Heavy-duty vehicle 6x2 drive knowledge gap briefing

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Heavy-Duty Vehicle 6x2 Drive Knowledge Gap Briefing

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ABSTRACT

Transport Canada has retained the National Research Council Canada, as represented by the Automotive and Surface Transportation portfolio, to evaluate heavy-duty 6x2 drive technology, the implications the use of such technology may have for Canada, and to develop a test plan which, upon execution, will provide the necessary data to evaluate the technology. The present document contains the results of the literature review performed to evaluate the use of 6x2 drive technology in support of the test plan development. Contained within this document are an overview of various 6x2 architectures and a review of the current regulations applicable to 6x2 use in Canada. Also included is a review of various operational considerations for the use of 6x2 drive highway tractors including implications on vehicle weights, traction, tire wear, maintainability, and stability.

EXECUTIVE SUMMARY

Transport Canada has retained the National Research Council Canada (NRC), as represented by the Automotive and Surface Transportation (AST) portfolio, to evaluate heavy-duty 6x2 drive technology, the implications the use of such technology may have for Canada, and develop a test plan which upon execution will provide the necessary data to help evaluate the technology, with a focus on Canadian operational requirements.

The scope of the current study consists of three main tasks:

1. A review of the available literature to assess the current global state of 6x2 drive highway tractors;
2. An analysis of the available information as revealed by the literature review;
3. The development of a test plan to characterize the use of 6x2 drive highway tractors in Canadian environments.

The present study is limited by the availability of information and data pertaining to the operation of 6x2 drive highway tractors existing in scientific journals, technical publications and promotional literature. This report sought to objectively characterize the various implications of the use of 6x2 drive tractors in Canada. The findings may be classified into two separate perspectives: the regulatory perspective and the fleet operator perspective.

From a regulatory perspective, it has been found that there are varying degrees to which 6x2 drive tractors are allowed and practical amongst the provinces. In one province (B.C.) 6x2 drives are explicitly prohibited, while the remaining provinces implicitly restrict their potential utility through axle load regulations.

The impact on greenhouse gas (GHG) emissions from the fuel savings is variable and depends on the rate of market adoption and the magnitude of fuel savings. Allowing the sale of 6x2 drive technology and anticipating a market uptake rate comparable to the U.S. of 2.5%, the use of 6x2 drive technology within Canada could result in a yearly nationwide fuel savings of roughly 5.34 million liters to 15.3 million litres, which equates to a yearly reduction of approximately 14,200 to 40,900 tonnes in emitted CO_2.

From a fleet operator perspective, the use of 6x2 drive tractors as a method to increase fleet operational efficiencies can be highly sensitive to the operational parameters of that particular fleet. The reduced traction and increased tire wear must be carefully weighed against any expected gains in fuel savings. These factors are not independent of one another and must be considered together to fully evaluate 6x2 effectiveness for a given fleet.

The ability of automated weigh-in-motion to determine compliance of 6x2 weight shifting technologies is tenuous at best, as the 6x2 weight shifting systems are always equalizing the axle loads between the live and dead axles, unless a slippage is detected. In order for weigh-in-motion to capture a weight shifting event, a method of inducing wheel slip would be necessary.

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1 INTRODUCTION

1.1 Purpose

Transport Canada has retained the National Research Council Canada (NRC), as represented by the Automotive and Surface Transportation (AST) portfolio, hereafter known as NRC-AST, to evaluate 6x2 drive technology and the implications the use of such technology may have for Canada. The purpose of this study it to evaluate the use of 6x2 drive tractors based upon the available literature and, where literature is lacking, develop a test plan which upon execution will provide the necessary data to evaluate the technology, with a focus on Canadian operational requirements.

1.2 Scope

The scope of the current study consists of three main tasks:

1. A review of the available literature to assess the current global state of 6x2 drive highway tractors;
2. An analysis of the available information as revealed by the literature review;
3. The development of a test plan to characterize the use of 6x2 drive highway tractors in Canadian environments.

1.3 Limitations

The present study is limited by the availability of information and data pertaining to the operation of 6x2 drive highway tractors existing in scientific journals, technical publications and promotional literature. Wherever possible, inferences have been made to fill any existing gaps within the available literature. When available, industry experts have also been contacted to gather additional information and mitigate this limitation; this includes the manufacturers of heavy duty trucks and parts suppliers.

2 6X2 TRACTORS

2.1 Drive Architectures

The primary difference between 6x2 and 6x4 highway tractors is the number of wheel stations present to which engine power is delivered. Both 6x2 and 6x4 vehicles have six available wheel stations. Also common between the two vehicle configurations is the presence of a forward, unpowered steer axle that provides directional control of the tractor. Where the two designs differ is in the number of powered wheel stations.

Figure 1 shows the standard 6x4 drive layout of a typical tractor. The 6x4 drive tractor has four powered wheel stations located on the rear drive axles (shown in red). In the 6x4 configuration, the lead and trail driven axles are connected with an inter-axle drive shaft. There is also an inter-axle differential (sometimes called a splitter) that allows the lead and trail axles to operate at different rotational velocities that would normally be encountered when turning.

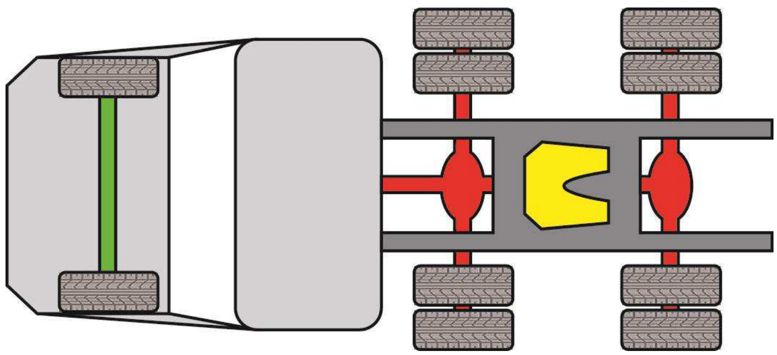

Figure 1: 6x4 arrangement (adapted from [1])

Truck manufacturers generally have two types of drive axle arrangements they can choose from when designing a 6x2 tractor. The first available system architecture consists of a powered lead axle in the tandem group (middle axle of the tractor) while the trailing axle in the tandem group is unpowered. This architecture, shown in Figure 2, is commonly referred to as a tag tandem 6x2 configuration. The dead axle within this configuration is also known as a tag axle.

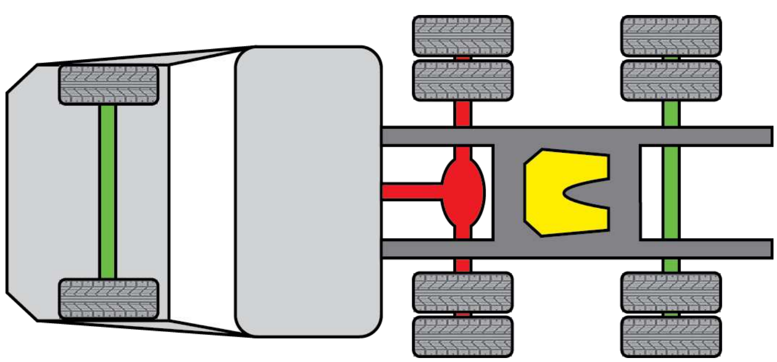

Figure 2: 6x2 tag tandem 6x2 architecture [1]

The second available architecture consists of powering the rearmost axle and leaving the tractor's middle axle unpowered. This particular architecture, as shown in Figure 3, is also referred to as a pusher tag 6x2 configuration. The dead axle within this configuration is commonly known as a pusher axle.

The pusher tag 6x2 configuration allows for the possibility of making the pusher axle an automatic lift axle. This lift axle feature is designed to reduce tire wear and fuel consumption when operating at lighter Gross Vehicle Weights (GVW). At least one manufacturer offers a 6x2 tractor with this type of automatic lift axle feature [2].

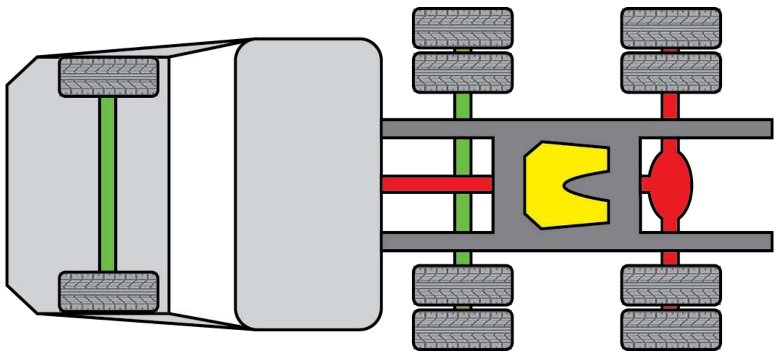

Figure 3: 6x2 pusher tag 6x2 architecture [1]

In both 6x2 architectures, weight transfer methods are generally used to improve traction in marginal conditions. An axle differential lock can also assist in limiting wheel slip between the left and right wheels of the driven axle.

