreline of the rearmost axle of the trailer deviates laterally from the path of the centreline of the front axle of the tractor. It is the highest measured lateral deviation during the entire manoeuvre that is considered to be the value for transient high-speed offtracking. Figure 6 shows a visual representation of transient high-speed offtracking. Clearly, the lower the value the better, since a higher value would mean that the rear of the tractor-semitrailer is not going where the driver is intending to go and this could result in cars or other obstacles in other lanes being hit by the tractor-semitrailer.

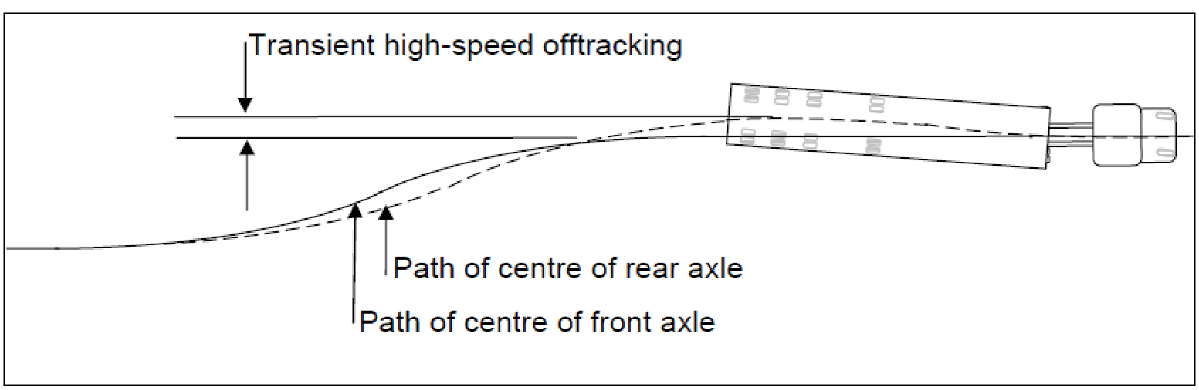

Figure 6: Visualization of transient high-speed offtracking in the high-speed lane change manoeuvre [8].

An example output of the transient high-speed offtracking can be seen in Figure 7. The top-right plot shows the path of the front and rear axles. The bottom-left plot is the difference in lateral position between the path of the front axle and the path of the rearmost axle of the trailer. The highest absolute value of this plot was recorded as the transient high-speed offtracking value. In addition to this, the absolute acceleration can be seen in the bottom-right plot in the figure.

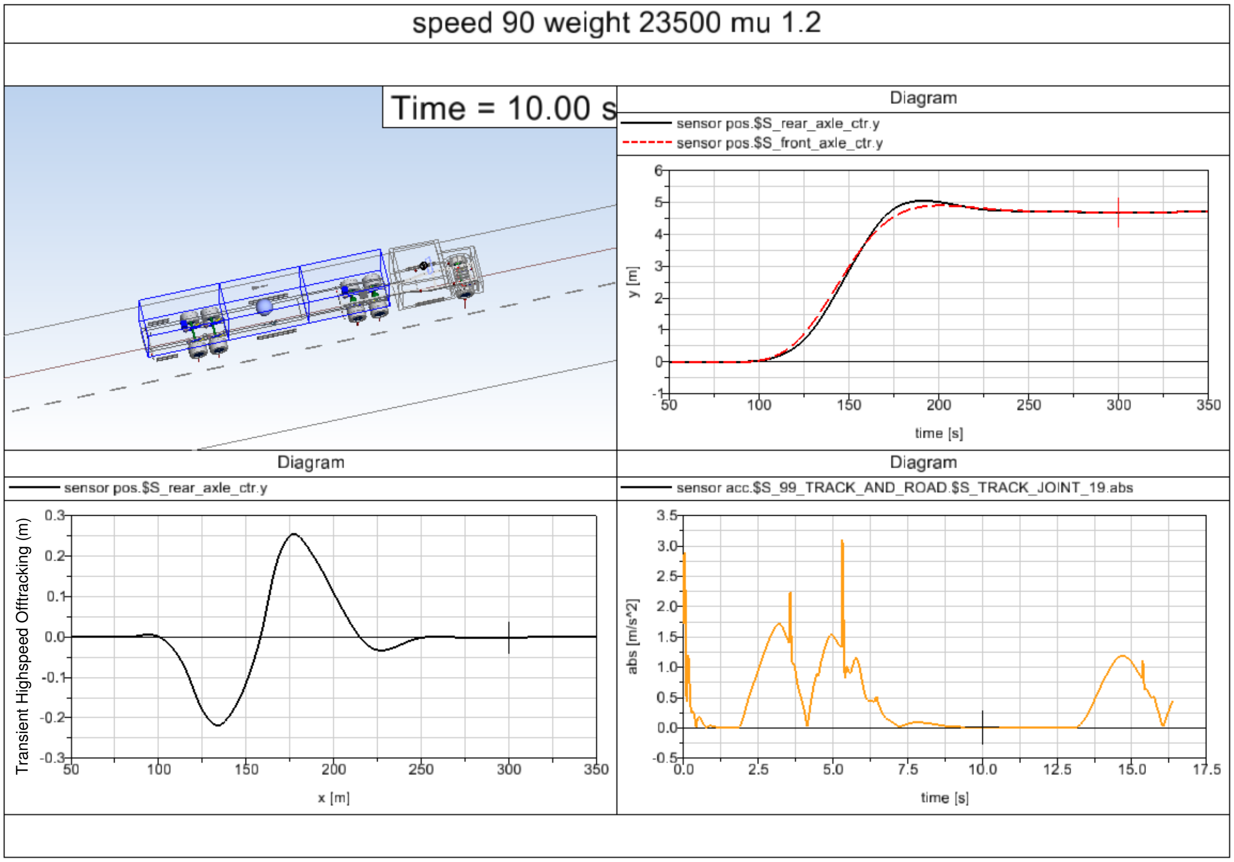

Figure 7: Sample output of transient high-speed offtracking (bottom-left plot) in a high-speed lane change manoeuvre. Transient high-speed offtracking reaches a peak of 0.25 m at x=155 m, and thus 0.25 m is the transient high-speed offtracking value recorded for this manoeuvre.

3.3.2 High-Speed Curve

The high speed curve manoeuvre was set up in way that was similar to the high speed lane change manoeuvre. The coefficient of friction used was 1.2 as this evaluation was also meant to be for a high friction surface. Additionally, the same procedure of evaluating performance for one load at three different speeds of 90, 100, and 110 km/h and evaluating performance for four different load cases at 90 km/h was followed. Vehicle performance in the high speed curve was evaluated using two measures – static rollover threshold and high-speed offtracking.

In the manoeuvre, the high-speed offtracking was evaluated by setting the curve radius to a value that resulted in a lateral acceleration of 0.2 g in accordance with the RTAC study [6], [7].

Then, to evaluate the static rollover threshold, the curve radius was gradually decreased until the truck rolled over.

High-speed offtracking is similar to the transient high-speed offtracking from the high-speed lane change manoeuvre in that it is defined as the maximum deviation of the path of the centreline of the rearmost axle from the path of the centreline of the front axle. The difference is that high-speed offtracking occurs in a steady-state turn, and transient high-speed offtracking occurs in a high-speed lane change. This value is important because a large amount of offtracking can cause the truck to hit cars or other obstacles that are not in its lane.

Figure 8 shows a sample output for the high-speed offtracking. The top-right plot shows the lateral acceleration, whereas the bottom-left plot shows the path of the front and rear axles. The bottom-right plot shows the maximum lateral distance between the paths of these axles on the y-axis. This was the value used for the high-speed offtracking.

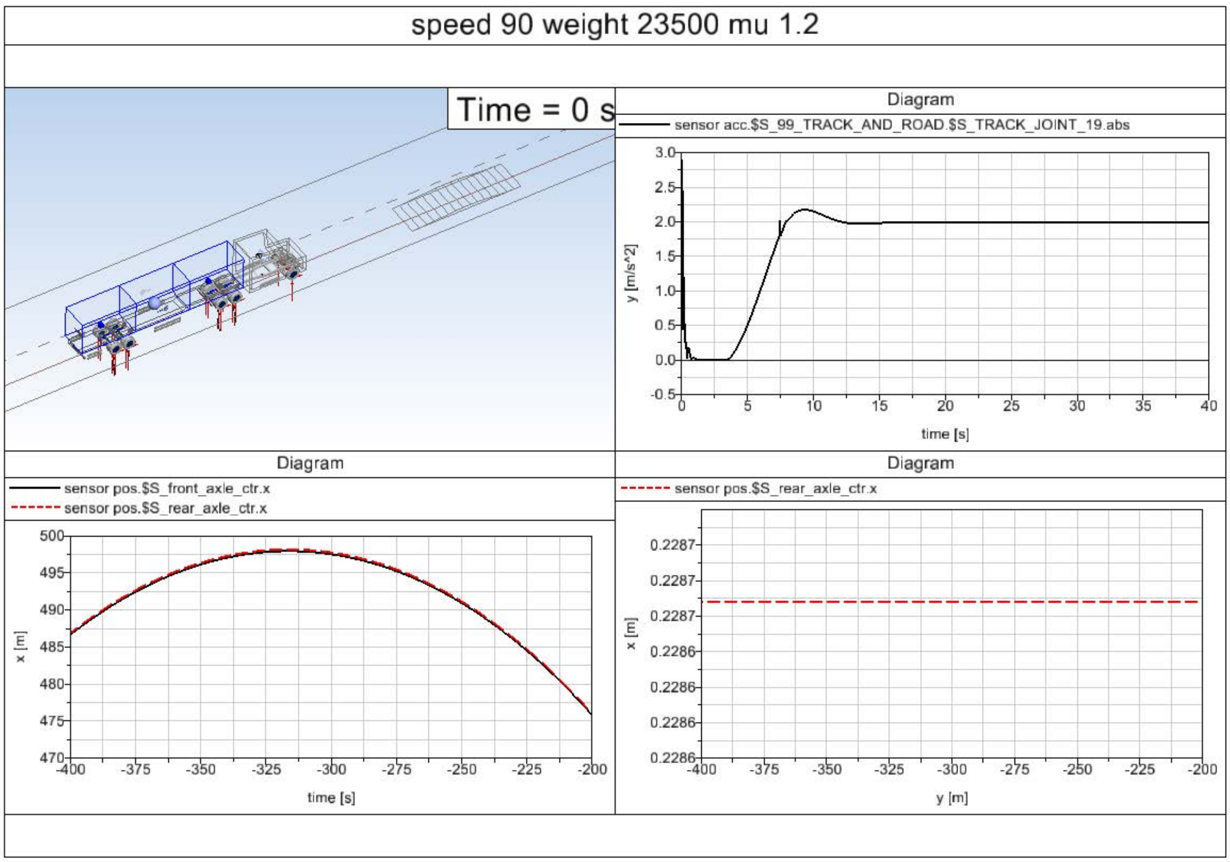

Figure 8: Sample output used to evaluate high-speed offtracking from the high-speed curve manoeuvre.

Static rollover threshold is defined as the minimum lateral acceleration at which the truck will start to roll over while performing a steady curve. Clearly, a tractor-semitrailer that has a higher static rollover threshold would be preferred since this would decrease the chance of the truck rolling over.

A sample output of the static rollover threshold simulation can be seen in Figure 9 **Error! Reference source not found.**. The top-right plot shows the lateral acceleration of the truck, whereas the bottom plots show the wheel forces on different axles. The bottom-left plot shows the middle axle on the tractor and the bottom-right plot shows the rear axle on the trailer. Once the two right wheels lifted off on both of these axles, the truck would roll over and, therefore, this is where the lateral acceleration was recorded for the static rollover threshold.

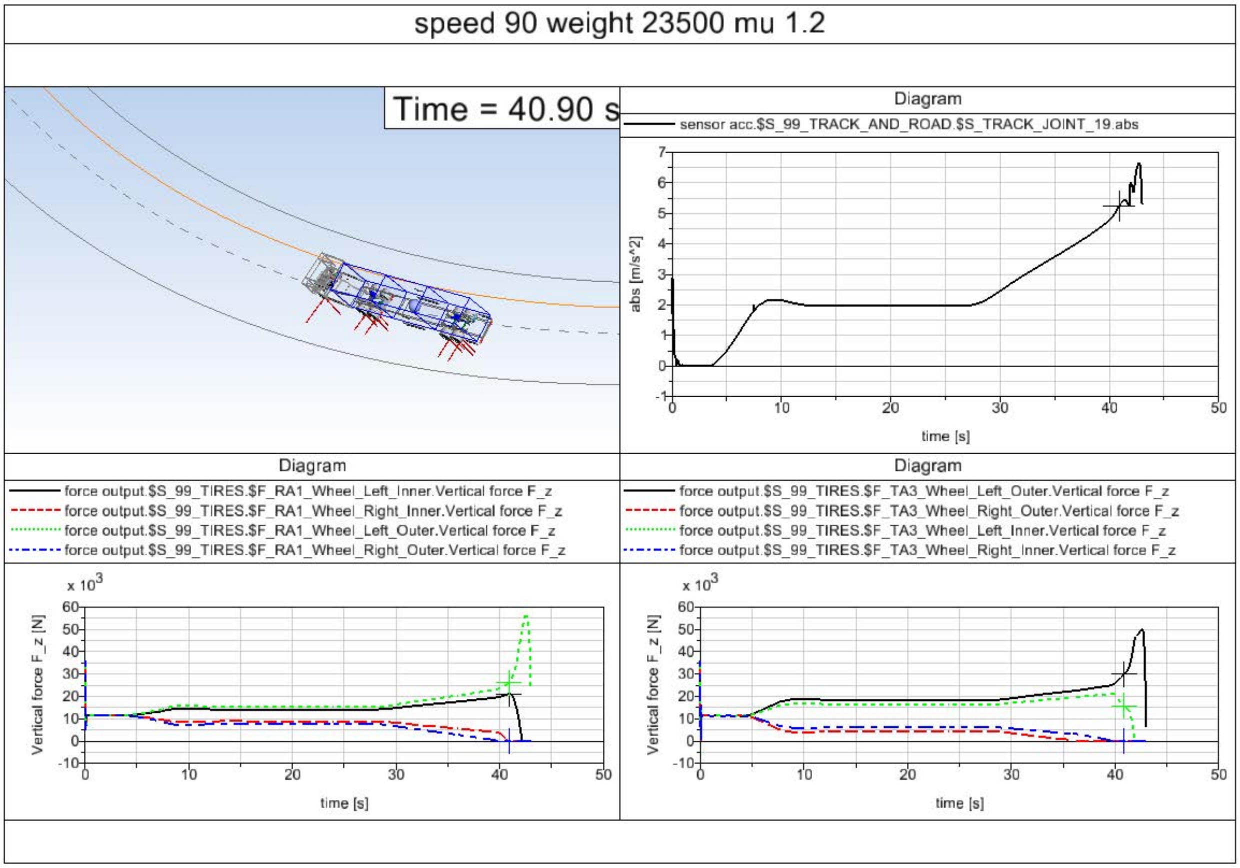

Figure 9: Sample output used to evaluate static rollover threshold from the high-speed curve manoeuvre.