The use of 6x2 tractors is not necessarily a new technology. They have been available in the North America and in use in Europe for several decades and have been slowly growing in popularity in the United States for several years [3]. There are both advantages and disadvantages to the use of 6x2 tractors over 6x4 tractors which are described in detail within section 5.

2.2 6x2 Axles

All major axle suppliers offer a version of a 6x2 axle configuration. Some manufacturers, such as Meritor (FUELite Tandem) or Dana (Spicer EconoTrek) offer a complete rear axle package consisting of an appropriate drive axle and dead axle. The truck OEM is responsible for the suspension and suspension controller.

The other option to creating a 6x2 tractor is to pair a more traditional single rear drive axle product with a standard un-driven axle product to become the dead axle. This un-driven axle can be supplied from the same supplier as the drive axle, or it can be supplied from somewhere else, depending on how the truck OEM prefers to manage their supply chain. The truck OEM is also responsible for the suspension system details.

As an alternative, at least one axle manufacturer is currently exploring if a traditional 6x4 drive configuration axle set could transition between a 6x2 for efficiency and a 6x4 for traction through the use of a series of disconnect clutches. This technology is in the development phase and is not in series production at the time this report was written [4].

2.3 Suspensions and Suspension Controllers

In a 6x4 tractor, the rear two axles are powered. In a 6x2 tractor, only one of the rear axles is powered while the other axle is free-rolling. Since tractive effort or pulling power is directly related to the number of drive axles and the vertical load acting on each drive axle, a 6x2 tractor with equal axle loading could have reduced tractive effort compared to a 6x4 tractor under the same conditions.

Modern long-haul tractor-semitrailers all use some type of air suspension system. In this system, the weight of the vehicle is supported by rubber air bladders (air springs) instead of more familiar steel springs. Air springs offer more comfort to the operator and to the cargo and provide a consistent ride height independent of loading. The air springs also allow automatic equalization of load on each drive axle to optimize traction.

At its simplest, a tractor manufacturer could create or convert an 6x4 tractor into a 6x2 tractor by replacing the two driven axles with a standard single driven axle with an un-driven axle. All other factors being equivalent to 6x4 tractors, this arrangement should not create any concerns regarding pavement impact and increased infrastructure damage as the axles remain equally loaded.

However, because there is one less driven axle, in marginal traction conditions this arrangement could suffer from reduced tractive effort. As a means to mitigate this potential loss, one method is to alter inflation pressure of the air springs to increase the effective vertical load on the driven axle by temporarily reducing the vertical load on the dead axle. This is generally the most cost effective method and is employed by nearly all tractor manufacturers.

Other traction related technologies such as differential locks are often used in conjunction with load shifting, however differential locks only address slippage between the left and right wheels on an axle and does not necessarily mitigate traction loss if both sides of an axle are spinning. It is this load shifting technology that is the source of jurisdictional concerns regarding the effects of 6x2 tractors on highway infrastructure.

The enabling piece of the suspension system is the suspension controller. It controls the distribution of air pressure to each axle (and in some cases to each air spring) and allows for the various features such as ride height and load leveling to work. In the case of 6x2 drive tractors, the suspension controller also enables the load shifting function. The suspension controller consists of a control module, valve module(s), and related sensors. The software program running on the control module manages the interplay the various features.

Most truck OEM's (Kenworth, Volvo, etc.) purchase a complete system from suppliers (Wabco, Bendix, et al.) though it is possible for an OEM to purchase discrete components and integrate the system by themselves for highly specialized custom applications. The suspension controller supplier can, at the OEM's option, provide a pre-configured solution with a generic program, develop a customized program in partnership with an OEM, or the supplier can provide the OEM with tools that allow the OEM's to develop their own programming to suit their desires.

During the research of 6x2 drive systems, published literature for suspension controllers and OEM trucks equipped with 6x2 drives indicated a range of available cutout speeds, depending on the function and use case. In the case of controls with optional driver initiated manual override, this feature is only available to the driver when the vehicle speed is below a certain threshold, typically around 29 km/h (18 mph) or less, and automatically disables operator override at higher vehicle speeds.

The driver control is an option on most systems, with the vast majority of systems operating in fully automatic mode. Under automatic control, the system will gradually equalize the axle load as the vehicle speed increases, and is fully equalized around 40 km/h (25 mph) [5], as well as when stopped or parked. Examination of OEM sourced literature shows good agreement with these values, though there was some variability, which indicates that some OEM's have a certain amount of customization from a generic program.

3 REGULATORY IMPLICATIONS

A comprehensive review of provincial regulations and their applicability towards 6x2 drive tractors has been performed by J.R. Billing [5]. The review has found that “the definitions and requirements for axles and axle groups among the provinces are similar, but sufficiently different that the controlled 6x2 drive may or may not be allowed, and if allowed, may or may not be practical, depending on the particular wording used by each province."

The controlled 6x2 drive appears to be allowed in Alberta, Saskatchewan, and Manitoba, because these provinces do not require axle load equalisation within a tandem axle, and a requirement that the maximum load on either axle not exceed 9,100 kg (20,062 lb) appears to make it practical.

The controlled 6x2 drive appears to be allowed in the Northwest Territories, because there is no requirement for axle load equalisation within a tandem axle, also making it practical.

The controlled 6x2 drive appears to be allowed in New Brunswick, Prince Edward Island, Nova Scotia and Newfoundland and Labrador, and under the M.o.U.[1], but a requirement for a maximum 1,000 kg (2,205 lb) difference in axle loads appears too tight for it to be practical.

The controlled 6x2 drive appears to be precluded in British Columbia by the definition of a tandem drive axle, and in Ontario, Quebec and the Yukon Territory by a strict requirement for equalisation within a tandem axle with no tolerance.

[1] 1989 Memorandum of Understanding on Vehicle Weights and Dimensions between all provinces.

4 MARKET SURVEY

In order to determine the current available makes and models of 6x2 drive tractors, seven major manufacturers were contacted for information on their vehicles and pricing. Of the manufacturers contacted, all offered a 6x2 drive option on at least one of their models with very few of the dealers maintaining any 6x2 tractors in their inventory. The results of the market survey may be found in Table 1.

Dependent upon the vehicle dealer contacted, the price differential between 6x2 and 6x4 tractors was reported to range between $0 and $2,500 with a majority of the dealers citing no cost difference at all. Since dealers are free to set their own selling price, the cost premium for a 6x2 tractor can vary from dealer to dealer. However, due to the multitude of configurable options available when ordering a highway tractor, the contacted dealers could not – or would not – offer a definitive price differential; the information received concerning price was a best estimate on the part of the dealer.

Table 1: Truck manufacturers offering 6x2 axle configurations

Make	Model	Axle Set Provider(s)
Freightliner	Cascadia Cascadia Evolution	Detroit
International	Prostar Prostar ES	Meritor FUELite
Kenworth	T660	Dana Spicer EconoTrek Meritor FUELite Hendrickson Optimaax
Mack	Pinnacle	Link Manufacturing
Peterbilt	579	Dana Spicer
Volvo	VNL300 VNL430 VNL630 VNL670 VNL730 VNL780	Link Manufacturing Hendrickson Optimaax
Western Star	5700 XE	Detroit

5 OPERATIONAL CONSIDERATIONS

5.1 Fuel Economy

The primary cited benefit of selecting a 6x2 tractor over a 6x4 tractor is in an expected increase in fuel economy. The improved fuel economy of 6x2 drives arises mainly from the reduced amount of mechanical gearing, although some fuel economy improvements could also be attributed to vehicle weight reductions. The reduction of internal gearing prevents losses from internal friction as well as losses from lubricant churning. There have been several studies performed on the expected fuel efficiency gains that may be realized with the use of a 6x2 drive tractor. The following sections provide details on the available data on 6x2 fuel efficiency testing.

5.1.1 Tata Motors Road Testing

The first published study concerning 6x2 fuel efficiency gains was performed in 2009 by Tata Motors [6]. The test team wanted to evaluate the possible fuel savings that could be achieved with a 6x4 drive that could be instantly configured to a 6x2 drive for specific road conditions. However, the test team did not have such a vehicle at their disposal. Instead, two vehicles were tested – a 6x2 and a 6x4 – along a roughly 220 km (137 mi) long test route that was divided into sections of similar roadway. The fuel consumption was then compared between the two vehicles for each section of the test course. The results of the testing are summarized in Table 2.

Table 2: Fuel consumption measurements of 6x2 and 6x4 vehicles [6]

Test Course Section	Road Type	Total Distance (km)	Fuel Consumed (L)		Percent Improvement (%)
			6 x 4	6 x 2	
1	City	16.09	12.920	10.158	23.94
2	Flat Expressway	27.45	7.120	6.268	12.73
3	Flat + Normal grade	54.90	11.830	12.949	-9.03
4	Downhill	57.20	0.618	0.020	187.46
5	Downhill	75.73	0.512	0.090	140.20
6	Downhill	78.57	0.525	0.454	14.50
7	Normal grade	110.75	8.513	11.473	-29.62
8	Flat+ Normal Downhill	142.74	13.778	13.306	3.49
9	Flat	144.83	1.776	0.580	101.53
10	Steep Uphill	162.82	24.350	25.140	-3.19
11	Flat + Normal Downhill	165.66	4.790	4.477	6.76
12	Flat	194.05	12.971	12.380	4.66
13	Flat	206.36	3.999	3.641	9.37
14	City	221.98	10.510	9.979	5.18
		TOTAL:	**114.212**	**110.915**	**2.93**

The Tata Motors test team reported an overall decrease in fuel consumption of 2.93% while using 6x2 vehicles instead of 6x4 over the entire test course. However, the results of this test are suspect since, as may be seen in Table 2, some of the test course sections resulted in 6x2 fuel efficiency gains of as high as 187.46% over 6x4 use, a highly unlikely result. This may be a result of inaccurate fuel consumption measurements over each test section, or perhaps a misalignment of test course sectioning between the 6x2 vehicle test and the 6x4 vehicle test. Nevertheless, the 2.93% increase in fuel efficiency for 6x2 drive tractors is a reasonable overall result and aligns well with other literature available.

5.1.2 **OEM and Fleet Datasets**

In addition to the Tata Motors study, the North American Council for Freight Efficiency (NACFE) also provides various data points for fuel efficiency gains reported by OEMs and fleets operating 6x2 tractors [3]. The results of all of the provided data points are shown in Figure 4.

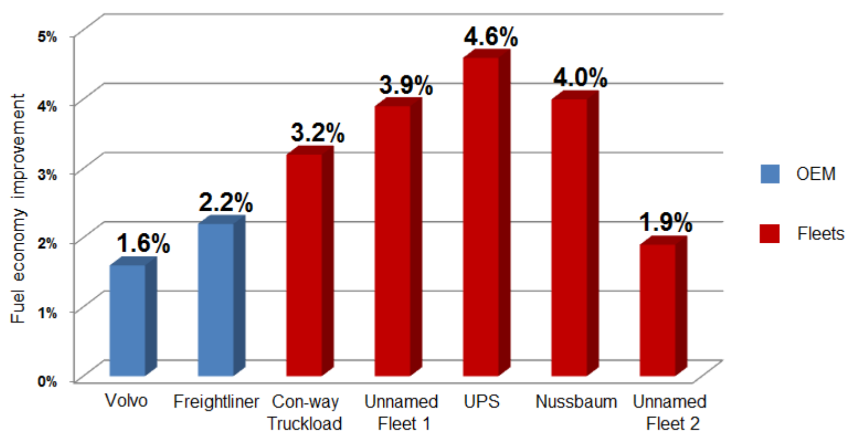

Figure 4: Decreases in fuel consumption attributed to 6x2 drives [3]

The first data point provided by NACFE outlines test results from Volvo. The Volvo team operated a control and a test vehicle, a VNL670, both equipped with D13 engines. The test vehicle was first performed with the vehicle configured as a 6x4 with a Meritor axle set, and then reconfigured to operate as a 6x2, again with a Meritor axle set. The control vehicle maintained the 6x4 configuration throughout the testing. Testing occurred over an 80 km (50 mi) test route with an overall elevation change of less than 60 m (200 ft), a maximum grade of less than 4% and a vehicle speed of roughly 100 km/h (62 mph). The results of the Volvo testing revealed a 1.6% improvement in fuel economy using a 6x2 over a 6x4.

Daimler Trucks was also reported to have performed fuel efficiency testing of 6x2 tractors using two Freightliner Cascadia vehicles equipped with Detroit Diesel 15L engines, DT12 transmissions and Michelin XDA Energy dual tires on the drive axles. The selected test route was roughly 650 km (400 mi) with a maximum grade of ±5%. The test vehicles were operated at a speed of roughly 90 km/h (55 mph) with cruise control engaged. The results of the Daimler testing were a 2.2 ± 0.3% reduction in fuel consumption while operating the 6x2 drive vehicle.

In addition to the two OEM data points, NACFE also presented five sets of fleet data. Con-way Truckload, UPS, Nussbaum and two unnamed fleets provided fuel consumption data to NACFE in order to compare the fuel efficiency of 6x2 drive tractors against 6x4 drive tractors. Con-way Truckload provided fuel consumption data for 2,394 tractors over a 12 month period beginning in November 2012. NACFE reviewed the available data for a subset of 1,283 Kenworth tractors, 1,224 of which were 6x2 tractors and 59 were 6x4 tractors. The 6x2 tractors were also equipped with direct drive transmissions and wide-base single tires, neither of which were equipped on the 6x4 tractors. The comparison of fuel consumption data revealed a 6.7% decrease in fuel consumption for the 6x2 tractors. However, 1.5% and 2% of the decrease in fuel consumption were attributed to the direct drive transmissions and the wide-base singles, respectively. Roughly 3.2% reduction in fuel consumption was attributed to the 6x2 drive technology.

UPS performed a 12 month study in which they operated two identically equipped Mack Pinnacle tractors with Mack 13L engines. The only difference between the two vehicles was that one was equipped with 6x2 drive and the other with 6x4 drive. The two vehicles operated on the same route at the same time of day between Charlotte, NC and Atlanta, GA twice a day for a year resulting in the accrual of approximately 140,000 km (87,000 mi) on each vehicle. The result of the yearlong trial was a 4.6% increase in fuel efficiency in operating the 6x2 versus the 6x4 tractor.

Nussbaum, the third named fleet within the NACFE report, provided one month's worth of fuel consumption data for their fleet. The fuel consumption of 14 Volvo tractors was monitored, ten of which were 6x2 drive vehicles and four of which were 6x4 drive vehicles. The 6x4 drive vehicles were equipped with overdrive transmissions whereas the 6x2 vehicles were equipped with direct drive transmissions. A review of the fuel consumption data, over which approximately 16,000 km (1,000 mi) were traveled by each vehicle, revealed a 5.48% increase in fuel economy. The NACFE report attributes 1.5% of the fuel savings to the use of direct drive transmissions, leaving roughly 3.98% of fuel economy improvements attributed to the use of 6x2 drive technology.

Finally, one of the two unnamed fleets within the NACFE document reported a 3.9% increase in fuel economy while operating 2010 Freightliner Columbia tractors over a 12 month period. The other unnamed fleet reported an average of 1.94% in fuel efficiency improvements over a four month period.

5.1.3 **Track Testing**

Fuel consumption testing has also been performed on closed course tracks. The Performance Innovation Transport (PIT) group of FPInnovations performed such closed course testing in collaboration with NACFE [1]. The PIT test team performed two sets of testing to compare the fuel efficiency between 6x2 and 6x4 tractors. The first test compared three Kenworth T660 tractors, all of which were stock 6x4 drives. The PIT team modified two of these tractors to 6x2 configurations. The first modification involved emptying the axle housing of the rearmost axle and removing the inter-axle drive shaft. The second modification involved moving the rearmost powered axle to the forward powered axle position, emptying the components of the forward axle and moving it rearward to the tag position. Both modifications resulted in tag tandem 6x2 configurations, but with different mechanical components used in each tractor. The fuel consumption tests were performed in compliance with SAE J1321 Fuel Consumption Test Procedure, Type II. The results of the testing revealed a fuel savings of 2.57 ± 2.04% with the first modification and a fuel savings of 3.45 ± 1.16% with the second modification, both in comparison to the stock 6x4 tractor.

The second set of track testing performed by the PIT group involved the comparison of two Volvo VNL 64T tractors. The 6x4 tractor was equipped with a Meritor MT40-14X4C tandem and the 6x2 was equipped with a Meritor RS23-160 single drive axle and an unpowered Volvo tag axle. The fuel consumption tests were performed in compliance with SAE J1321 Fuel

Consumption Test Procedure, Type III. The results of the testing revealed a fuel savings of 3.29% in favour of the 6x2 drive tractor. However, the two vehicles also had slight differences in terms of the aero devices they employed. After consultation with aerodynamics experts, it was determined, after removing the effects of the differing aerodynamic drag reduction devices, the net improvement in fuel consumption between the 6x4 and 6x2 tractors was likely closer to 2.3%.