3.3.3 Low-Speed Corner

Similar to the previous scenarios, the low-speed corner manoeuvre was also specified to be done on a high friction surface. Therefore, a coefficient of friction of 1.2 was used for this scenario as well. This manoeuvre involved having the tractor-semitrailer turn around a 90° corner with a radius of 10.97 m while travelling at 8.8 km/h [7]. Three vehicle performance parameters were used to evaluate vehicle perfomance in this manoeuvre. They include low-speed offtracking, front outswing, and rear outswing.

Low-speed offtracking is defined in a way that is similar to that for transient high-speed offtracking in Section 3.3.1 and high-speed offtracking in Section 3.3.2. It is a measure of how far the path of the centreline of the rearmost axle deviates from the path of the centreline of front axle in the low-speed corner manoeuvre. Again, the lower the value, the better and safer the performance is since the truck is less likely to hit anything outside its lane.

Figure 10 shows a sample output for the low-speed offtracking parameter. The top-right plot shows the distance between the paths of the front and rear axles, and the bottom-left plot shows the maximum difference, which was the recorded low-speed offtracking value.

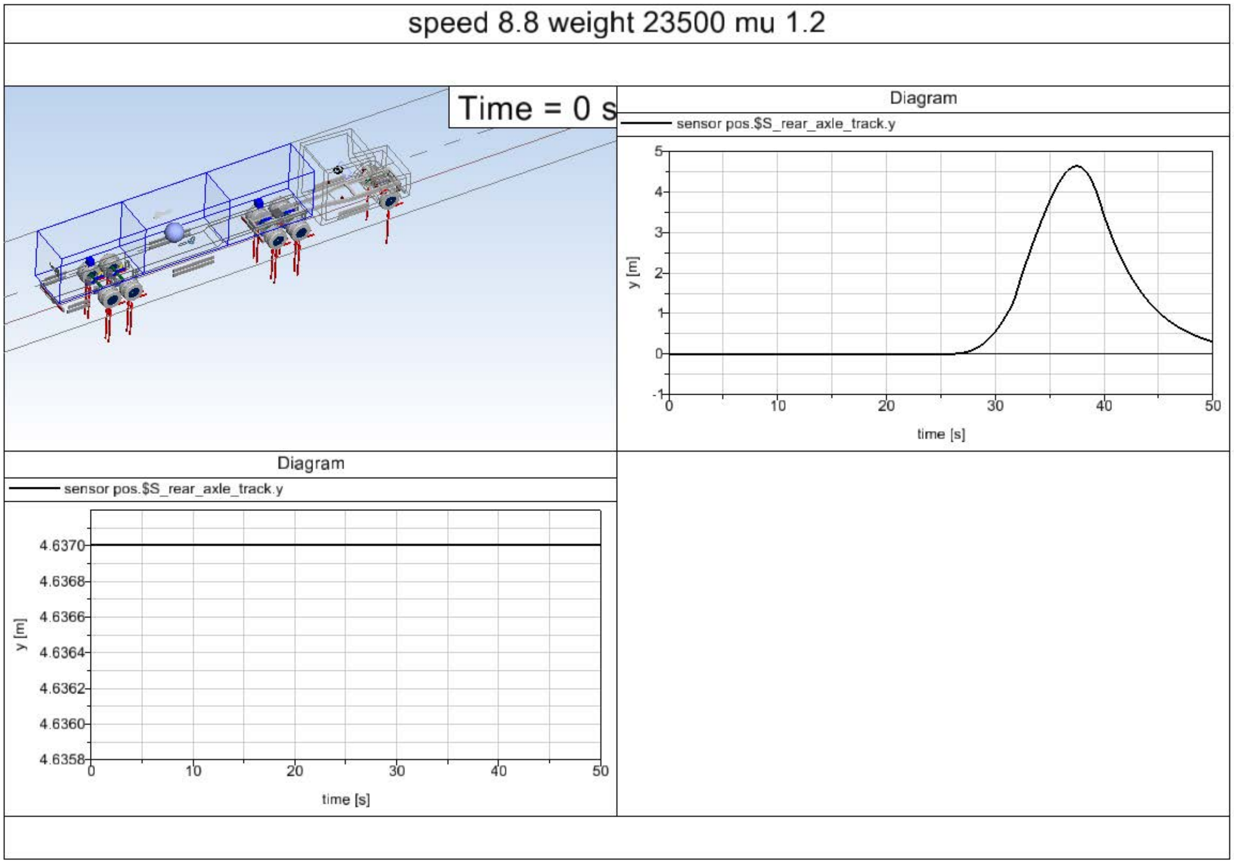

Figure 10: Sample output used to evaluate low-speed offtracking from the low-speed corner manoeuvre.

Front outswing is a vehicle performance parameter describing how much farther the outside front corner of the tractor-semitrailer sticks out from the path of the outside front wheel. Rear outswing is similar in that it is the distance that the outside rear corner of the trailer sticks out from the path of the outside front wheel. Figure 11 shows a plan view explaining the vehicle performance parameters from the low-speed corner manoeuvre.

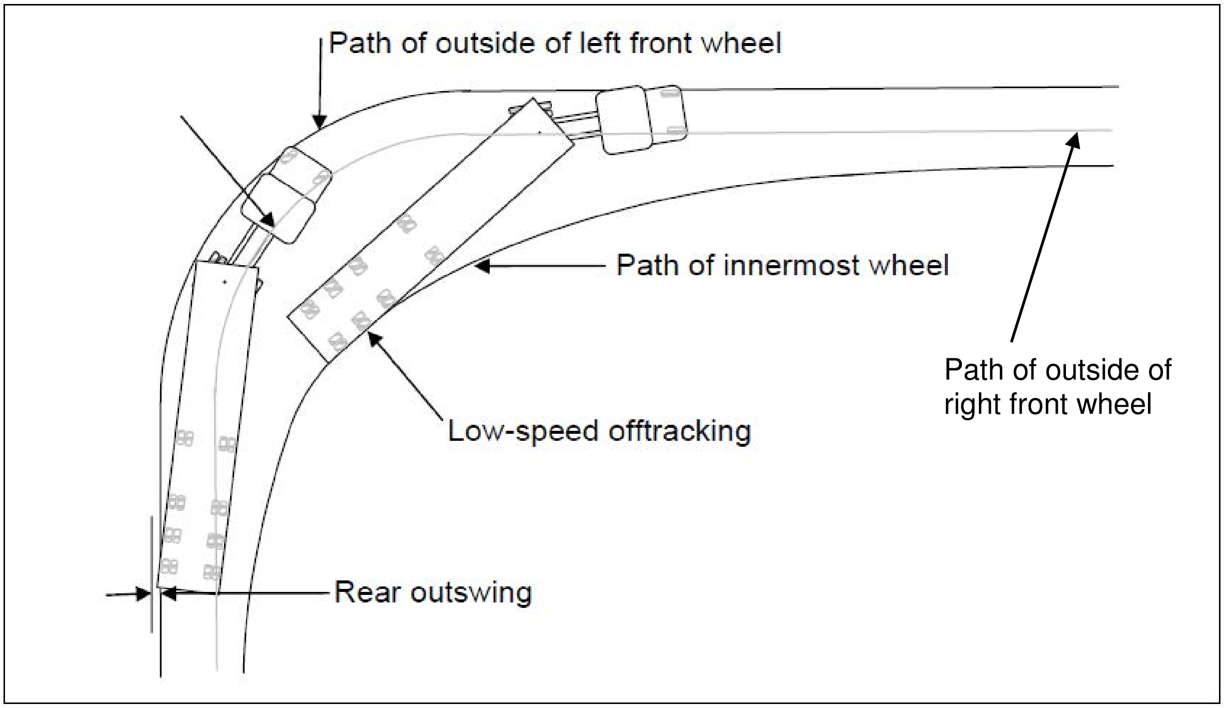

Figure 11: Plan view showing vehicle performance parameters used to evaluate tractor-semitrailer performance in the low-speed corner manoeuvre [8].

A sample output for the rear outswing can be seen in Figure 12. The top-right plot shows the distance between the path of the outside rear corner and the path of the centre of the front axle. The bottom-left plot shows this value minus the distance between outside front wheel and the centre of the front axle. The minimum value represents the maximum outswing and is shown in the bottom-right plot. This was the value used for the rear outswing.

Figure 13 shows the sample output for the front outswing. The top-right plot shows the distance between the path of the outside front wheel and the outside front corner and the bottom-left plot shows the minimum value, the magnitude of which is the front outswing.

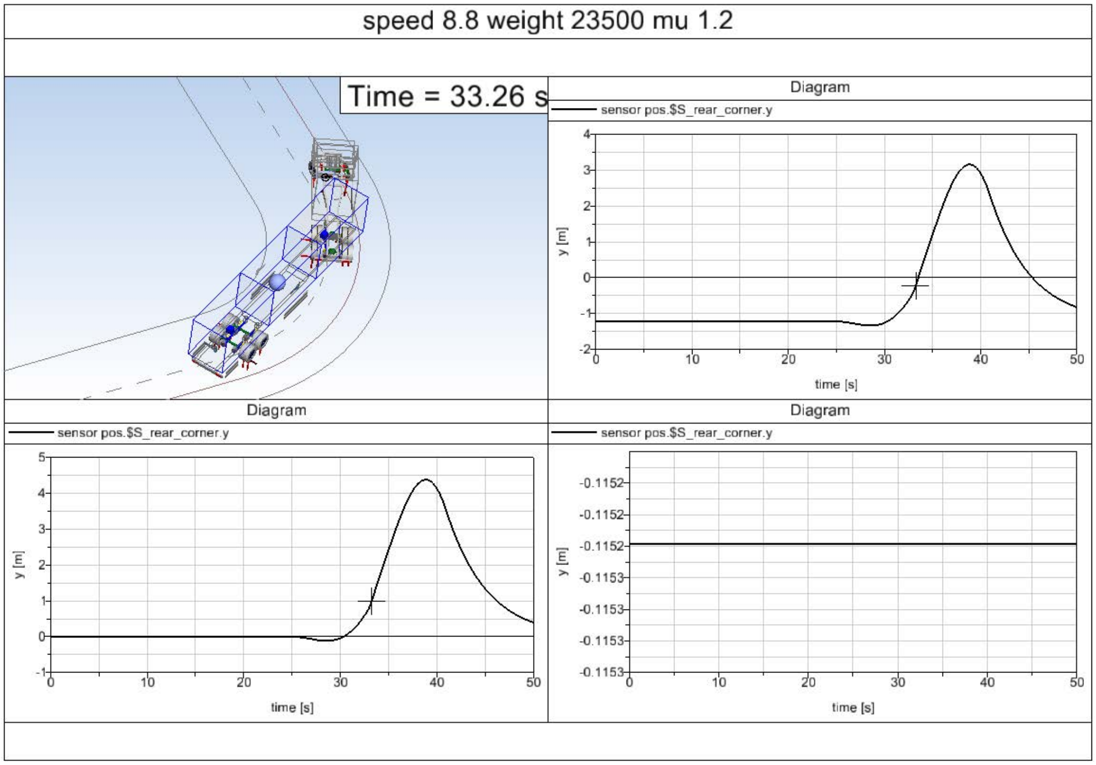

Figure 12: Sample output used to evaluate rear outswing from the low-speed corner manoeuvre.

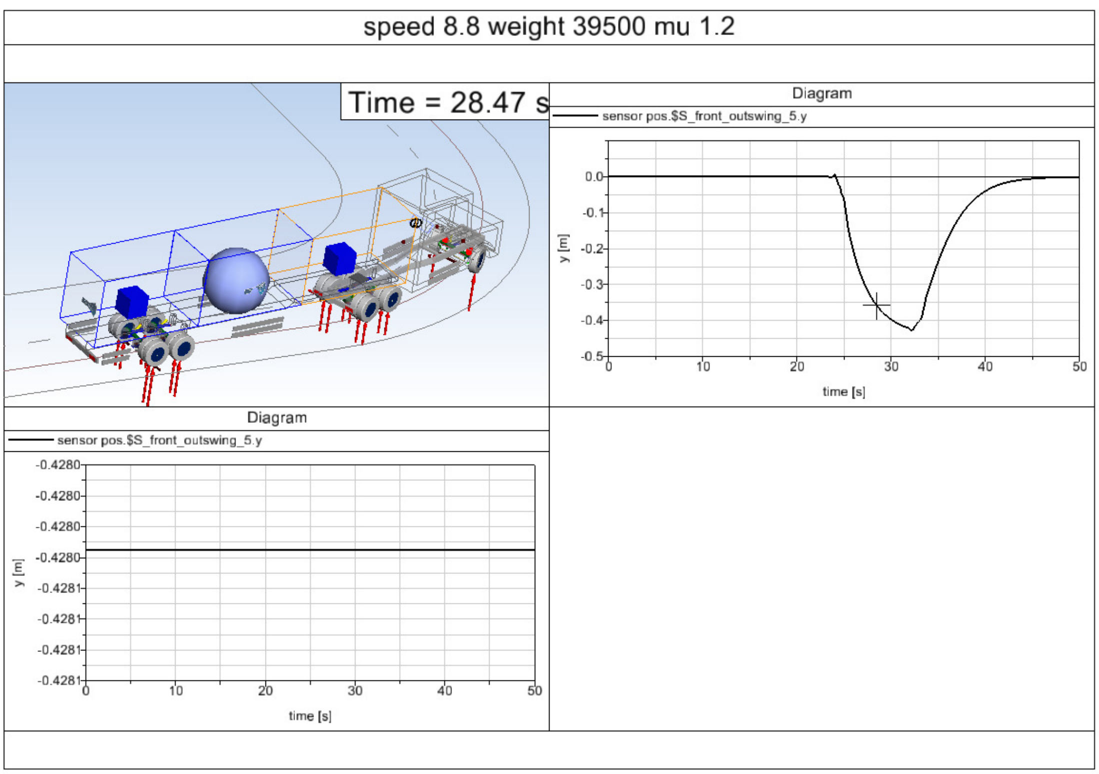

Figure 13: Sample output used to evaluate front outswing from the low-speed corner manoeuvre.

To further assess the performance of the 6x2 tractor-semitrailer, in addition to the baseline 6x2 load cases where the weight was not shifted, an unexpected-load-shift case was defined by starting with the load case 2 payload (10300 kg), and then shifting almost all of the load from the rear axle in the tag-tandem tractor's tandem group to the front axle in the group, while remaining under the axle load limits. This was necessary for this low-speed corner manoeuvre, as opposed to the previous high-speed lane change and high-speed curve manoeuvres, since the speed here was under 70 km/h and thus load shifting is allowed to occur. The low-speed corner does not necessarily require the tractor to develop particularly high levels of tractive effort to pull the semitrailer through the turn, and hence the longitudinal slip at the tractor axles is likely to remain below the threshold that would cause the 6x2 tractor to consider this to be a slip event and initiate load shifting. However, load shifting could be present within the manoeuvre since, as has been observed in previous real-world tests, it can take 30 seconds or more to equalize the load after it has been shifted [1], or it's possible the load shift system might make an error in detecting a slip event and cause load to shift onto the drive axle inadvertently.