5.1.4 **Implications for Canada Greenhouse Gas Emissions**

Calculating the gross amount of fuel that could be saved as a result of allowing 6x2 drive tractors is the first step in quantifying the associated reduction of greenhouse gas (GHG) emissions in Canada through the use of such technology. In order to estimate the gross amount of fuel saved, the following equation may be used:

$$\begin{aligned} &total\ fuel\ saved\ per\ year \\ &= number\ of\ tractors\ \times market\ uptake\ \times fuel\ consumption\ \times distance\ travelled\ \times \%\ reduction \end{aligned}$$

In the above equation, *number of tractors* is the total number of tractors in use in Canada, *market uptake* is the expected percentage of tractors on the road that employ 6x2 drives, *fuel consumption* is an estimated average fuel consumption for a typical tractor, *distance travelled* is the average distance travelled by a typical tractor per year, and *% reduction* is the expected reduction in fuel consumption associated with the use of 6x2 drives.

In order to estimate the total number of tractors in Canada, data from Statistics Canada was used. The latest year in which they performed an annual trucking survey was 2010. In 2010, approximately 182,000 powered tractor units were in operation on Canadian roads [7].

The market uptake of 6x2 drive tractors is estimated to be roughly 2.5%, similar to that reported in the United States [8] [9]. In practice, the market uptake for 6x2 tractors in Canada may be lower or higher than that realized in the United Stated. However, a market uptake of 2.5% provides a reasonable estimate without any other available data.

The U.S. Environmental Protection Agency (EPA) estimates that, on average, today's tractors achieve an average fuel economy of roughly 42.8 l/100 km to 36.2 l/100 km (5.5 mpg to 6.5 mpg) [10, p. 2.23]. For the purposes of this report, an average fuel economy of 39.2 l/100 km (6.0 mpg) will be assumed.

Data for typical distance travelled in a year for a Canadian tractor was gathered from Natural Resources Canada [11]. A 2000 study revealed that the average distance travelled by a Canadian tractor was roughly 187,000 km (115,000 mi) per year. Although this data is outdated, it is assumed to still be representative of typical Canadian operations.

There exists a wide range of fuel economy improvements presented by the literature, as detailed in sections 5.1.1 through 5.1.3. The range of 1.6% to 4.6% reported improvements in fuel economy, as reported by the Volvo OEM tests and UPS fleet tests, respectively, will be used to calculate the total amount of fuel saved per year.

Using the parameters as detailed above, allowing the widespread use of 6x2 drive technology within Canada could result in a yearly nationwide fuel savings of roughly 5.34 million litres to 15.3 million litres. Using a value of 2.663 kg of CO_2 per liter of diesel fuel burnt [12], the use of 6x2 drive technology would result in a yearly reduction of approximately 14,200 to 40,900 tonnes in emitted CO_2.

5.2 Vehicle Weight

The use of 6x2 drive will reduce the overall weight of a highway tractor due to several factors. Firstly, tag axles weigh inherently less than driven axles. Secondly, the lack of certain drivetrain components will also reduce weight; the lack of an inter-axle drive shaft, inter-axle differential, or differential gear set in tag axle all contribute to the overall weight savings. The resulting weight differential between 6x2 and 6x4 tractors is between 159 kg to 204 kg (350 lbs to 450 lbs) [13] [14], depending on the axle manufacturer.

The reduction in vehicle weight can have various implications to vehicle operators as well as equipment manufacturers. For example, vehicle operators could benefit by using the excess capacity to increase the overall cargo capacity of their combination vehicles, or use the weight savings to employ additional fuel saving technologies such as auxiliary power units or aerodynamic drag reduction devices such as side skirts or boat tails. From the vehicle manufacturers' point of view, the weight savings offered by a 6x2 could be used to offset other weight requirements; an example being emission control equipment such as selective catalytic reduction systems [14].

5.3 Maintenance

There is also the maintenance side of a fleet's operation to consider when evaluating the use of 6x2 tractors. The reduced mechanical complexity of a 6x2 drive system provides for some opportunities for cost reduction in the area of maintenance. The dead axle eliminates one axle's lubricant reservoir and lubricating oil. New lubricant, labour incurred in replacing the used lubricant, and the disposal of the used lubricant, can collectively be a small but significant sum of money for a fleet. Other minor maintenance gains include the elimination of grease and inspection points for the inter-axle driveshaft components such as universal joints, slip joints, and boots. It has been estimated that the yearly reduction in maintenance costs for 6x2 tractors versus 6x4 tractors is roughly $100 [3].

5.4 Tire Wear

While 6x2 tractors can reduce the amount of maintenance required over its life, the drive tires have been found to wear more quickly. Early adopters of 6x2 tractors have found that the remaining drive tires wear at a rate of two to three times faster than a more traditional 6x4 drive tractor. Part of the cost of higher drive tire wear and more frequent replacement can be reduced by moving partially worn tires to the dead axle or the trailer axles. [15]

5.5 Traction Availability

Most 6x4 trucks allow the locking of the inter-axle differential to force the lead and trail drive axles to turn at the same speed; this is helpful when one axle is slipping. For maximum traction, some 6x4 trucks are equipped with axle differential locks in conjunction with an inter-axle differential lock. Locking all three (inter-axle lock plus two axle locks) causes all drive wheels to turn at the same speed, regardless of slip or traction at any tire.

On 6x2 tractors, the differential is also equipped with a lock, but with only one drive axle, other means are employed to achieve additional traction in marginal conditions. Since traction is proportional to the weight acting on the tire through the contact patch, a drive axle with a heavier load can produce a higher level of traction. By altering the air spring pressure between the drive axle and the dead axle, the effective weight on the drive axle can be increased, which would increase traction proportionally. However, this additional load may cause the drive axle to temporarily exceed regulatory limits even though mechanical axle limits are not exceeded.

Automatic lift axles use of load shifting methods to lift certain axles until the load on each axle approaches, but does not exceed, the permissible limits. This reduces the wear on the lifted axle components such as tires, brakes and bearings. This technology is complementary to 6x2 tractors, and is applied to empty trailers by regulation or permit in the western provinces, and to quad-axle semitrailers in the six eastern provinces [5]. However, the use of lift axles on trailers is not the focus of this report.

Loss of traction and wheel spin is likely to occur when a vehicle is starting from a stop, accelerating away from a turn or making a turn on a wet or slippery road. These conditions generally occur at intersections and the beginning of hill climbs, which would often be in urban areas, and off-road in yards. Consequently, such events would generally occur at low speed, less than 40 km/h (25 mi/h).

Theoretically, assuming that axle load shifting is permissible for transient occurrences, it is possible for a 6x2 tractor to achieve most – approximately 85% to 90% of the tractive effort of a 6x4 tractor by shifting 100% of the dead axle's load onto the driven axle. However, this would cause damage to the axle itself unless the driven axle components to be substantially reinforced for those transient occurrences, which would render it uneconomical to manufacture. It would also most likely exceed the tire load limits. For those reasons, the load shifting is generally limited to the axle’s mechanical load bearing limits or less.

Most three-axle highway tractors are generally equipped with tandem axle sets that are colloquially known as "40K" or "46K". These are the most common sizes and the designations refer to load ratings of 18,181 kg (40,000 lb) and 20,909 kg (46,000 lb) respectively, for the tandem set. This corresponds to a mechanical design limit of 9,090 kg (20,000 lb) and 10,454 kg (23,000 lb) respectively for each axle within the tandem set for each type.

Depending on the jurisdiction, the legal axle load limits can be very close to the mechanical limits of the tandem axle set. For a tractor-trailer loaded to the legal limit, there may not be much headroom for the load shifting technology to work as the control must remain within the mechanical design limits.

For example, in Alberta, the regulations allow for a tandem axle set equipped with dual tire assemblies to carry 17,000 kg (37,500 lb), 8,500 kg per axle (18,750 lb); while no axle within each set may exceed 9,100 kg (20,000 lb) [5]. For a 6x2 tractor equipped with "40K" axles and loaded to the legal limit, this would correspond to a maximum headroom of 6.7% for use as part of the load shifting technology in low traction situations. For a 6x2 tractor equipped with "46K" axles, this increases to 23% for the same province.

In the case of an empty tractor-semitrailer, it is possible for the gross axle weight rating to be respected while unloading the dead axle completely. In this case, it would be no different than a 4x2 tractor. While this would not be a violation of the provincial maximum single axle allowable weight, it would violate the letter of most regulations requiring axle equalization (as detailed within Appendix A), even though the tractor would remain within the provincial maximum single axle allowable weight even with an axle lifted.

In the same example for a lightly loaded with an tractor axle load of 6,000 kg (13,200 lb) per axle for a total of 12,000 kg (26,400 lb) for the tandem set, it would be possible to shift up to 3,100 kg (6,820 lb) from the dead axle to the drive axle and still be within the legal limits for both the single axle and tandem set allowable limits.

In a study performed by FPInnovations in 2014 [1], the traction issue was studied by comparing the performance of a 6x4 and a 6x2 tractor. The 6x2 tractor was a converted 6x4 tractor unit and was converted to a tag-tandem style 6x2 by emptying the rear-most axle housing. The study evaluated traction performance by means of a tractor-pull style sled on a gravel road. The result of that testing showed a noticeable traction advantage for the 6x4 tractor, regardless of whether the 6x2 tractor used increased drive axle load or equally distributed axle load. The study concluded that while the difference in traction was noticeable, it would likely not be noticed in actual service, save for specific conditions.

The study did not examine the gradeability or startability of the 6x2 versus 6x4 tractors, nor did they examine the effects of low-friction surfaces, such as ice and/or snow covered roads. The test plan for this program seeks to address those gaps in knowledge.

Using engine [16], transmission [17], and axle [18] information for a typical long haul tractor, a comparative graph of tractive force versus friction force (friction demand) for specific combinations of axle load, friction coefficient, and grade were produced.

Figure 5 illustrates the friction demand of a 6x2 tractor on flat, dry pavement, with an axle load of 7,700 kg (17,000 lb) per axle. In this plot, the friction demand axis (vertical axis) is the theoretical amount of friction force, in percent, required at the contact patch in order to transmit the applied torque. The applied torque is computed based on the maximum torque available at the engine speed listed, the current gear of the transmission, the final drive ratio, and the loaded radius of the tire. For the purposes of calculation, the tire's loaded radius is assumed to be constant and all differential locks are engaged. A coefficient of friction value, mu, of 1.00 is assumed as an average for dry pavement (the actual value will vary depending on weathering, temperature and other environmental and surface condition factors, and generally falls between 0.95 and 1.05 for highway asphalt). The gold line at 100% indicates the onset of slip.

Figure 6 illustrates the friction demand for the equivalent 6x4 tractor under the same conditions as Figure 5. These charts are not intended to be an absolute determination of tire slip but rather a comparative tool to estimate the probability and severity of tire slippage between 6x2 and 6x4 tractors.

Only the expected friction demand for the first five forward gears of a 16 speed transmission are shown. These gears were selected as they represent the expected range for starting/pulling away, which is where any slip is most likely to occur. Not included are the effects of the tractor's traction control system intervening to limit applied engine torque. Various strategies are employed by electronic systems which include pedal override, second gear launching and skip shifting, which can all assist in limiting wheel spin.

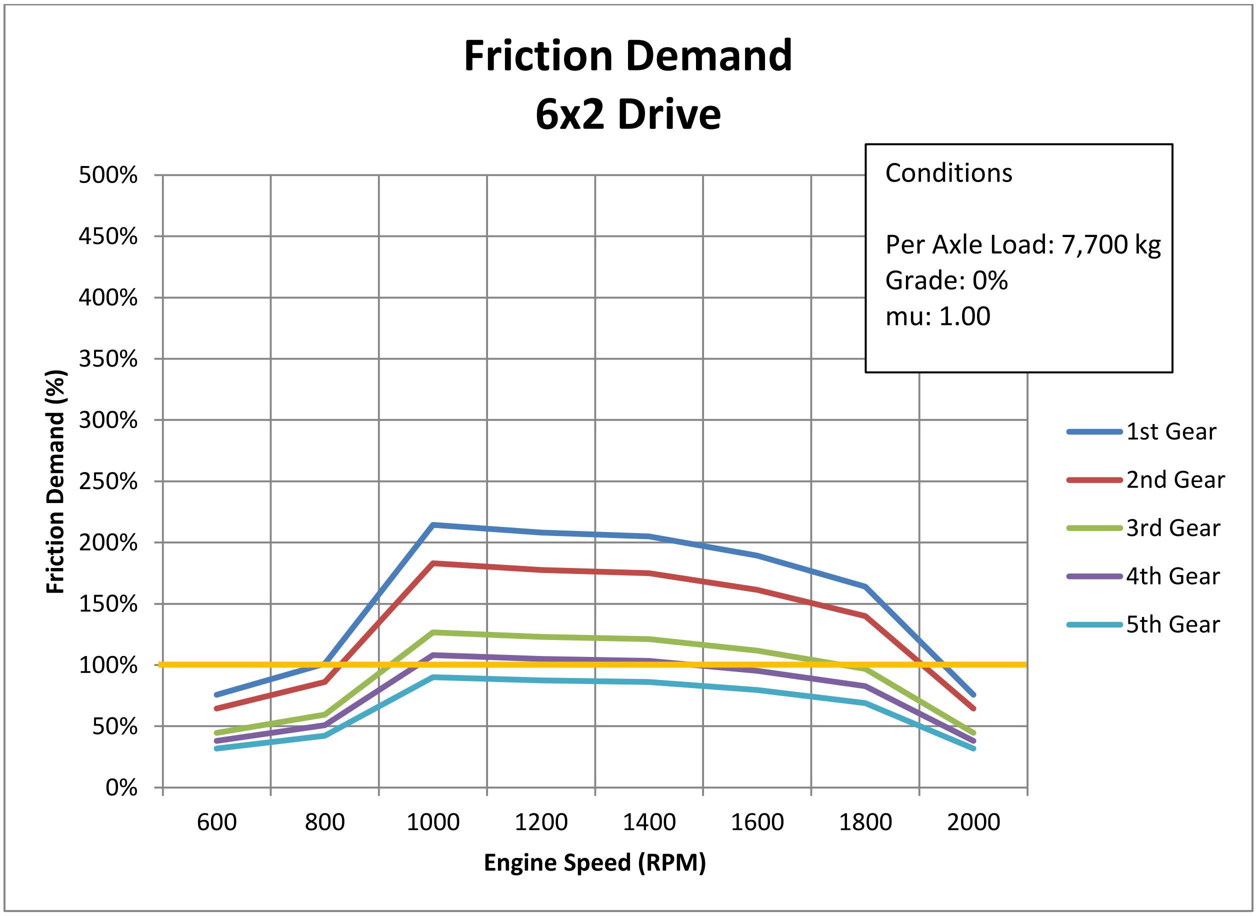

Figure 5: 6x2 friction demand (7,700 kg axle load, 0% grade, mu of 1.00)

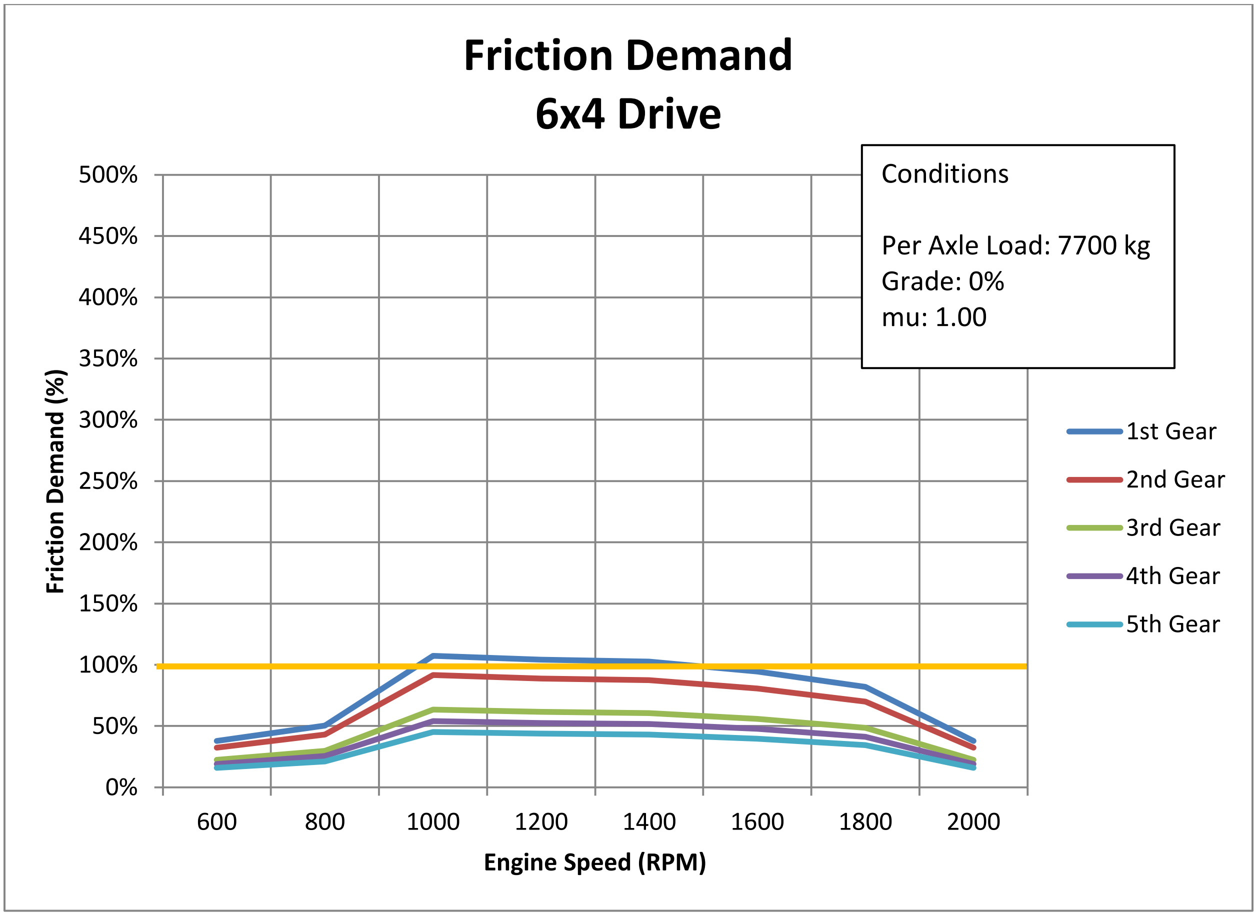

Figure 6: 6x4 friction demand (7,700 kg axle load, 0% grade, mu of 1.00)