3.3.4 Tight Turn

The tight turn manoeuvre involved having the tractor-semitrailer negotiate a curve with a constant radius of curvature until it reached a steady-state behaviour. The radius of curvature was reduced in subsequent simulations until the truck rolled over or slid out of the curve. This manoeuvre was run at a single speed, 50 km/h, for four different loads, load case 1 to load case 4. Additionally, the evaluations were done on two different surface friction levels, a high friction coefficient of 1.2 and a low friction coefficient of 0.2. The value of 0.2 corresponds to values on snowy or icy surfaces obtained in previous studies [9].

Similar to the case for the low-speed corner manoeuvre, the performance of the 6x2 tractor-semitrailer in the tight turn manoeuvre was evaluated with the baseline load cases where the load was not shifted, and with an unexpected-load-shift case that was defined by starting with the load case 2 payload (10300 kg), and then shifting almost all of the load from the rear axle in the tag-tandem tractor's tandem group to the front axle in the group, while remaining under the axle load limit. This was again necessary for this manoeuvre, as opposed to the high-speed manoeuvres, since the speed here was under 70 km/h, which means that load shifting can occur. Also, similar to the low-speed corner manoeuvre, this tight turn manoeuvre does not necessarily require the tractor to develop particularly high levels of tractive effort to pull the semitrailer through the turn, and hence the longitudinal slip at the tractor axles is likely to remain below the slip event threshold that would normally initiate load shifting. However, load shifting could be present within the manoeuvre since, as has been observed in previous real-world tests, it can take 30 seconds or more to equalize the load after it has been shifted [1]. This case was evaluated to ensure safety if, for some reason, there was load shifting present.

The output for the tight turn manoeuvre was the smallest radius of curvature that each of the tractor-semitrailer configurations could negotiate successfully.

3.3.5 Steep Hill

The steep hill manoeuvre includes evaluations of all of the vehicle types, vehicle payloads, and vehicle speeds that were included in the tight turn manoeuvre described in Section 3.3.4. However, in this case, a search is conducted for the largest tire traction-limited grade of hill that the vehicle can climb at a speed of approximately 50 km/h, instead of the smallest radius of curvature that the vehicle can safely negotiate. In the process, a trial grade was selected, torque was applied to the driven wheels on the tractor with a magnitude that causes maximum longitudinal tractive effort of the tires on the driven wheels without excessively high level of longitudinal slip. If the trial grade could be ascended with increasing speed then a new, higher, trial grade was selected. If the speed was decreasing, then a new shallower grade was selected, and the process continued until a grade was found that resulted in a constant rate of ascent. This grade was then recorded as the maximum traction-limited grade that this specific tractor-semitrailer configuration could climb.

As noted in Section 3.3, this steep hill manoeuvre was used to evaluate two different 6x2 technologies, the tag-tandem configuration (where the front axle of the tractor's tandem group was driven) and the pusher-tag configuration (where the rear axle of the tractor's tandem axle group was driven). This is a change from the level-ground manoeuvres described in Sections 3.3.1 to 3.3.4, where the tag-tandem was the only 6x2 configuration evaluated. The two technologies both cause load shifting to occur since the vehicle speed is within the zero to 70 km/h speed range in which the technologies are functional.

Another parameter that was evaluated for this steep hill manoeuvre was the tire type. A standard tire model was used in the level-ground manoeuvres described in Sections 3.3.1 to 3.3.4, and in this manoeuvre. However, since the steep hill manoeuvre was the one in which the performance of the different tractor-semitrailer configurations varied the most, a second tire type was also evaluated here. The second tire type was a tire that was capable of obtaining higher levels of traction, particularly on icy or snowy surfaces.

A sample of the simulation output used to determine if the tractor-semitrailer could maintain speed while ascending the grade, optimize the torque, and ensure the axle load limits were being followed is shown in Figure 14. The top-right plot shows the speed, which in this case was increasing slightly. The bottom-left plot gives an indication of the longitudinal slip between the tires and the road surface. If the tires start to slip excessively (leading to spin out), this value increases throughout the simulation. In this case, the slip stayed relatively constant throughout the simulation and, therefore, with the speed increasing, a new steeper grade needed to selected, and the performance evaluated there. The bottom-right plot in the figure shows the axle loads normal to the road surface. Since this sample is for a 6x2 tractor-semitrailer, the higher loads are on the driven axle of the tractor's tandem axle group, and the lower loads are on the non-driven axle of the group. If this were the 6x4 tractor-semitrailer, the loads carried by the two driven axles would be similar to each other.

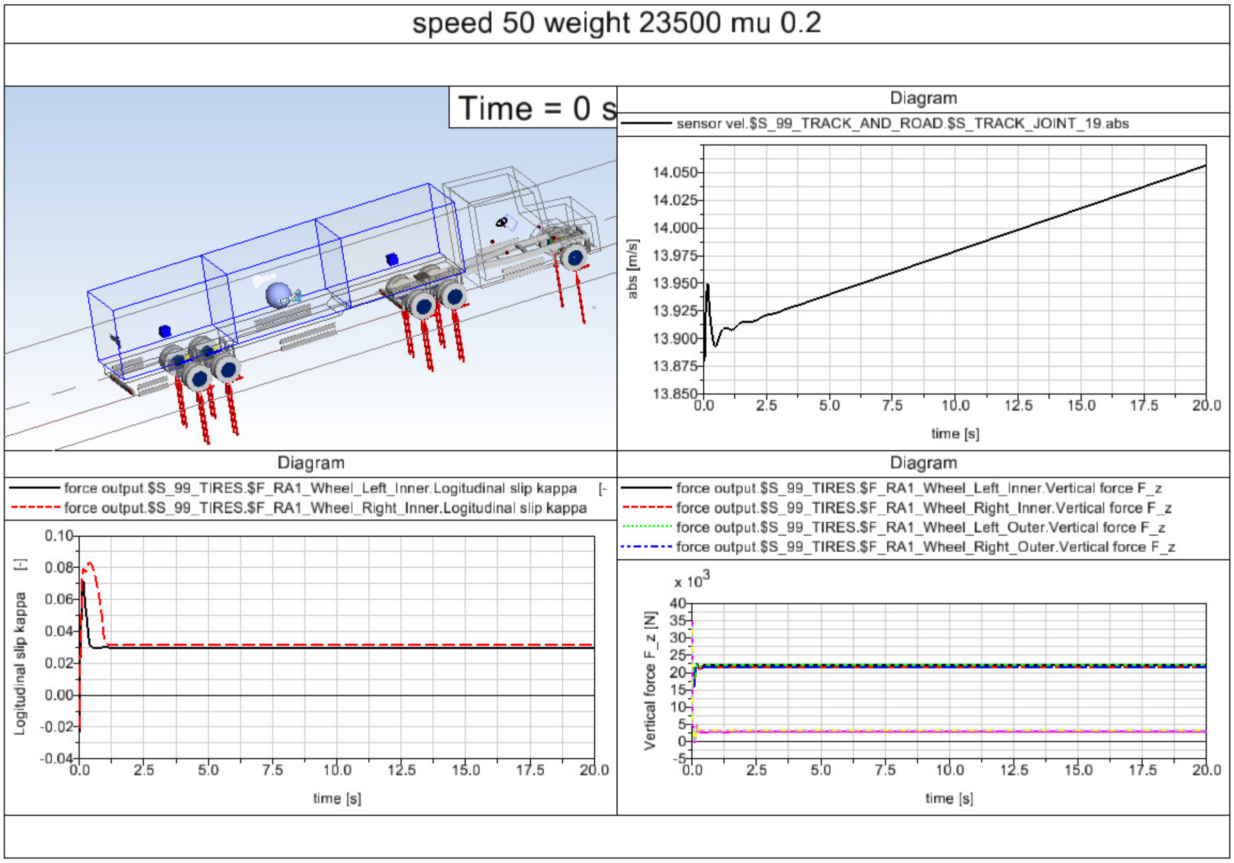

Figure 14: Sample output used to evaluate hill climbing ability of a tractor-semitrailer from the steep hill manoeuvre.

There were also more coefficients of friction evaluated for this steep hill scenario than for the other scenarios. The value of the coefficient of friction has been shown, at its most extreme value, to be able to reach values almost as low as about 0.1 on icy surfaces [9]. Therefore, the maximum grade was evaluated at values ranging from 0.1 to 1.2. As a general guideline, the coefficient of friction of ice or ice with loose snow is the lowest, with values of about 0.1 [9]. If the surface is sanded, the value can increase to 0.3 or higher [9]. Additionally, a packed snow surface can be around 0.4, a wet road can be around 0.5, a dry dirt road can be around 0.6, and a dry asphalt road can be around 0.8 or 1 [9].

3.3.6 Downhill Curve

In the downhill curve manoeuvre, the tractor-semitrailer was made to descend a 12% grade. This grade was selected to align with some of the steepest grades found on Canadian roads [10]. Additionally, a radius of curvature of 333 m was selected, along with the truck having a speed of 46 km/h, thus resulting in a nominal lateral acceleration of .05 g. A torque resisting the forward motion of the truck was applied to each wheel station in order to simulate a braking force. This resisting torque was maximized while remaining low enough that the wheels did not have excessively high levels of longitudinal tire slip on the road or lock up. In this way, the effect of an ABS system was simulated in the model, but the effect is not necessarily the same as any real ABS system actually used on trucks.

In this manoeuvre, the goal was to have the tractor-semitrailer descend the grade without gaining speed. The simulation compared the minimum value for the coefficient of friction that would be required to accomplish this.

Since a braking force would be applied on all of the wheels of the tractor-semitrailer, and not just the driven wheels, there would be very little difference in performance between the 6x4 truck and the 6x2 truck if the 6x2 truck did not have the weight shifted. The difference would be purely a result of the difference in weight between the axle that is driven on the 6x4 that is not driven on the 6x2. In order to determine if there could be a significant difference in performance between the 6x2 and 6x4 configurations, the 6x2 configuration would need to have the weight shifted to the drive axle. However, it should be noted that this would likely not occur if the truck were descending a hill since the braking would not cause the wheels to have levels of longitudinal tire slip that would cause the manoeuvre to be identified as a slip event and the load to shift. Therefore, this situation would likely only occur if the weight were shifted from a previous manoeuvre, such as having just climbed a hill that may have been detected as a slip event. If the truck had just climbed a hill, and then started the descending a hill, the weight may still be shifted for a while as was shown in a previous NRC study [1].

Since the case where the load is shifted is of the most concern in this scenario, the loading case where the payload was 10300 kg was considered in this scenario. This is because, with this payload, the 6x2 tractor can shift almost all of the weight on the tandem axle of the tractor to the drive axle, while leaving very little weight on the non-driven axle. Therefore, this could be considered a worst-case scenario and, for this reason, it was the only payload evaluated for this scenario.

A sample of the simulation output for the downhill curve manoeuvre can be seen in Figure 15. This shows the speed profiles of both the 6x2 and 6x4 configurations. Only one line is visible, since both the 6x2 and 6x4 configurations had the same speed profile when they were able to prevent the acceleration of the truck.

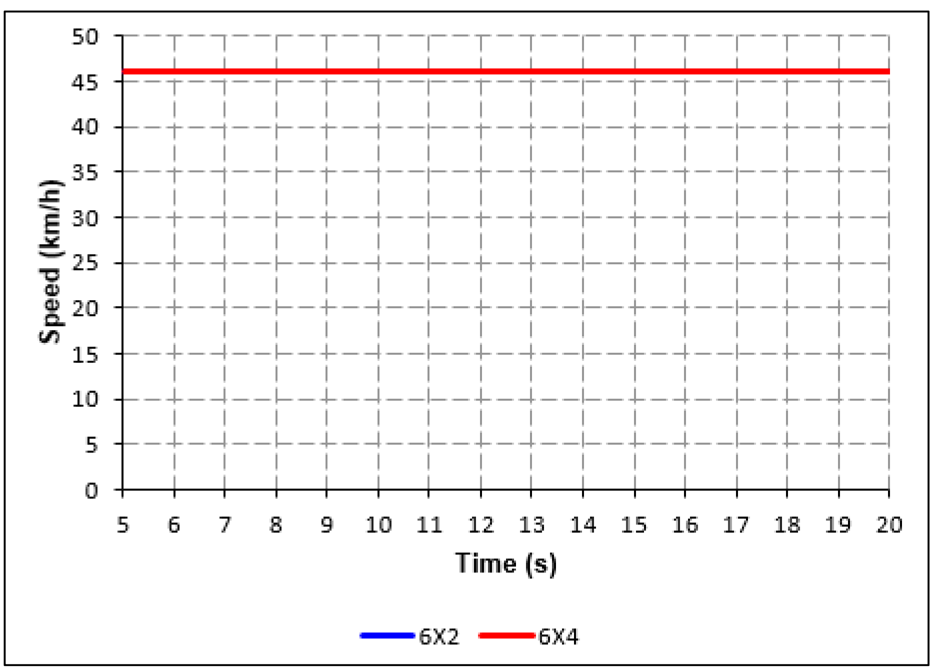

Figure 15: Sample output showing speed profiles of tractor-semitrailers in the downhill curve manoeuvre.

This manoeuvre was also repeated under different truck handling conditions. The truck was run through this same simulation with the truck decelerating and with the truck accelerating. Additionally, since there was a difference seen in the results of the 6x2 and 6x4 trucks in terms of the minimum required coefficient of friction, this manoeuvre was repeated with high performance tires. The purpose of this was to determine if the 6x2 truck could be improved enough by high performance tires in order to match the performance of the 6x4 truck with the regular tires.

4 RESULTS OF DYNAMIC SIMULATION

4.1 Results from the High-Speed Lane Change

Table 3 shows the results for the comparison of the transient high-speed offtracking at speeds of 90, 100, and 110 km/h for both the 6x2 and 6x4 tractor configurations when the tractor-semitrailer, with load case 2 (payload of 10300 kg, and a gross combination weight of 23510 kg for the 6x4 and 23210 for the 6x2) was performing the high-speed lane change manoeuvre. From these results, it is clear that the increase in speed causes an increase in transient high-speed offtracking. However, the purpose is to compare the 6x2 to the 6x4. Therefore, the important result from this table is that the 6x2 configuration results in a slightly lower value for transient high-speed offtracking than the 6x4 configuration. However, the difference is slight, with a 2% improvement on the 6x2.

Table 3: Transient high-speed offtracking of 6x4 configurations and 6x2 load-not-shifted configurations evaluated at three speeds for load case 2 (payload of 10300 kg, and gross combination weights of 23510 kg for 6x4 and 23210 kg for 6x2).

Tractor Configuration	Transient High-Speed Offtracking (m)		
	At 90 km/h	At 100 km/h	At 110 km/h
6x4	0.255	0.335	0.418
6x2	0.250	0.329	0.410

The results in the previous table were obtained when the tractor-semitrailer was assumed to be carrying a payload of 10300 kg, which results in a gross combination weight of 23510 kg for the 6x4 configuration as shown in Table 1, and a gross combination weight of 23210 kg for the 6x2 configuration as shown in Table 2.

Table 4 shows the values of transient high-speed offtracking for the 6x4 and 6x2 tractor-semitrailer configurations with all four of the load cases described in Table 1 and Table 2 (i.e., with payloads of 1300 kg, 10300 kg, 20300 kg and 26300 kg) when performing a high-speed lane change at manoeuvre at a 90 km/h.

Table 4: Transient high-speed offtracking of 6x4 configurations and 6x2 load-not-shifted configurations evaluated at four load cases and a speed of 90 km/h.

Tractor Configuration	Transient High-Speed Offtracking (m)			
	1300 kg payload	10300 kg payload	20300 kg payload	26300 kg payload
6x4	0.065	0.255	0.547	0.753
6x2	0.062	0.250	0.540	0.743

From Table 4 it is clear that there is an increase in transient high-speed offtracking as the payload increases. However, again the more relevant results are the differences between the 6x4 and 6x2 configurations. The table shows that the 6x2 configuration results in a lower amount of transient high-speed offtracking for each load. There is not much of a difference as the improvement ranges from to 1.3% to 4.6%.

The next two tables show a similar comparison for the load transfer ratio that was obtained by performing the high-speed lane change manoeuvre. Table 5 shows the comparison at each of the different speeds for load case 2 where the payload was 10300 kg. From this it is clear that the 6x2 configuration results in a higher load transfer ratio by a small amount ranging from 0.2% to 1.2%. This means that the 6x2 configuration actually performs worse than the 6x4 in this case.

Table 5: Load transfer ratio of 6x4 configurations and 6x2 load-not-shifted configurations evaluated at three speeds for load case 2 (payload of 10300 kg, and gross combination weights of 23510 kg for 6x4 and 23210 kg for 6x2).

Tractor Configuration	Load Transfer Ratio		
	At 90 km/h	At 100 km/h	At 110 km/h
6x4	0.413	0.460	0.499
6x2	0.418	0.461	0.504

Table 6 shows the load transfer ratio comparison for the same four load cases used for transient high-speed offtracking and a speed of 90 km/h. The results here are not very conclusive. For the lowest payload of 1300 kg and for the payload of 20300 kg, the load transfer ratios are the same for both the 6x2 and 6x4 configurations. However, for the payload of 10300 kg, the load transfer ratio is 1.2% higher for the 6x2 configuration, whereas it is 0.2% lower when the payload is 26300 kg.

Table 6: Load transfer ratio of 6x4 configurations and 6x2 load-not-shifted configurations evaluated at four load cases and a speed of 90 km/h.

Tractor Configuration	Load Transfer Ratio			
	1300 kg payload	10300 kg payload	20300 kg payload	26300 kg payload
6x4	0.187	0.413	0.617	0.764
6x2	0.187	0.418	0.617	0.762

4.2 Results from the High-Speed Curve

The same comparisons were done on the high-speed curve manoeuvre as were done on the high-speed lane change manoeuvre. However, the parameters being compared in this case were high-speed offtracking and static rollover threshold.

Table 7 shows the comparison of the high-speed offtracking of the 6x4 and 6x2 configurations evaluated at three speeds for load case 2 (payload of 10300 kg, and gross combination weights of 23510 kg for the 6x4 and 23210 kg for the 6x2). From this table it is clear that the 6x2 configuration results in a slight advantage in each case. The values obtained for the 6x2 are 1 to 1.3% lower than those obtained for the 6x4.

Table 7: High-speed offtracking of 6x4 configurations and 6x2 load-not-shifted configurations evaluated at three speeds for load case 2 (payload of 10300 kg, and gross combination weights of 23510 kg for 6x4 and 23210 kg for 6x2).

Tractor Configuration	High-Speed Offtracking (m)		
	At 90 km/h	At 100 km/h	At 110 km/h
6x4	0.229	0.267	0.295
6x2	0.226	0.264	0.292

Table 8 shows the high-speed offtracking of the 6x4 and 6x2 configurations evaluated at four load cases and a speed of 90 km/h. In the table it can be seen that there is again a slight improvement in the high-speed offtracking values for the 6x2 configuration. The values are 1.3 to 4.2% lower than for the 6x4 when the first three load cases are considered. However, it can be seen that, for the 6x2 configuration with the 26300 kg payload, rather than being lower than the 6x4 results, this 6x2 high-speed offtracking value was 10.8% higher than the corresponding 6x4 value, and corresponds to an increase in high-speed offtracking of 7.8 cm. This increase in high-speed offtracking for the 6x2 was observed to be related to an instability of the truck in the simulation. For this payload only, the 6x2 configuration would start to rock from side to side as it took the curve. It is possible that this instability is caused by a problem with the computer simulation model, rather than an indication that the 6x2 tractor-semitrailer with a 26300 kg payload is unstable. This should be investigated further in any future work that may be done with these 6x2 and 6x4 tractor-semitrailer simulation models.

Table 8: High-speed offtracking of 6x4 configurations and 6x2 load-not-shifted configurations evaluated at four load cases and a speed of 90 km/h.

Tractor Configuration	High-Speed Offtracking (m)			
	1300 kg payload	10300 kg payload	20300 kg payload	26300 kg payload
6x4	0.095	0.229	0.366	0.645
6x2	0.091	0.226	0.360	0.723[1]

1. Unrealistically high value for high-speed offtracking from simulation model results that show hunting or rocking of the tractor-semitrailer for this case only.

A comparison of the static rollover threshold of the 6x4 and 6x2 configurations evaluated at three speeds for load case 2 (payload of 10300 kg, and gross combination weights of 23510 kg for 6x4 and 23210 kg for 6x2) is shown in Table 9. From this table, it can be seen that the 6x2 performed better at all speeds. The improvement ranged from 0.6% to 1.3%.

Table 9: Static rollover threshold of 6x4 configurations and 6x2 load-not-shifted configurations evaluated at three speeds for load case 2 (payload of 10300 kg, and gross combination weights of 23510 kg for 6x4 and 23210 kg for 6x2).

Tractor Configuration	Static Rollover Threshold (g)		
	At 90 km/h	At 100 km/h	At 110 km/h
6x4	0.530	0.534	0.529
6x2	0.537	0.537	0.536

The changes that occurred in the static rollover threshold when different payloads were considered were not as consistent. From Table 10, it can be seen that for two of the payloads (1300 kg and 20300 kg) the static rollover threshold decreased when the 6x2 configuration was used in place of the 6x4. For the other two payloads (10300 kg and 26300 kg), the static rollover threshold increased. However, the differences are again only around 1%.

Table 10: Static rollover threshold of 6x4 configurations and 6x2 load-not-shifted configurations evaluated at four load cases and a speed of 90 km/h.

Tractor Configuration	Static Rollover Threshold (g)			
	1300 kg payload	10300 kg payload	20300 kg payload	26300 kg payload
6x4	0.709	0.530	0.429	0.376
6x2	0.701	0.537	0.425	0.382

4.3 Results from the Low-Speed Corner

The first vehicle performance parameter for the low-speed corner manoeuvre is low-speed offtracking of the 6x4 and 6x2 configurations, and it was evaluated with the four load cases described in Table 1 and Table 2. Table 11 shows the results for this parameter. From this table it can be seen that the 6x2 configuration outperforms the 6x4 in each case. The low-speed offtracking values are only are between 4 and 16 millimeters lower in each case, which corresponds to differences of 0.1% to 0.4%.

Table 11: Low-speed offtracking of 6x4 configurations and 6x2 load-not-shifted configurations evaluated at four load cases.

Tractor Configuration	Low-Speed Offtracking (m)			
	1300 kg payload	10300 kg payload	20300 kg payload	26300 kg payload
6x4	4.647	4.637	4.619	4.619
6x2	4.631	4.628	4.614	4.615

The second vehicle performance parameter for the low-speed corner manoeuvre is the rear outswing. The values for the rear outswing for the 6x4 and 6x2 configurations and at each of the four load cases are shown in Table 12. The table shows that there is very little difference between the rear outswing values for each configuration. The largest change is a 2 mm increase in the rear outswing for the 6x2, which corresponds to a 1.3 % decrease in performance.

Table 12: Rear outswing of 6x4 configurations and 6x2 load-not-shifted configurations evaluated at four load cases.

Tractor Configuration	Rear Outswing (m)			
	1300 kg payload	10300 kg payload	20300 kg payload	26300 kg payload
6x4	0.107	0.115	0.130	0.147
6x2	0.107	0.116	0.131	0.149

The last vehicle performance parameter for the low-speed corner manoeuvre is the front outswing. Table 13 shows front outswing of the 6x4 and 6x2 configurations evaluated for the four load cases. Using the 6x2 configuration in place of the 6x4 results in lower outswing values by 2 mm to 3 mm in each case. This corresponds to an increase in performance ranging from 0.5% to 0.7%.

Table 13: Front outswing of 6x4 configurations and 6x2 load-not-shifted configurations evaluated at four load cases

Tractor Configuration	Front Outswing (m)			
	1300 kg payload	10300 kg payload	20300 kg payload	26300 kg payload
6x4	0.419	0.422	0.426	0.428
6x2	0.416	0.420	0.423	0.426

In addition to the standard 6x2 results, an evaluation was done of a 6x2 unexpected-load-shift case where, with the load case 2 payload of 10300 kg, and most of the weight on the undriven axle in the tractor's tandem axle group was shifted to the drive axle so that the drive axle was up to its maximum allowable weight limit. The performance criteria for this unexpected-load-shift case were compared to the 6x2 results where the load was not shifted. With the load shifted, the low-speed offtracking was 4.498 m, the rear outswing was 0.118 m, and the front outswing was 0.399 m. These values are not far off the values obtained with no load shifting. They vary by 2.8%, 1.7%, and 5.0% on the low-speed offtracking, rear outswing, and front outswing values respectively. It should also be noted that, for low-speed offtracking and front outswing, performance was improved slightly when the load was shifted, and for the rear outswing performance got slightly worse when the load was shifted.

4.4 Results from the Tight Turn

There was only one vehicle performance parameter for the tight turn manoeuvre, and that was the minimum radius of curvature that could be maintained by the tractor-semitrailer travelling at 50 km/h without rolling over or sliding out. When done on a high friction surface with a coefficient of friction of 1.2, the results from Table 14 were obtained. It should be noted that on this high friction surface, the truck rolled over in all cases and did not slide out of the turn. From Table 14, it can be seen that the minimum radius of curvature for the 6x2 configuration is either the same as or slightly lower than that of the 6x4 configuration. The maximum benefit occurs with a payload of 1300 kg, where the minimum radius of curvature decreased by 2 m or 7%.

Table 14: Minimum radius of curvature of 6x4 configurations and 6x2 load-not-shifted configurations evaluated at four load cases on a high friction surface.

Tractor Configuration	Minimum Radius of Curvature (m)			
	1300 kg payload	10300 kg payload	20300 kg payload	26300 kg payload
6x4	31	42	50	56
6x2	29	42	49	55

The minimum radius of curvature was also determined when the simulation was run on a low friction surface with a coefficient of friction of 0.2. Table 15 shows the results for this comparison. On this low-friction surface, the minimum radius of curvature was limited by the fact that the truck would slide out of the curve if the radius of curvature was decreased any further. These results show that the two configurations perform almost exactly the same. The only difference appears when a load of 10300 kg is used where a 1 m decrease in the minimum radius of curvature is seen.

Table 15: Minimum radius of curvature of 6x4 configurations and 6x2 load-not-shifted configurations evaluated at four load cases on a low friction surface.

Tractor Configuration	Minimum Radius of Curvature (m)			
	1300 kg payload	10300 kg payload	20300 kg payload	26300 kg payload
6x4	128	129	129	130
6x2	128	128	129	130

In addition to the standard 6x2 results, there are results for a 6x2 unexpected-load-shift case where, with the load case 2 payload of 10300 kg, most of the weight on the undriven axle in the tractor's tandem group is shifted to the drive axle so that the drive axle was up to its maximum allowable weight limit. The performance criteria were compared to the 6x2 load-not-shifted results. With the unexpected load shift configuration, the minimum radius of curvature values were very similar to those for the 6x2 configuration with the load not shifted. When the high-friction surface was considered, the minimum radius of curvature was 42 m, which is the same as when the load was not shifted. There was a slight difference seen when the simulation was run on a low-friction surface, but the value was still 127 m, which is only 1 m less than the value of 128 m obtained when there was no load shifting.

4.5 Results from the Steep Hill

The steep hill manoeuvre also only had one vehicle performance parameter: the maximum grade that the tractor-semitrailer could climb while maintaining its speed. However, since the maximum grade for roads in Canada is 7% to 12% [10], grades in the steep hill manoeuvre that are above 15% are reported here as ">15%".

Table 16 shows the specific maximum grades that were obtained from the steep hill manoeuvre when the 6x4 truck climbed the hill with the four load cases (i.e, payloads of 1300 kg, 10300 kg, 20300 kg and 26300 kg), and with seven different values for the coefficient of friction between the tires and the road surface (0.1, 0.2, 0.4, 0.6, 0.8, 1.0 and 1.2). It is evident that, for coefficient of friction values of 0.6 and higher, all of the 6x4 load cases were able to ascend grades in excess of 15%.

Table 17 and Table 18 show the results for the 6x2 tag-tandem (front axle of the tractor's tandem axle group is driven) and pusher-tag (rear axle of the tractor's tandem axle group is driven) configurations, respectively, with the load from the non-driven axle in the tractor's tandem axle group shifted to provide additional load on the driven axle and enhance hill climbing. The two tables show the maximum grade for the four load cases and seven coefficient of friction values that were used to describe the performance of the 6x4 configuration in the steep hill manoeuvre.

When higher friction surfaces were considered, the tractor-semitrailer was sometimes able to maintain its speed while ascending a 15% grade for both 6x2 and 6x4 configurations with each of the four load cases. This was not the case when lower friction surfaces were considered. In this case, there was often quite a difference between the 6x4 and 6x2 configurations that was amplified when the payload increased.

Table 16: Maximum grade that can be ascended at constant speed by the 6x4 tractor-semitrailer with four load cases and seven values of the coefficient of friction between the tires and the road surface.

Coefficient of Friction	Maximum Grade (%)			
	1300 kg payload	10300 kg payload	20300 kg payload	26300 kg payload
0.1	3.0	3.0	2.9	2.9
0.2	6.2	6.2	6.1	6.1
0.4	12.7	13.2	12.5	12.5
0.6	>15	>15	>15	>15
0.8	>15	>15	>15	>15
1.0	>15	>15	>15	>15
1.2	>15	>15	>15	>15

Table 17: Maximum grade that can be ascended at constant speed by the 6x2 tag-tandem (i.e., front axle in tractor tandem group is driven) shifted-load tractor-semitrailer with four load cases and seven values of the coefficient of friction between the tires and the road surface.