Figure 7 changes only the mu value to 0.5, but keeps all other conditions the same for a 6x2 tractor. A mu value of 0.5 approximates snow covered pavement (i.e. snow packed into pavement surface voids) that would be found on urban roads in winter. Here it can be seen that 6x2 tractors will most likely experience wheel spin unless additional measures are taken to limit the engine's torque delivery.

Figure 8 shows the results of changing the mu value to 0.5 for a 6x4 tractor. Slippage is still probable, even for 6x4 under these conditions, but it can be seen that the severity of such events would be reduced significantly.

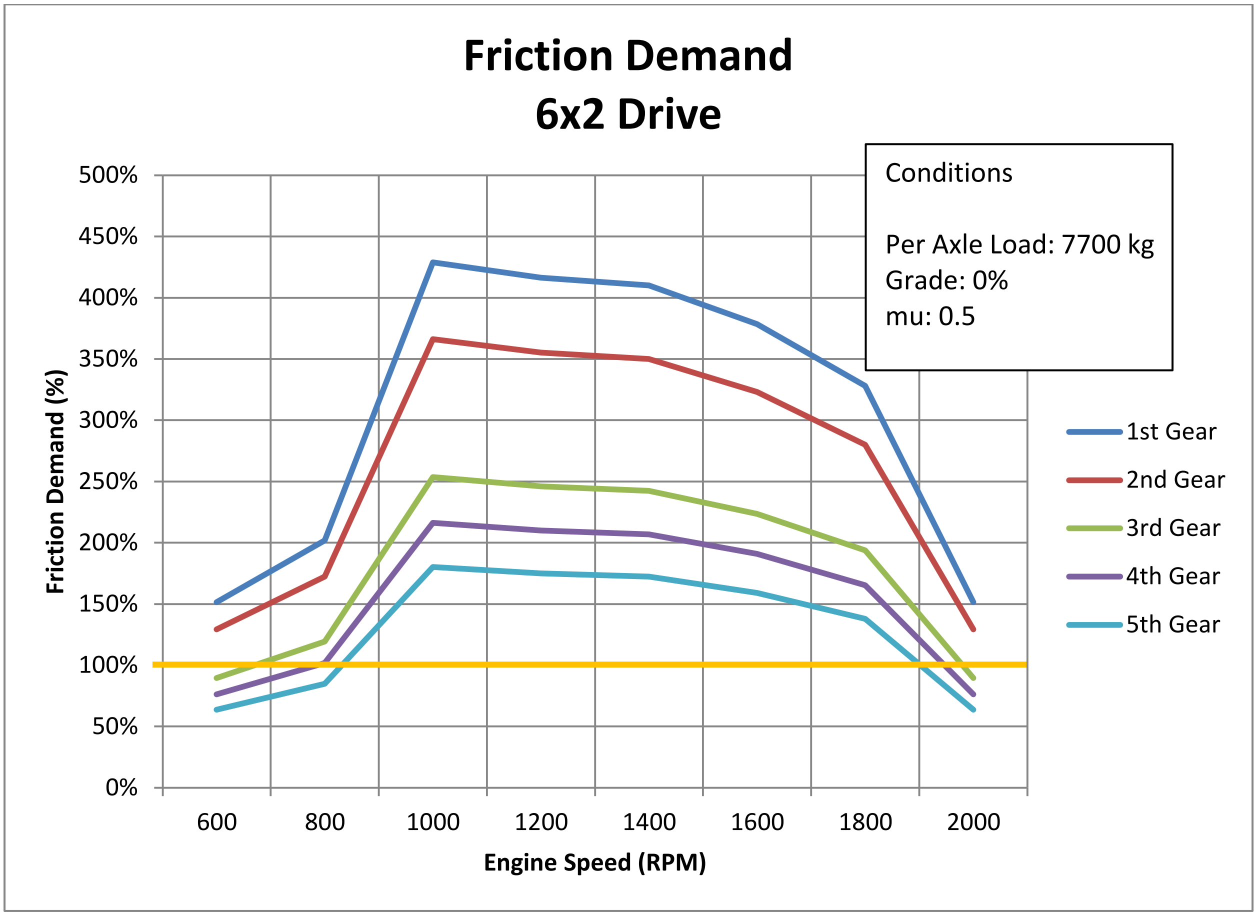

Figure 7: 6x2 friction demand (7,700 kg axle load, 0% grade, mu of 0.5)

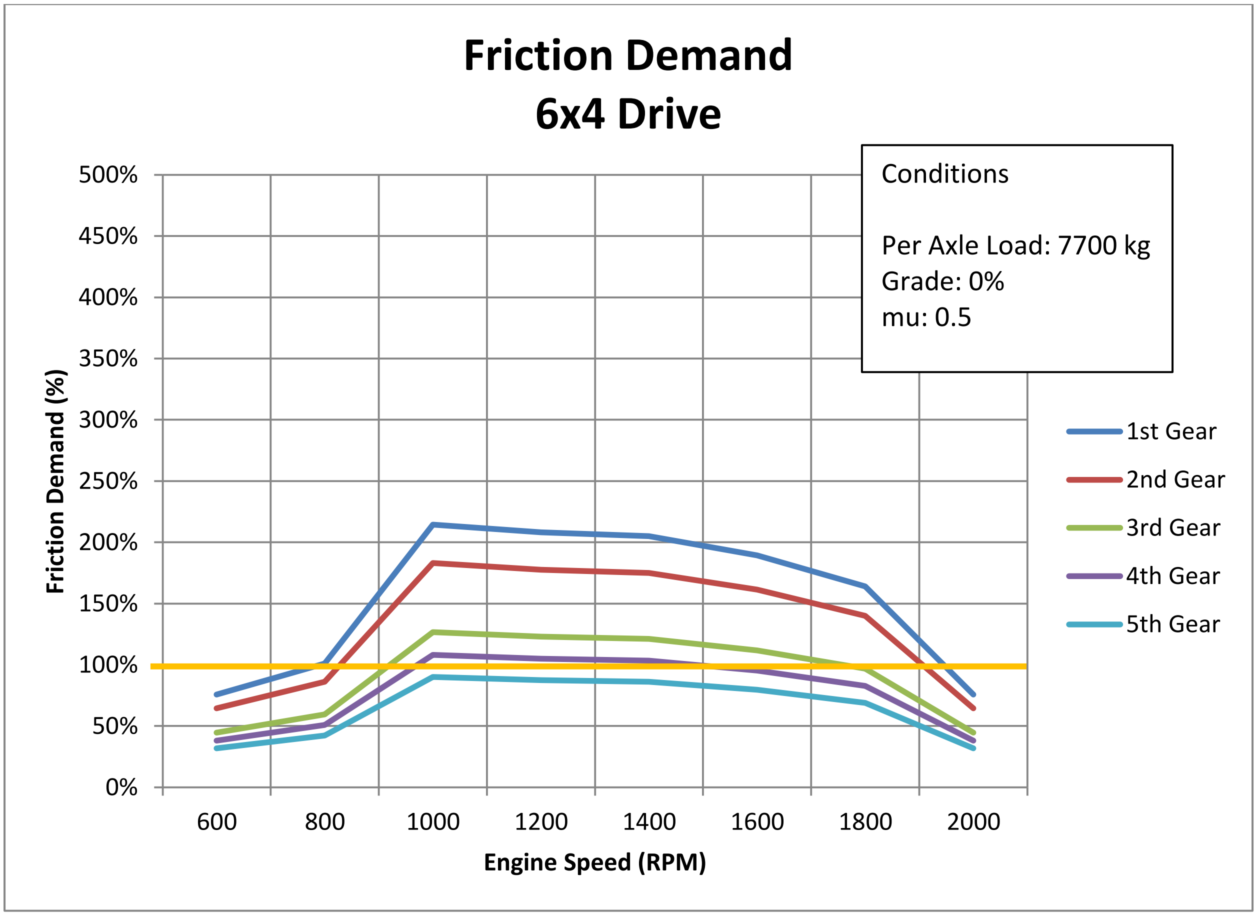

Figure 8: 6x4 friction demand (7,700 kg axle load, 0% grade, mu of 0.5)

Finally, Figure 9 illustrates the effects of 10% grade and a low coefficient of friction (mu = 0.5) together for a 6x2 tractor. Such a situation could occur at a loading dock or highway on- or off-ramp in winter. In this case, starting from stationary may be very difficult as even with the engine at idle, it may be possible to slip.