Coefficient of Friction	Maximum Grade (%)			
	1300 kg payload	10300 kg payload	20300 kg payload	26300 kg payload
0.1	3.0	2.8	1.9	1.4
0.2	6.2	5.8	3.8	3.4
0.4	12.8	11.7	7.6	6.5
0.6	>15	>15	11.9	10.1
0.8	>15	>15	>15	13.5
1.0	>15	>15	>15	>15
1.2	>15	>15	>15	>15

Table 18: Maximum grade that can be ascended by the 6x2 pusher-tag (i.e., rear axle in tractor tandem group is driven) shifted-load tractor-semitrailer with four load cases and seven values of the coefficient of friction between the tires and the road surface.

Coefficient of Friction	Maximum Grade (%)			
	1300 kg payload	10300 kg payload	20300 kg payload	26300 kg payload
0.1	2.6	2.6	1.9	1.4
0.2	5.2	5.2	3.8	3.4
0.4	11.1	11.0	7.5	6.5
0.6	>15	>15	11.9	10.2
0.8	>15	>15	>15	13.4
1.0	>15	>15	>15	>15
1.2	>15	>15	>15	>15

From Table 16 it can be seen that the maximum grade for the 6x4 configuration is not too affected by the load. This trend is not present for the 6x2 configurations. In Table 17, it can be seen that the maximum grade decreases as the load increases for the 6x2 tag-tandem configuration. However, in Table 18 it can be seen that the maximum grade remains the same for the first two load cases when the 6x2 pusher-tag configuration is used, but when the load is increased further, the maximum grade decreases to about the same values as the 6x2 tag-tandem configuration.

Additionally, even at the lowest payload of 1300 kg, the 6x2 tag-tandem configuration has a maximum grade that is almost identical to that of the 6x4 configuration for all coefficients of friction considered. The 6x2 pusher-tag, on the other hand, has values that are lower. The 6x2 pusher-tag has values for maximum grade that, when compared with the values for the 6x2 tag-tandem or 6x4 configurations, yield a percent difference of up to 16%. In the worst case, where the payload is 26300 kg and the coefficient of friction is 0.1, there is a difference in maximum grade of 1.5% between the 6x4 configuration and both 6x2 configurations (the tag-tandem and pusher-tag), which corresponds to a difference of 52%.

In the hill climb manoeuvre, the tire models were also changed to examine the effect of using a tire with higher traction. Table 19 shows the results of using the better tires with the 6x4 configuration, and Table 20 and Table 21 show the results of using the better tires on the 6x2 tag-tandem and 6x2 pusher-tag configurations respectively.

Table 19: Maximum grade that can be ascended at constant speed by the 6x4 tractor-semitrailer with high-traction tires, and with four load cases and seven values of the coefficient of friction between the tires and the road surface.

Coefficient of Friction	Maximum Grade (%)			
	1300 kg payload	10300 kg payload	20300 kg payload	26300 kg payload
0.1	4.0	4.0	3.9	3.9
0.2	7.8	8.0	7.9	7.9
0.4	>15	>15	>15	>15
0.6	>15	>15	>15	>15
0.8	>15	>15	>15	>15
1.0	>15	>15	>15	>15
1.2	>15	>15	>15	>15

Table 20: Maximum grade that can be ascended at constant speed by the 6x2 tag-tandem (i.e., front axle in tractor tandem group is driven) shifted-load tractor-semitrailer with high-traction tires, with four load cases and seven values of the coefficient of friction between the tires and the road surface.

Coefficient of Friction	Maximum Grade (%)			
	1300 kg payload	10300 kg payload	20300 kg payload	26300 kg payload
0.1	4.1	3.7	2.6	2.2
0.2	8.3	7.5	5.2	4.4
0.4	>15	15.0	10.2	8.8
0.6	>15	>15	>15	13.3
0.8	>15	>15	>15	>15
1.0	>15	>15	>15	>15
1.2	>15	>15	>15	>15

Table 21: Maximum grade that can be ascended at constant speed by the 6x2 pusher-tag (i.e., rear axle in tractor tandem group is driven) shifted-load tractor-semitrailer with high-traction tires, with four load cases and seven values of the coefficient of friction between the tires and the road surface.

Coefficient of Friction	Maximum Grade (%)			
	1300 kg payload	10300 kg payload	20300 kg payload	26300 kg payload
0.1	3.3	3.4	2.6	2.2
0.2	6.8	6.9	5.2	4.5
0.4	14.3	14.1	10.2	8.8
0.6	>15	>15	>15	13.3
0.8	>15	>15	>15	>15
1.0	>15	>15	>15	>15
1.2	>15	>15	>15	>15

From the fact that the values in the tables for the high-traction tires (Table 19 to Table 21 are all higher than the values found in the table for the standard tires (Table 16 to Table 18), it is clear that the maximum grade that can be ascended is increased when the better tires are used. In fact, the lowest values, which occur when the coefficient of friction is only 0.1, can be increased by grades of 0.7 to 1.0%, which can correspond to a difference of up to 57%.

It is also apparent from the tables above that the trends within each table are not changed by the use of the better tires. In the case of the 6x4 configuration, the values are not too affected by the increase in load, but do increase as the coefficient of friction increases. Furthermore, the 6x2 tag-tandem configuration is shown to perform worse as the load is increased and the 6x2 pusher-tag configuration is shown to do this as well, but not between the first and second load cases. However, the 6x2 pusher-tag configuration is again shown to perform worse than the 6x2 tag-tandem configuration under these first two load cases.

4.6 Results from the Downhill Curve

The downhill curve manoeuvre had only one vehicle performance parameter to compare the performance of the 6x2 and 6x4 tractor-semitrailer configurations: the minimum coefficient of friction required for the trucks to be able to descend the 12% grade with a radius of curvature of 333 m without gaining speed. In a worst-case scenario, where the payload was 10300 kg so that almost all of the load was shifted to the driven axle on the 6x2 tag-tandem configuration, the 6x2 tag-tandem underperformed the 6x4 configuration. The 6x2 tag-tandem configuration was able to prevent acceleration and maintain speed when the coefficient of friction was 0.22. However, the 6x4 configuration was able to accomplish this when the coefficient of friction was 0.17. This result might be changed somewhat for the two cases if a better model of the ABS system were used, but with the simplistic ABS model used here, these were the results.

Figure 16 to Figure 18 show the vertical forces on the inner wheels for each of the axles for both the 6x2 tag-tandem and 6x4 configurations when the minimum coefficients of friction for each case were considered. The plots on the left are for the wheels on the left side of the truck and the plots on the right are for the wheels on the right side of the truck. From Figure 16 and Figure 17, it is clear that the 6x2 tag-tandem with the load shifted to the drive axle results in very different loads being present on all of the axles on the tractor. The 6x2 tag-tandem has about twice the load carried by the 6x4 configuration on the front axle of the tractor's tandem group, but has very little load on the non-driven axle in the tandem group. Additionally, the tractor's steer axle is shown to have a higher load in the case of the 6x4 configuration compared to the

6x2 tag-tandem configuration. However, Figure 18 shows that there is almost no effect on the load on the trailer axles. The vertical force is seen to be almost exactly the same.

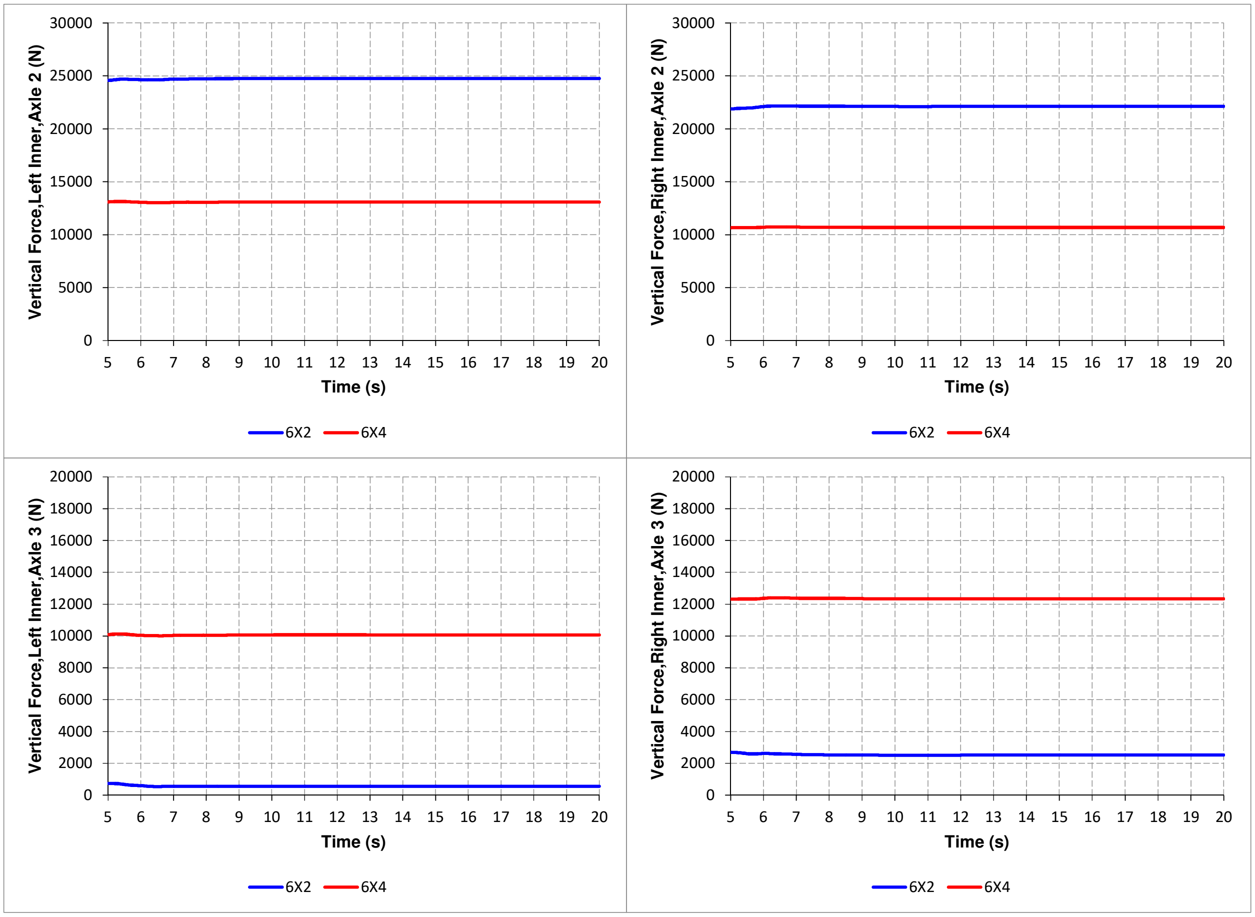

Figure 16: Vertical forces on the left and right inner wheels of the front (Axle 2) and rear axles (Axle 3) in the tandem group on the tractor for the 6x2 tag-tandem unexpected-load-shift tractor-semitrailer and the 6x4 tractor-semitrailer.

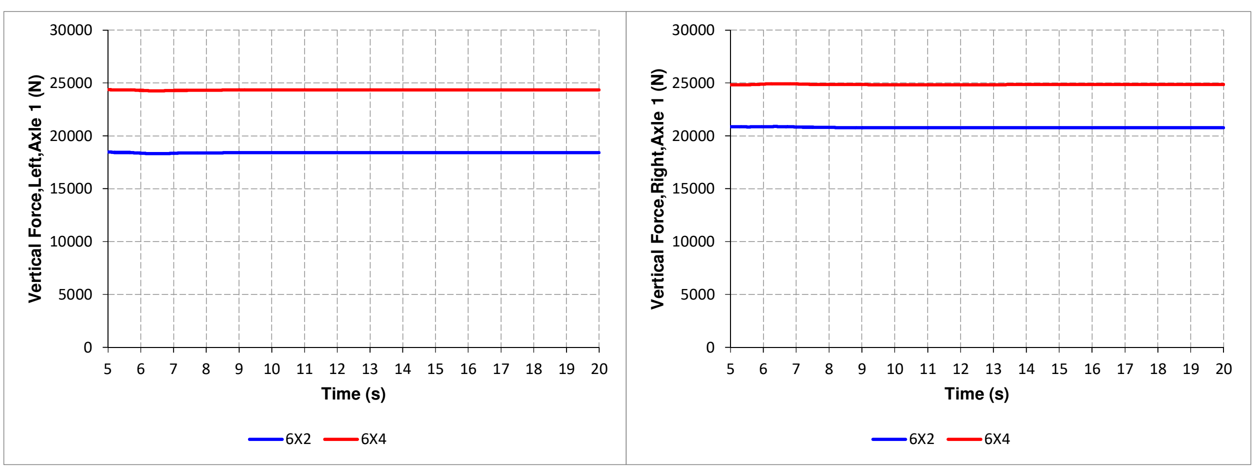

Figure 17: Vertical forces on the left and right wheels of the steer axle (Axle 1) of the tractor for the 6x2 tag-tandem unexpected-load-shift tractor-semitrailer and the 6x4 tractor-semitrailer.

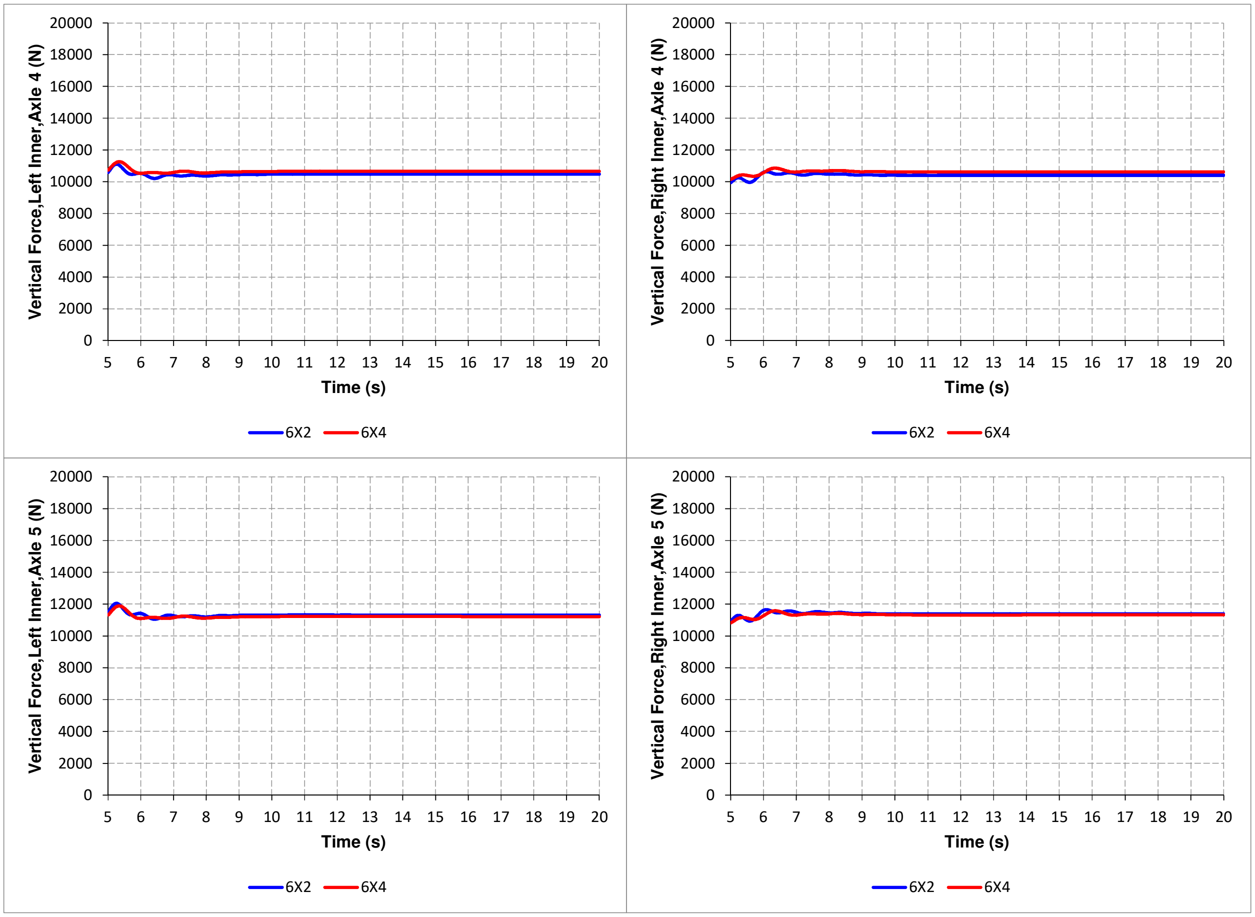

Figure 18: Vertical forces on the left and right inner wheels of the front (Axle 4) and rear axles (Axle 5) in the tandem group on the trailer for the 6x2 tag-tandem unexpected-load-shift tractor-semitrailer configuration and the 6x4 tractor-semitrailer.

These vertical loads are important because they affect the amount of brake torque that was applied on these wheels so the tractor-semitrailer could maintain the required speed of 46 km/h in the downhill curve manoeuvre. If the brake torques had not been applied, the configurations would all have gained speed. Figure 19 to Figure 21 show the brake torques that were applied to each wheel station on the truck. Since the front axle in the tractor tandem axle group (Axle 2) had a larger load, the torques applied on this axle would be expected to be larger. This is confirmed by Figure 19, which shows that the 6x2 tag-tandem has a much higher torque on this axle. The figure also shows that the rear axle in the tractor's tandem group (Axle 3), where the load was shifted from in the case of the 6x2 tag-tandem, has almost no resistive torque applied. With such a low vertical force on these wheels, a larger resistive torque would have potentially caused locking of the wheels on Axle 3 and damage to the tires. Figure 20 shows that the steer axle had greater brake torques applied in the case of the 6x4 configuration when compared to the 6x2 tag-tandem configuration, which was again possible due to the higher vertical force present in the case of the 6x4. In Figure 21 it can be seen that the trailer axles on the 6x2 truck have a higher resistive torque even though the vertical forces were the same as on the 6x4 truck. The applied torque was the same in each of these cases, but due to the presence of the outer wheels and the internal torsional stiffness, the net value of the resistive torque did not end up being exactly the same.

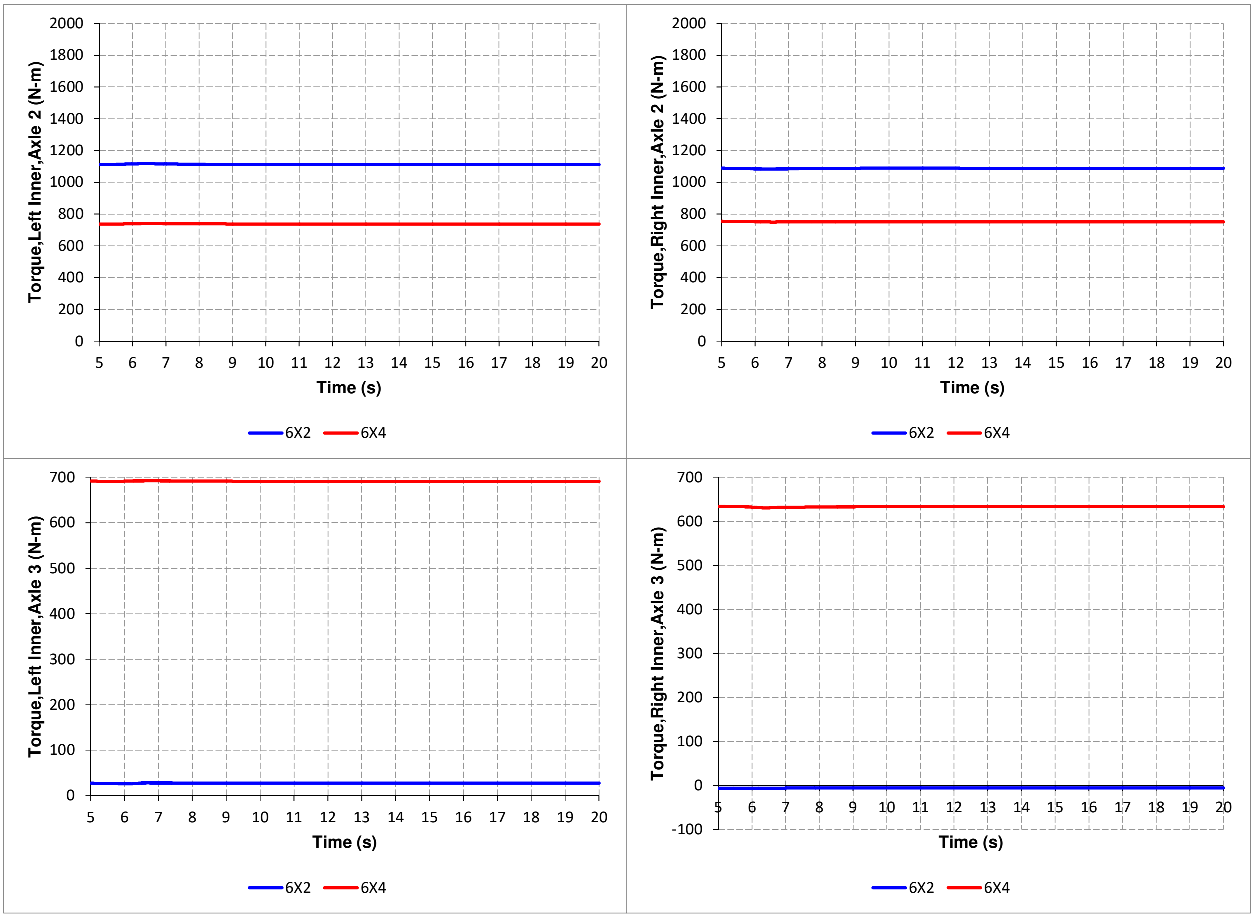

Figure 19: Brake torques applied to the left and right inner wheels of the front (Axle 2) and rear axles (Axle 3) in the tandem group on the tractor for the 6x2 tag-tandem unexpected-load-shift tractor-semitrailer and the 6x4 tractor-semitrailer.

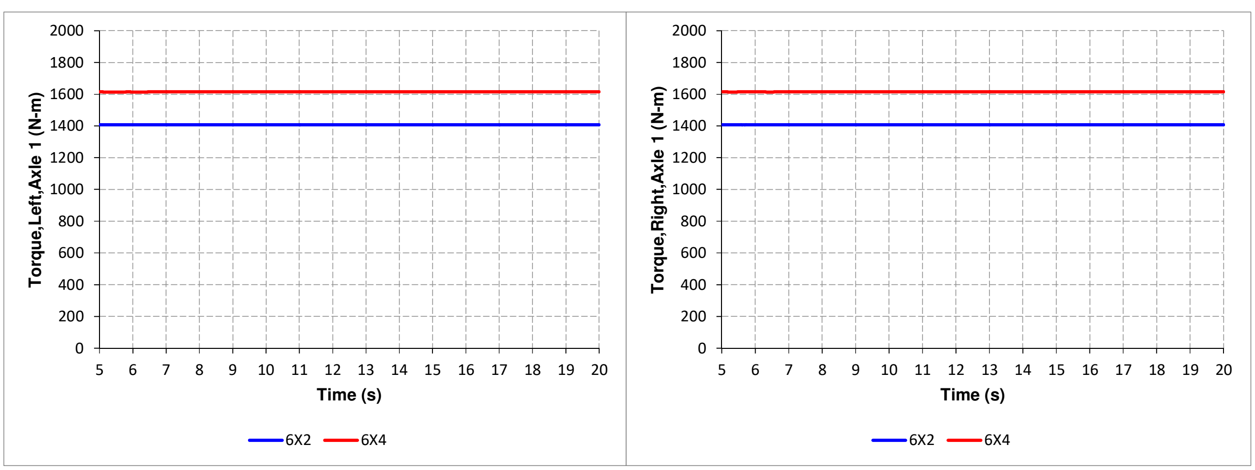

Figure 20: Brake torques applied to the left and right wheel stations on the steer axle (Axle 1) of the tractor for the 6x2 tag-tandem unexpected-load-shift tractor-semitrailer and the 6x4 tractor-semitrailer.

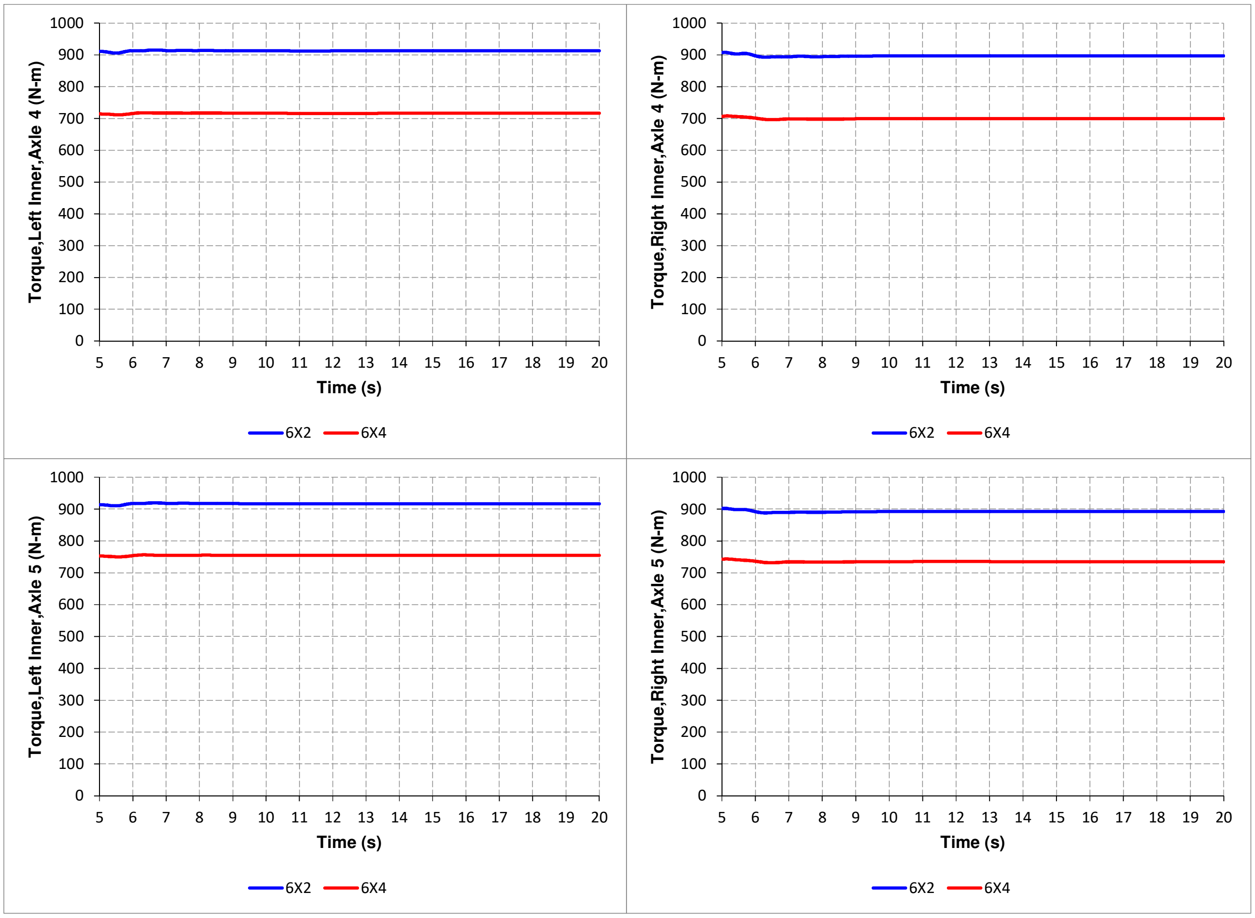

Figure 21: Brake torques applied to the left and right inner wheels of the front (Axle 4) and rear axle (Axle 5) on the trailer for the 6x2 tag-tandem unexpected-load-shift tractor-semitrailer and the 6x4 tractor-semitrailer.

Results were also obtained from running this same simulation, but with the tractor-semitrailers decelerating and accelerating in the downhil curve manoeuvre, rather than maintaining the specified speed of 46 km/h. The speed profile for the deceleration case can be seen in Figure 22, and the speed profile for the acceleration case can be seen in Figure 23.The results for these evaluations were very similar to the results when the truck was maintaining its speed; the 6x2 tag-tandem and 6x4 configurations could again both perform these manoeuvres with a coefficient of friction of 0.22, but only the 6x4 configuration could perform the deceleration and acceleration versions of the downhill curve manoeuvre with a coefficient of friction of 0.17.

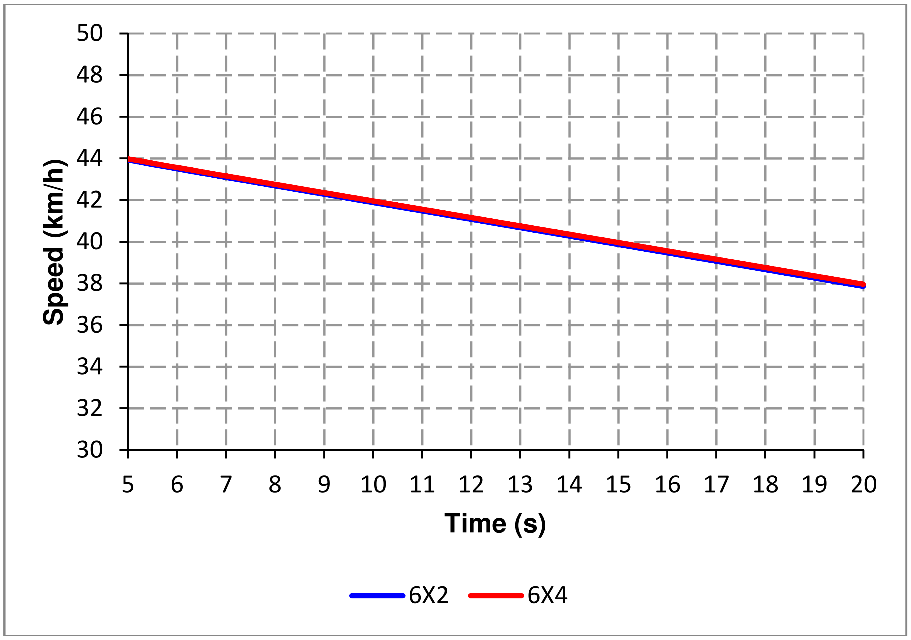

Figure 22: Speed profiles of the 6x2 tag-tandem unexpected-load-shift tractor-semitrailer and the 6x4 tractor-semitrailer while decelerating on the downhill curve.