Contrast the result in Figure 10 with the previous Figure 9 with the same friction and grade conditions but with a 6x4 drive. In the case of a 6x4, while wheel slip is likely to still occur (as with the 6x2), the severity of the slip is not expected to be as severe.

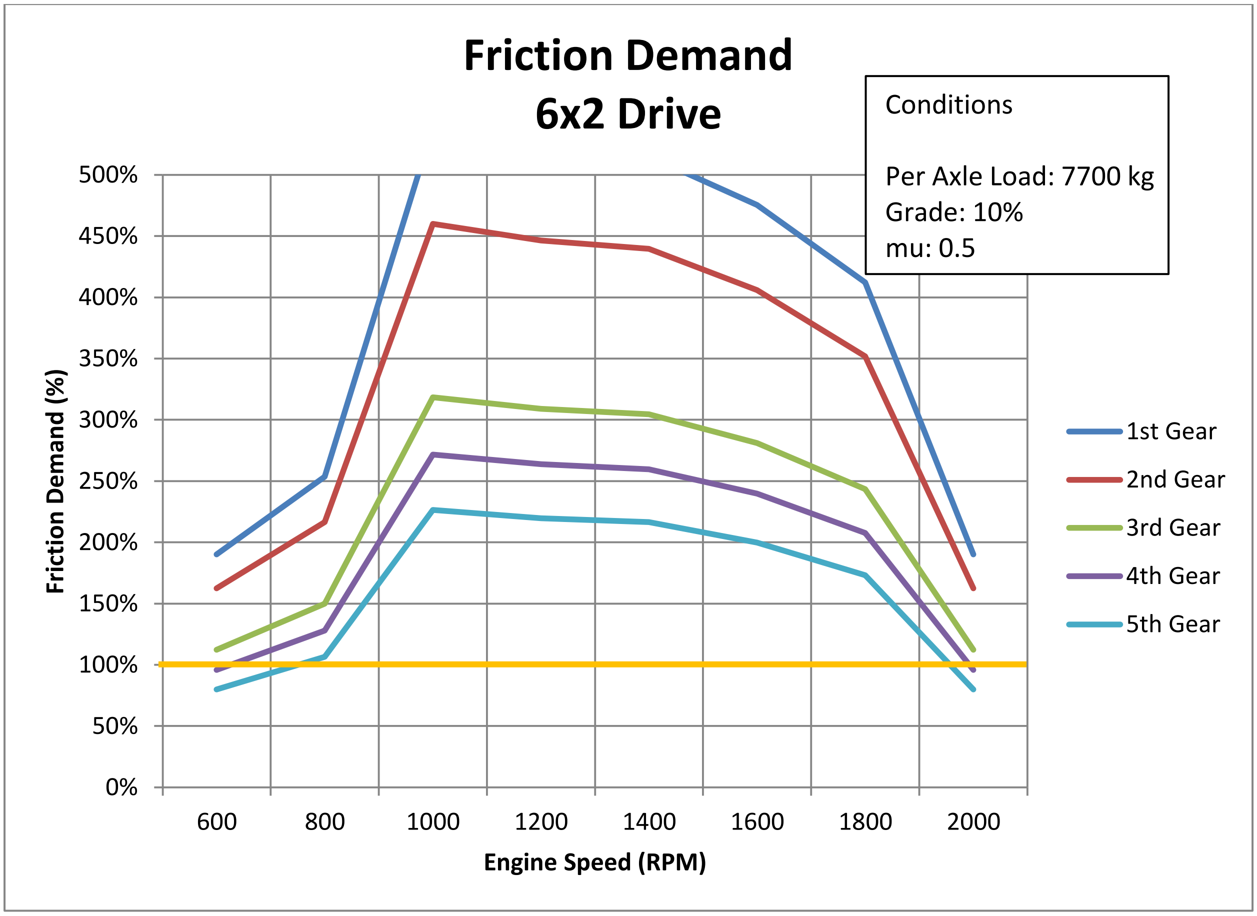

Figure 9: 6x2 friction demand (7,700 kg axle load, 10% grade, mu of 0.5)

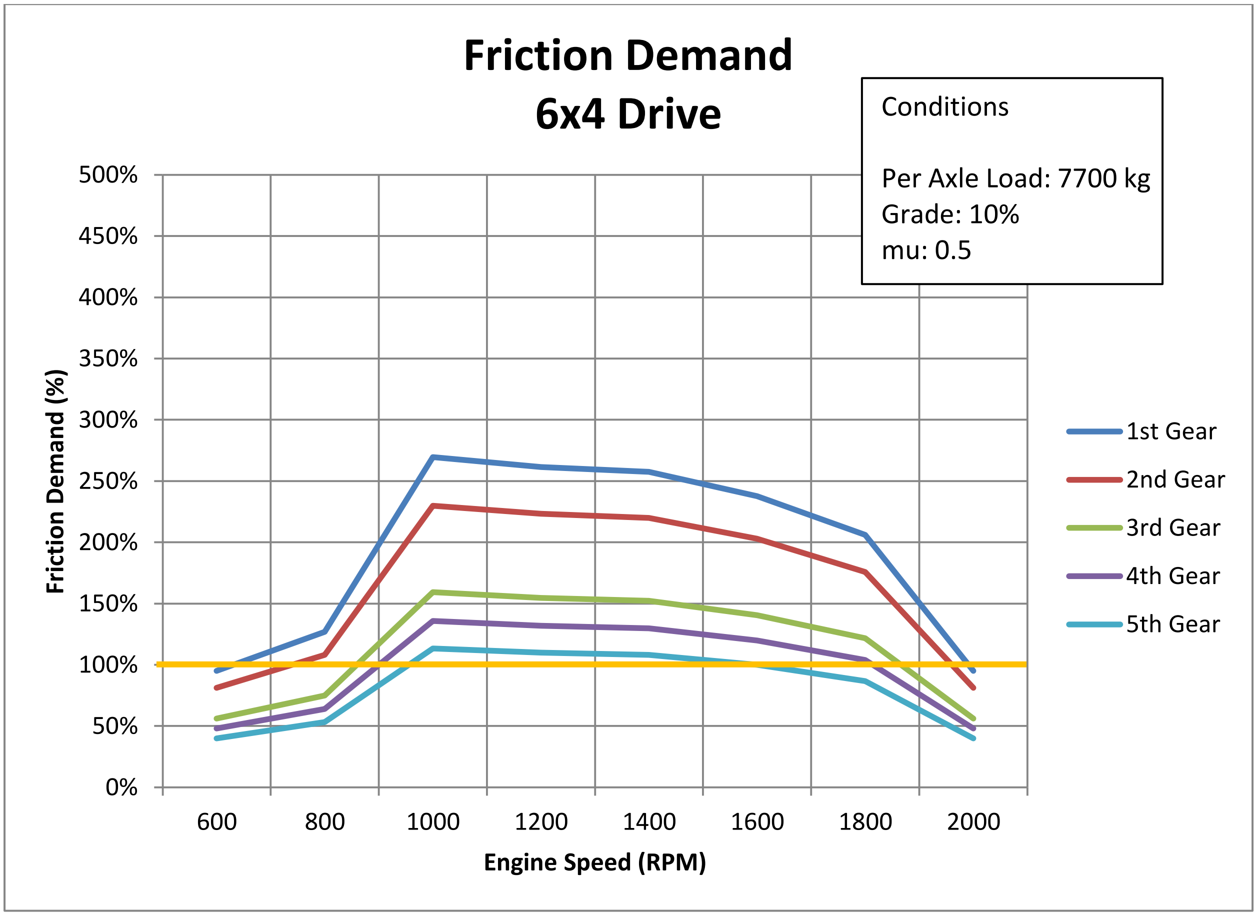

Figure 10: 6x4 friction demand (7,700 kg axle load, 10% grade, mu of 0.5)

What the preceding charts are intended to do is to give a visual representation in the differences in traction between 6x4 and 6x2 drives with no weight shifting.