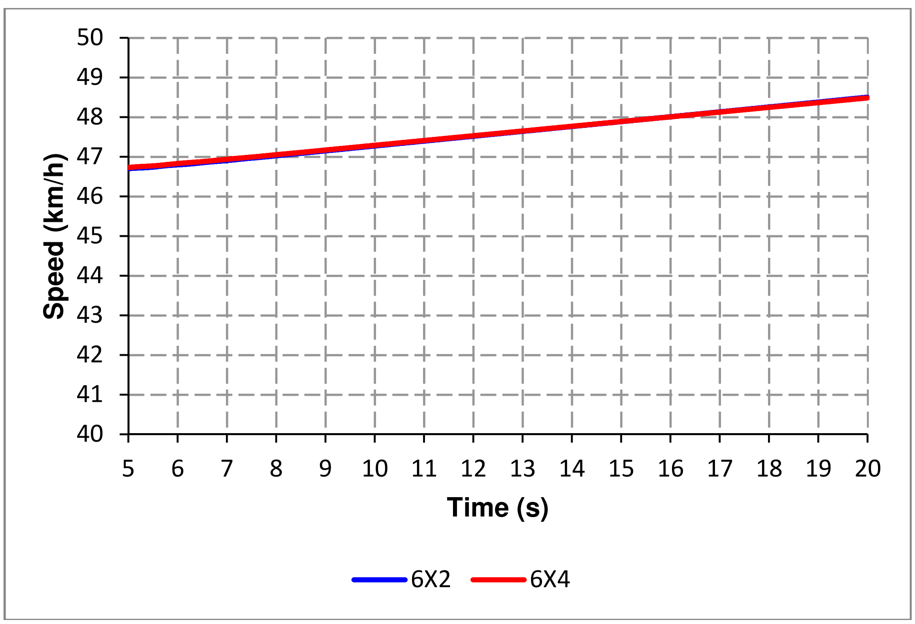

Figure 23: Speed profiles of 6x2 tag-tandem unexpected-load-shift tractor-semitrailer and 6x4 tractor-semitrailer while accelerating on the downhill curve.

Another key result is the performance of the 6x2 tag-tandem tractor-semitrailer using the high-performance tires. With the use of the high-performance tires, the 6x2 tag-tandem still had different vertical forces on the tractor axles compared to the 6x4 configuration, but the coefficient of friction was able to be reduced to 0.18.

5 ANALYSIS AND DISCUSSION OF RESULTS

5.1 High-Speed Lane Change and High-Speed Curve

The manoeuvres involving high speeds were the high-speed lane change and the high-speed curve. It was apparent from the results that there was not much of a difference between the 6x2 tag-tandem and 6x4 tractor-semitrailer configurations. The RTAC study specified that the manoeuvres be done on a high-friction surface [6], [7]. On the high friction surface, the amounts of slip that occurred between the tires and the road surface remained relatively small, and there was very little difference between the results for the two cases. Additionally, at speeds greater than 70 km/h, which was the case in both the high-speed lane change manoeuvre and the high-speed curve manoeuvre, there was no load shifting between the axles in the 6x2 tractor's tandem group. This means that this could not have come into play.

Although the results were quite similar, there were some differences between the 6x2 tag-tandem and 6x4 configurations. These differences were almost always below 5% and are likely explained by the weight differences. Since the 6x2 tractor has only one driven axle, compared to the 6x4 tractor having two driven axles, the 6x2 truck ends up being 300 kg lighter in each simulation. This is because a non-driven axle has a mass that is about 300 kg less than a driven axle. This lighter axle also caused a change in the location of the CG of the tractor, and in the gross combination weight of the tractor-semitrailer.

There was one instance where the difference between the results was 10.8%. This was for the high-speed offtracking when the tractor-semitrailer was going through the high-speed curve manoeuvre. In this case, it was noted that the 6x2 tag-tandem configuration had a higher high-speed offtracking value when the load was 26300 kg. The reason for this appeared to have been that the truck would become unstable and would start to rock back and forth. Therefore, at some points along the curve, the high-speed offtracking value would be lower than that of the 6x4 tractor-semitrailer, and at other times it would be higher. This was because the offtracking value would oscillate as the truck rocked from side to side. The value recorded in the results was the maximum high-speed offtracking value. This was the only simulation result where an instability of this type was observed, and it is possible that the side-to-side rocking of the truck was caused by a problem with the computer simulation model rather an inherent problem with the 6x2 tractor-semitrailer when it carries a payload of 26300 kg. This should be investigated further in any future work that may be done with these 6x2 and 6x4 tractor-semitrailer simulation models.

5.2 Low-Speed Corner

The low-speed corner manoeuvre also yielded results for the 6x2 tag-tandem and 6x4 tractor-semitrailer configurations that were quite similar. Since this manoeuvre was run at a low speed, there was the possibility of having load shifting between the axles in the tractor tandem axle group on the 6x2 configuration.

Load shifting did not play a big role in this manoeuvre, presumably because the requirements for tractive effort are relatively low. As a verification for this, the 6x2 tag-tandem tractor-semitrailer was run through the simulation with some load shifting present, and it was observed that this made very little difference in the results. When the load was shifted, the largest difference was seen in the rear outswing, where the 6x2 tag-tandem with the load shifted outperformed the 6x2 tag-tandem with no load shifting by 5.0%. However, this was likely due to the decrease in the effective wheelbase (the distance between the front axle and the centre of load of the tandem axle group on the tractor).

In the end, the 6x2 tag-tandem appeared to outperform the 6x4 in both low-speed offtracking and front outswing, but underperformed the 6x4 in rear outswing. However, the difference was never more than 1.3%, which is likely explained by the change in mass and location of the CG due to the use of a different axle weights for the tandem group of the 6x2 tractor compared to the axle weights in the tandem group of the 6x4 tractor.

5.3 Tight Turn

The minimum radius of curvature results that were obtained from the tight turn manoeuvre were quite similar for the 6x2 tag-tandem and 6x4 tractor-semitrailer configurations. For some cases, the 6x2 tag-tandem would outperform the 6x4, but never by more than 2 m and it was more often that they were the same. This difference can again be explained by the difference in mass between the configurations.

The fact that the results are quite similar for the evaluations involving the high-friction surface is not surprising. With the high-friction surface, the trucks rolled over, and amounts of lateral and longitudinal slip that occurred between the tires and the road surface remained relatively small. As was stated previously, this means that there will be no load shifting between the axles in the tandem axle group of the tractor.

The more interesting result is that the results remain quite similar when the surface has a low coefficient of friction of only 0.2. In this case, significant amounts of lateral slip did occur, and the trucks ended up sliding out of the turn instead of rolling over. If the levels of longitudinal slip were also higher, this might be expected to result in a slip event being detected, and the load being shifted to the driven axle of the 6x2 tractor in order to increase traction. However, changing the load distribution was observed to not have much of an effect on the results. This is explained by the fact that when the truck is slipping laterally (in a direction perpendicular to the path of travel), all of the axles on the tractor-semitrailer are able to generate lateral cornering forces to accelerate the vehicle around the turn, and the cornering forces are somewhat proportional to the vertical tire loads and to the slip angle that exists between each tire and the road surface. The purpose of shifting load onto the drive axle of a 6x2 tractor is to increase the load on the driven wheels, and hence increase the tractive effort the vehicle is capable of developing to climb hills or accelerate the vehicle forward. We would thus not expect to have much difference in how 6x4 and 6x2 tag-tandem tractor-semitrailers perform in this manoeuvre because the total cornering force that can be generated is not affected in a first-order manner by the vertical load distribution among the axles.

This was confirmed when the load was manually shifted to the drive axle of the 6x2 tag-tandem tractor-semitrailer with a payload of 10300 kg in a way that resulted in very little load on the non-driven axle of the tandem axle of the tractor and a load that was approximately equal to the axle load limit for the driven axle. This was considered to be a worst-case scenario for unexpected load shifting, but there was not much difference in the minimum radius of curvature results from the tight turn manoeuvre. On the high-friction surface, the results were the same, and on the low-friction surface, the truck would slide out at a radius of curvature that was 127 m, which was only 1 m lower than when the load was not shifted.

5.4 Steep Hill

The maximum grade that a tractor-semitrailer can climb in the 50 km/h steep hill manoeuvre is highly dependent on the load present on the driven wheels. This is because, an increase of load on the driven wheels would increase the normal force and therefore the tractive effort that can be developed to accelerate the vehicle or allow it to climb up a hill. In addition to being proportional to normal load on a tire, the tractive effort is proportional to the coefficient of friction between the tire and road surface, and to the amount of longitudinal slip that occurs. For the purposes of this study, the drive torque provided to the wheels on the driven axles in the simulation models ensured that the longitudinal slips that were developed by the tires on those axles were in a region that provided optimum tractive effort without providing excessive amounts of slip.

All of the steep hill manoeuvre results presented here for 6x2 tractor-semitrailer configurations are for cases where a slip event was detected and the load was shifted off the non-driven axle into the tractor's tandem axle group and onto the driven axle in that group. No results are shown for the 6x2 configurations where the load was not shifted.

As expected, the simulation results showed that there is a difference in the maximum grade of hill that can be climbed by the 6x2 tag-tandem and 6x4 tractor-semitrailers. This was clearly the case when a low-friction surface was considered. However, when a high-friction surface was considered the truck could always climb a hill with a grade of over 15%. There would likely have been a difference if grades higher than 15% were considered, but this was the highest grade considered in this study, since the maximum grade typically found on Canadian roads is limited to 12% [10].

The major difference between the 6x2 tag-tandem and 6x4 tractor-semitrailer configurations was seen with the low-friction surfaces. With the lowest payload of 1300 kg, there was not too much difference between the 6x2 tag-tandem and 6x4 configurations. The 6x2 tag-tandem configuration was only outperformed by the 6x4 configuration when the coefficient of friction was 0.4, but only by a grade difference of 0.1%; there was only a difference of 0.8%. When the payload was increased to 10300 kg, the difference between the results was still not too great. The maximum difference was still only a grade of 1.5% or a difference of 11%, and the maximum grade did not decrease much from when the payload was 1300 kg. However, this difference was magnified when the payloads increased. Once the payload was 20300 kg, there were significant differences in the results and when the load was increased again, there was an even greater difference. In the worst case there was a difference of 52% between the results when the maximum load was considered together with a coefficient of friction of 0.1. It was also evident that the maximum grade the 6x4 configuration could climb was not overly dependent on the mass of the payload. However, the 6x2 tag-tandem was affected by this when the payload exceeded 8300 kg.

The explanation for this result is that the 6x4 tractor has more of its total load on driven rather than non-driven wheels when compared with the 6x2 tractor. In the case of the 1300 kg payload, the 6x2 tag-tandem configuration comes somewhat close to the 6x4 configuration in terms of maximum ascendable grade because a large proportion of the load can be shifted to the driven axle of the 6x2 tractor. However, the non-driven axle of the 6x2 tractor still bears some of the load and for this reason, the 6x2 tractor-semitrailer still underperforms the 6x4 tractor-semitrailer.

When the payload was increased from 1300 kg to 10300 kg, the 6x4 configuration performance was essentially unaltered. In contrast, the 6x2 tag-tandem configuration experienced a decrease in maximum ascendable grade with a maximum difference of 8.6%. This is due to the fact that the total mass increased, but the load on the driven axle did not increase enough to make up for this. With the 10300 kg load, the 6x2 tag-tandem tractor-semitrailer is outperformed by the 6x4 configuration by a small amount, with a difference of 11% in the worst case. This is because the 6x2 tractor can still shift most of the load from the non-driven axle to the driven one without exceeding the 9100 kg axle load limit. The maximum load that can be applied on the tractor-semitrailer while still maintaining the ability to shift almost all of the load on the tandem axle of the tractor to the driven axle on the 6x2 tractor was 8300 kg. At any load greater than this, the performance of the 6x2 tractor starts to decrease, which explains the moderate decrease in performance when the payload was increased to 10300 kg.

When the payload increased again from 10300 kg to 20300 kg, the maximum grade for the 6x4 configuration stayed the same; for the 6x2 tag-tandem it dropped to only a 1.9% grade. This is because the non-driven axle of the tractor must retain a significant portion of its original load in order to keep the driven axle under the maximum allowable axle limit of 9100 kg. Some load is still shifted to the driven axle, but not enough to increase the traction sufficiently to make up for the increased total mass of the tractor-semitrailer. In other words, the proportion of load carried by the driven wheels is not high enough relative to the load on the non-driven wheels. This problem is made even worse when the payload is increased to 26300 kg. In this case, an even lower percentage of the load can be transferred from the non-driven to the driven axle because of the 9100 kg axle load limit. As a result, the maximum ascendable grade for 6x2 configurations decreases to much lower values compared to the values for the 6x4 configuration. Thus, 6x2 tag-tandem configurations are disadvantaged here due to the existing axle load limits, as they pose a serious limitation to their achievable performance.

All of the results discussed for the 6x2 tractor-semitrailer thus far were for the 6x2 tag-tandem tractor-semitrailer (i.e., where the front axle in the tractor’s tandem axle group is driven). However, the steep hill manoeuvre was also run with a 6x2 pusher-tag tractor (i.e., with the rear axle in the tractor’s tandem group being the only driven axle). The 6x2 pusher-tag configuration was shown to yield almost identical results to the 6x2 tag-tandem configuration when the payload was 20300 kg and 26300 kg. The cases with lower payloads, on the other hand, yielded different results.

For the case where a payload of 1300 kg was considered, the standard 6x2 tag-tandem configuration outperformed the 6x2 pusher-tag configuration by a maximum grade of 1.7% and a maximum difference of 16%. This is explained by examining the axle loads. When the standard 6x2 tag-tandem tractor (with the driven axle at the front of the tandem group) shifts all of the tractor’s tandem axle load to that driven axle, a higher force is placed on the driven axle than when the same is done for the 6x2 pusher-tag tractor (where the driven axle is at the rear of the tandem axle group). Part of this is due to the tractor itself which has a significant mass of over 9000 kg, and part is due to the load applied to the tractor at the fifth wheel by the trailer. These loads must be supported by the steer axle and the driven axle of the tractor. To attain equilibrium, the forces and moments must sum to zero. When the forces are considered, it makes no difference whether the front or rear axle in the tandem axle group is loaded, but it does make a difference for the moments. As a result, a lower axle load is obtained when the load is shifted to the rearmost axle as is the case for the 6x2 pusher-tag tractor (with the driven axle at the rear of the tandem axle group). As a result, there is less load on the drive axle for the same payload.

Another interesting result is that the 6x2 pusher-tag configuration did not experience a decrease in performance when the payload was increased from 1300 kg to 10300 kg. This is due to the fact that, even with a payload of 10300 kg, the driven axle of the 6x2 pusher-tag tractor is not fully loaded to the axle load limit. The maximum payload that can be carried before the 6x2 pusher-tag configuration can no longer shift all of the load on the tandem tractor axle to the driven axle is higher than 10300 kg, as opposed to the standard 6x2 tag-tandem configuration, where this maximum payload was only 8300 kg. This is again due to the fact that less load is required on the driven axle of the 6x2 pusher-tag tractor to maintain equilibrium. However, even though the performance of the 6x2 pusher-tag tractor did not decrease when the payload increased from 1300 kg to 10300 kg, the 6x2 pusher-tag tractor was still outperformed by the standard 6x2 tag-tandem tractor by a maximum grade of 0.7% and a maximum difference of 10%.

An additional parameter that was investigated was the quality of the tires. Each of the evaluations for the steep hill manoeuvre were repeated with high-traction tires. The high-traction tires were shown to significantly increase the maximum ascendable grade of all of the tractor-semitrailer configurations. The values were increased by a percentage of at least 25% in all cases and was often increased by even more. For the worst case, when the standard 6x2 tag-tandem configuration was considered with a coefficient of friction of 0.1 and a maximum payload of 26300 kg, the maximum ascendable grade increased from 1.4% to 2.2%, corresponding to an increase in performance of 57%.

Although the high-traction tires increased the performance of the tractor-semitrailer configurations, it did not change any of the trends previously described in this section. The 6x4 tractor-semitrailer configuration still outperformed the standard 6x2 tag-tandem and the 6x2 pusher-tag configurations, especially under high loads, and the 6x2 pusher-tag still performed worse than the standard 6x2 tag-tandem while carrying payloads of 1300 kg and 10300 kg.

5.5 Downhill Curve

Unlike the steep hill manoeuvre, the results for this 46 km/h downhill curve manoeuvre are not closely related to the load carried by the driven wheels of the tractor. For the downhill curve, 6x4 and 6x2 tractor-semitrailer configurations with a 10300 kg payload, with the load shifted onto the drive axle in the case of the 6x2 configurations, must descend a road with a 12% grade and 333 m –radius curve. All of the wheel stations on a truck have brakes, so brake torques are applied to all of the wheel stations so the truck speed does not rise above the specified manoeuvre speed of 46 km/h.

The vehicle performance parameter for the downhill curve was the lowest coefficient of friction that could exist between the tires of a tractor-semitrailer and the road surface, where the configuration can successfully complete the manoeuvre.

The 6x4 tractor-semitrailer was able to meet these conditions with a coefficient of friction of 0.17.The standard 6x2 tag-tandem, on the other hand, could only maintain its speed in this scenario with a coefficient of friction of 0.22. These values could potentially be determined more precisely if a more accurate or effective ABS system were implemented into the model.

This simulation was also run with the tractor-semitrailers accelerating and decelerating down the hill at a specified rate. This yielded the same results as when the tractor-semitrailer was maintaining its speed in terms of the minimum required coefficient of friction. Therefore, the exact handling of the tractor-semitrailer was shown to not make too much of a difference in terms of performance. However, if the tractor-semitrailer were to accelerate too much, it would eventually slide out laterally on the curve.

Although the performance is not directly related to the load on the driven wheels, the load distribution can have an effect. The results showed that the 6x2 tag-tandem configuration, with close to the maximum load shifted, resulted in a much higher vertical force on the front axle of the tandem axle group on the tractor, and a much lower vertical force on the rear axle of the tandem group. Additionally, the tractor steer axle ended up having a lower vertical force. Although, the axle loads on the trailer stayed the same between the 6x2 tag-tandem and 6x4 simulations, the tractor axles did not. This changed the amount of brake torque that could be applied to each of the wheel stations. This change in brake torque at each of the wheel stations on the tractor appeared to negatively impact the braking performance of the 6x2 tractor-semitrailer. Therefore, the shift in weight was a detriment to the performance and was likely the reason for the higher minimum coefficient of friction that was required by the 6x2 tag-tandem tractor-semitrailer configuration.

The performance of the 6x2 configuration could be improved by the use of high-performance tires. If these tires were used, the 6x2 tractor-semitrailer was able to descend the hill with a coefficient of friction as low as 0.18.

6 SUMMARY AND RECOMMENDATIONS

Analytical work was conducted to assess the difference in performance between a 6x2 tractor and a 6x4 tractor when used in a typical tractor-semitrailer application in Canada. Computer simulation models of the 6x2 and 6x4 tractor-semitrailers were made using Simpack, where the only differences between the two models were which of the tractor axles were driven, the weight of those axles, and the presence of a lifting axle. A standard 6x2 tag-tandem configuration (where the front axle of the tractor's tandem axle group was driven and the rear axle in not driven and could be lifted) was examined for all of the manoeuvres. An assumption was made that the 6x2 tractor could detect a slip event and shift load onto the driven axle at speeds up to 70 km/h in conditions where significant longitudinal tire slip was occurring that indicated a need for the tractor to provide additional tractive effort. Each of the tractor-semitrailer configurations was run through six test manoeuvres involving various curves, a lane change and hills. In addition, a 6x2 pusher-tag configuration (where the rear axle of the tractor's tandem axle group was driven and the front axle of the tandem group was not driven and could be lifted) was examined in a few of these manoeuvre.

The first two manoeuvres, a high-speed lane change and a high speed curve, involved evaluations of a single payload (10300 kg) at three different speeds (90, 100 and 110 km/h), and then evaluations of four payloads (1300, 10300, 20300 and 26300 kg) at a single speed (90 km/h). Since the manoeuvre speeds were above 70 km/h, no attempt was made to evaluate the performance of the configuration in cases where the 6x2 drive system might have unintentionally shifted load from the non-driven axle in the tractor's tandem axle group to the driven axle. The third and fourth manoeuvres, an 8.8 km/h low-speed corner and a 50 km/h tight turn, were done at speeds below the 70 km/h upper limit for load shifting, but would not normally result in longitudinal slip levels that would cause a slip event to be detected and then trigger load shifting. For these manoeuvres, the principal results presented here were for the load-not-shifted case. However, additional analysis was done for an unexpected-load-shift case where the load might have been improperly shifted, or where the load remained shifted after a previous event where load shifting was required [1]. The fifth manoeuvre, a 50 km/h steep hill, is one that requires load shifting, and thus the results presented here are for the shifted-load case. The sixth manoeuvre, a 46 km/h downhill curve, is one where the 6x2 drive system would not normally shift load. A preliminary review of the results for that load-not-shifted configurations (not presented here) showed essentially no difference between the performance of the 6x2 tag-tandem tractor-semitrailers with the load not shifted and the 6x4 tractor-semitrailers. As a result, all of the downhill curve results presented in this report for the 6x2 are for the unexpected-load-shift case.

It was found that, in most cases, when the tractor-semitrailer was negotiating turns or lane change manoeuvres on a flat surface, the performance of the truck was not affected much by whether the 6x2 tag-tandem tractor or 6x4 tractor was used. In fact, the difference in the various performance criteria in all but one of these cases was below 5%. In addition to this, it was not consistent which tractor configuration would outperform the other. This small difference was likely due to the fact that the 6x2 tractor has one axle in its tandem axle group that is lighter than the axle in the corresponding position on the 6x4 tractor. This is because the 6x4 tractor has two driven axles, which are heavier than non-driven axles, and the 6x2 tractor only has one driven axle. This change in mass of the axle has an effect on the empty weight of the tractor and on the location of the tractor CG.

The one case where the performance criteria of the two tractor-semitrailer configurations varied by more than 5% while performing a manoeuvre on a flat surface was when the tractor-semitrailers were going through the high-speed curve manoeuvre. In this case, the transient high-speed offtracking value with the vehicles loaded to the maximum payload studied of 26300 kg was 10.8% higher for the 6x2 tag-tandem configuration than for the 6x4 configuration. However, the 6x2 tractor-semitrailer was observed to be unstable during this simulation in that it would begin to rock back and forth. The transient high-speed offtracking value throughout the curve was seen to oscillate. The maximum value is what was taken and recorded in this study, but the average was closer to the value for the 6x4 tractor-semitrailer. This was the only simulation result where an instability of this type was observed, and it is possible that the side-to-side rocking of the truck was caused by a problem with the computer simulation model rather an inherent problem with the 6x2 tractor-semitrailer when it carries a payload of 26300 kg. This should be investigated further in any future work that may be done with these 6x2 and 6x4 tractor-semitrailer simulation models.

Additionally, it was determined that the performance of the 6x2 tag-tandem tractor-semitrailer configuration in the low-speed corner and tight turn manoeuvres was not too adversely affected by an unexpected load shift. As described previously, there could be some unexpected load shift still present from a previous manoeuvre where load shifting was required, and it has been shown that it can take some time for the load to equalize again [1]. It was shown that, when close to the maximum possible difference in axle load occurred between the driven and non-driven axles on the tandem axle of the 6x2 tractor, there was almost no difference in performance. The low-speed offtracking and outswing values changed by a maximum of 5% and the differences are explained by the change in effective wheelbase. Also, the minimum radius remained the same on the high-friction surface, but decreased from 128 m to 127 m on the low-friction surface. These differences are not large, and for the low-speed offtracking and rear outswing values in the low-speed corner manoeuvre, the performance was actually improved slightly when the unexpected load shift was considered. Therefore, it was determined that an unexpected load shift would be unlikely to cause any performance issues while performing this manoeuvre.

Once a hill was introduced with the steep hill manoeuvre, there was a much greater difference in performance between the 6x4 and 6x2 tag-tandem tractor-semitrailers. On a high friction surface, both configurations could climb grades that were in excess of 15%. However, on a low friction surface, the 6x4 outperformed the 6x2 tractor-semitrailer under many loading conditions. This was because the 6x2 tractor could not have as much load supported by the driven wheels, which meant that the traction was often lower. If the total mass of the tractor-semitrailer was low, then a higher percentage of the load could be shifted to the driven axle on the 6x2 tractor without exceeding the axle load limit. As the total mass of the tractor-semitrailer increased, the gap in performance would become larger since the 6x2 tractor could not shift much of the load to the driven axle without exceeding the axle load limit. In the end, the maximum difference in performance was observed when the payload was set to 26300 kg, which resulted in a gross combination weight of 39500 kg on the 6x4 configuration. Carrying this load, the 6x4 tractor-semitrailer could ascend a 2.9% grade at 50 km/h on a low-friction surface with a coefficient of friction of 0.1, whereas the 6x2 tag-tandem tractor-semitrailer could only ascend a 1.4% grade under the same conditions.

Additionally, the 6x2 pusher-tag tractor (i.e., the tractor with the rear axle in the tractor's tandem axle group being driven, and the front axle in the group being non-driven) was seen to perform worse in the steep hill manoeuvre than the standard 6x2 tag-tandem tractor under lower loading conditions. With the payload set to 1300 kg or 10300 kg, the 6x2 pusher-tag tractor-semitrailer was outperformed by the standard 6x2 tag-tandem tractor-semitrailer by a difference of up to 16%. However, once the load was increased to 20300 kg, there was little to no difference between the results of the standard 6x2 tag-tandem tractor and the 6x2 pusher-tag tractor when used in the tractor-semitrailer applications examined here.

It was also concluded that the use of better tires could significantly increase the performance of both 6x4 and 6x2 tag-tandem tractor-semitrailers. However, in the worst-case steep hill manoeuvre, where the payload was 26300 kg and the coefficient of friction was 0.1, the 6x2 tag-tandem configuration with the high-traction tires still only yielded a maximum ascendable grade of 2.2%. This is lower than the corresponding value of 2.9% for the 6x4 tractor under the same conditions using the standard tires. Therefore, although under some conditions the 6x2 tag-tandem tractor with the high-traction tires can outperform the 6x4 tractor with the standard tires, the 6x2 tractor with high-traction tires still cannot fully match the performance of the 6x4 tractor with standard tires under all conditions, when used in this tractor-semitrailer application.

The gap in maximum ascendable grade between the 6x4 tractor-semitrailer and the 6x2 tag-tandem tractor-semitrailers is significant and is a serious limitation of the 6x2 configuration. For this reason one recommendation is that 6x2 tractor-semitrailers would be limited in where they are allowed to be used to routes or regions with only lower grades of hills. Alternatively, the recommendation could be to limit the allowable payload that a 6x2 tractor-semitrailer can carry to values that allow most of the load on the tandem axle of the 6x2 tractor to be shifted to the driven axle. In this study, that load was 8300 kg for the standard 6x2 tag-tandem tractor and 11800 kg for the 6x2 pusher-tag tractor, but the weights and dimensions used in this study were approximations, so further study would be needed to determine this weight limit for each tractor-semitrailer application.

There was also a gap in performance when the tractor-semitrailer was performing the downhill curve manoeuvre. When descending a hill with a 12% grade and a radius of curvature of 333 m and while carrying a payload of 10300 kg, there was a difference in performance between the 6x4 tractor-semitrailer and the 6x2 tag-tandem tractor-semitrailer when there was an unexpected load shift on the 6x2 tractor. Although this load shift would not usually happen when descending a grade, there could be some unexpected load shift still present from a previous manoeuvre such as having just climbed a hill. It has been shown that it could take some time for the load to equalize again [1]. Therefore, under the worst-case conditions when almost all of the load is shifted from the rear axle in the tractor's tandem axle group to the front axle in the group, as could be the case when a 10300 kg payload is carried by the 6x2 tag-tandem tractor-semitrailer, the 6x4 configuration can outperform the 6x2 configuration in terms of the minimum required coefficient of friction by about 23%. This was also true when the tractor-semitrailer was decelerating or accelerating down the hill. Furthermore, it was found that, with the use of high-traction tires, the 6x2 tag-tandem tractor-semitrailer can come much closer to matching the performance of the 6x4 tractor-semitrailer using the original tires; in fact, the minimum required coefficient of friction only varies by 0.01 between these two cases.

This study was limited in that the simulation models made use of generic information to describe the various model components based on a few measurements that were made, since more precise information from various manufacturers was not available. The simulation model included estimates of tractor and semitrailer component weights, many dimensions, centre of gravity positions, and moments of inertia. It also included estimates of brake system performance, ABS brake system performance, and a simplified powertrain model. An engine traction control system was not included. Furthermore, the method by which the 6x2 tractor detects slip events and adjusts the 6x2 tag-tandem and 6x2 pusher-tag tractor axle loads in response to slip were not available, and a simplified representation of this was included in the simulation model. Due to the limitations in this study, it is recommended that further investigative work and analysis be done on more accurate models and on a wider variety of manoeuvres to fully and more accurately assess the difference in performance between the 6x2 and 6x4 tractors in this tractor-semitrailer application.

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