To better illustrate the potential effects, the case of a 6x2 tractor-trailer loaded to comply with Alberta's regulations [5] (as an example) will be used. In this example, the trailer has "cubed out" with low density cargo and the tractor axle group has a combined load of 10,000 kg. This represents a load of 5,000 kg per axle (when equalized), and the truck is attempting to start on an 8% grade covered in snow.

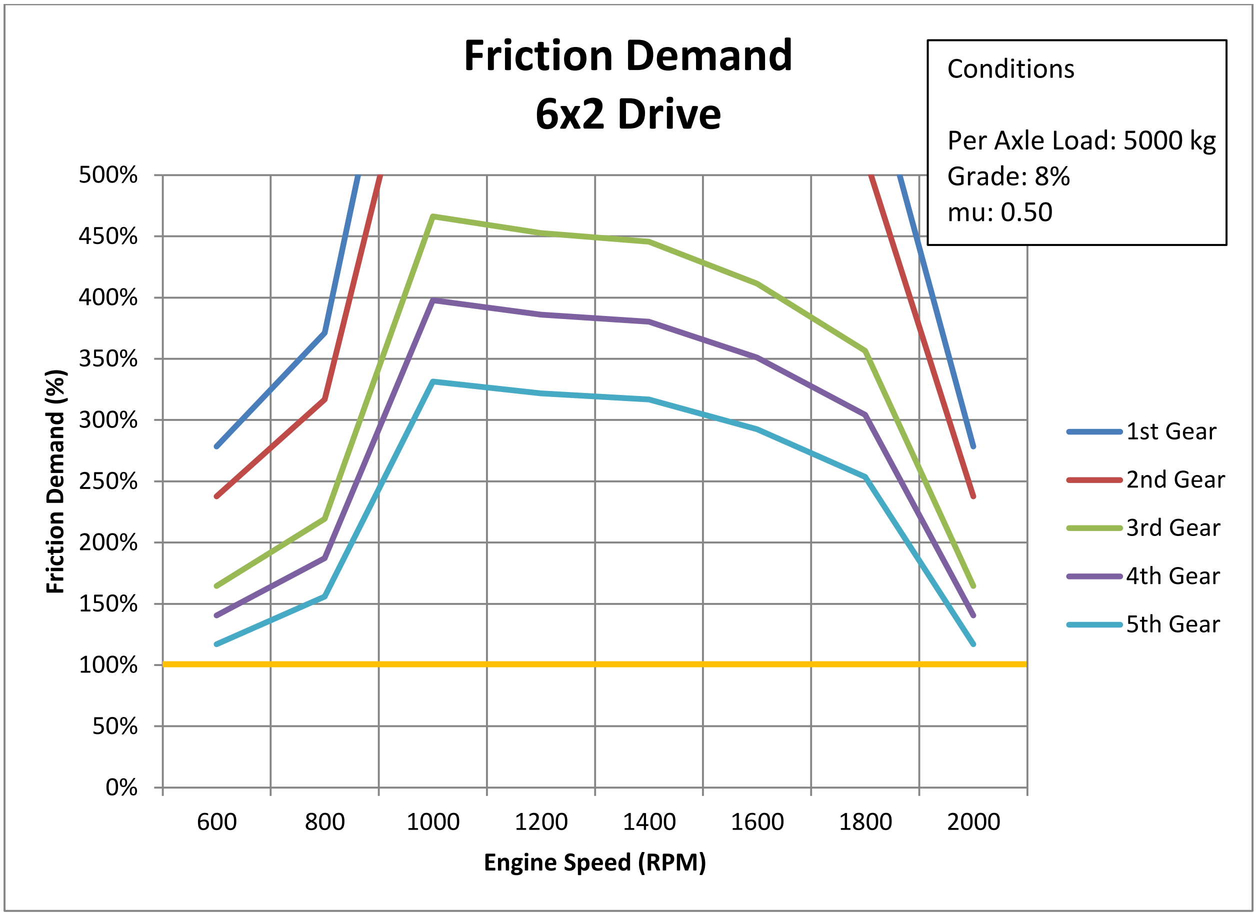

Figure 11: 6x2 friction demand (5,000 kg axle load, 8% grade, mu of 0.5)

Figure 11 shows that at any engine speed/gear combination that wheel spin is to be expected. As with the other examples, the differential is assumed to be locked and both sides of the drive axle are driving equally.

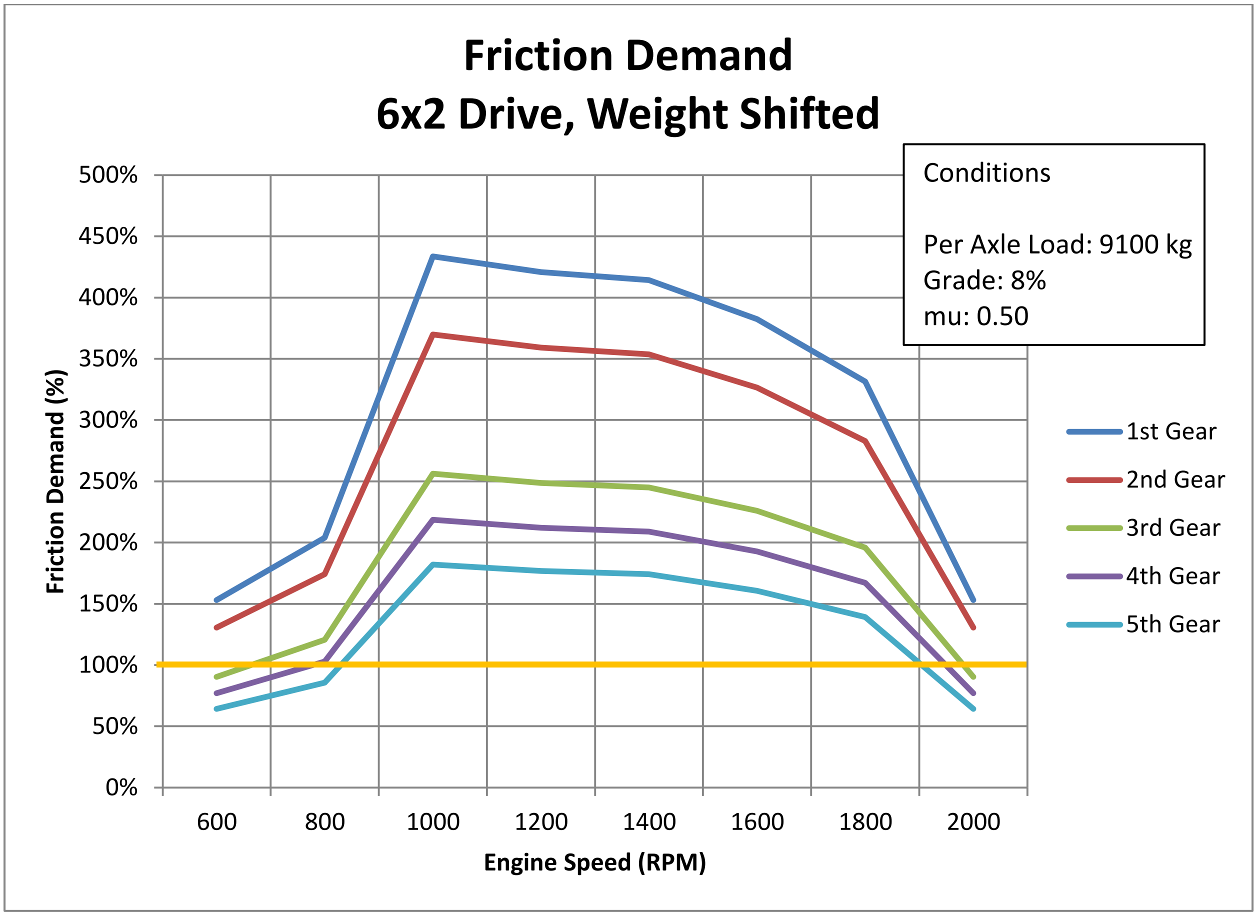

Figure 12: 6x2 friction demand (9,100 kg axle load, 8% grade, mu of 0.5)

Figure 12 shows the same truck as Figure 11, but with additional load transferred onto the drive axle. The axle load is still within the permissible single axle load for Alberta [5] of 9,100 kg. Only 900 kg remains on the dead axle, which is basically just the weight of axle assembly and suspension components.

As discussed earlier, except for cases where the truck is very lightly loaded, shifting almost all of the dead axle's load onto the drive axle would most certainly cause damage to the drive axle unless it were significantly reinforced for this additional load. This would render the drive axle uneconomical to manufacture and eliminate the weight savings of 6x2 drives.

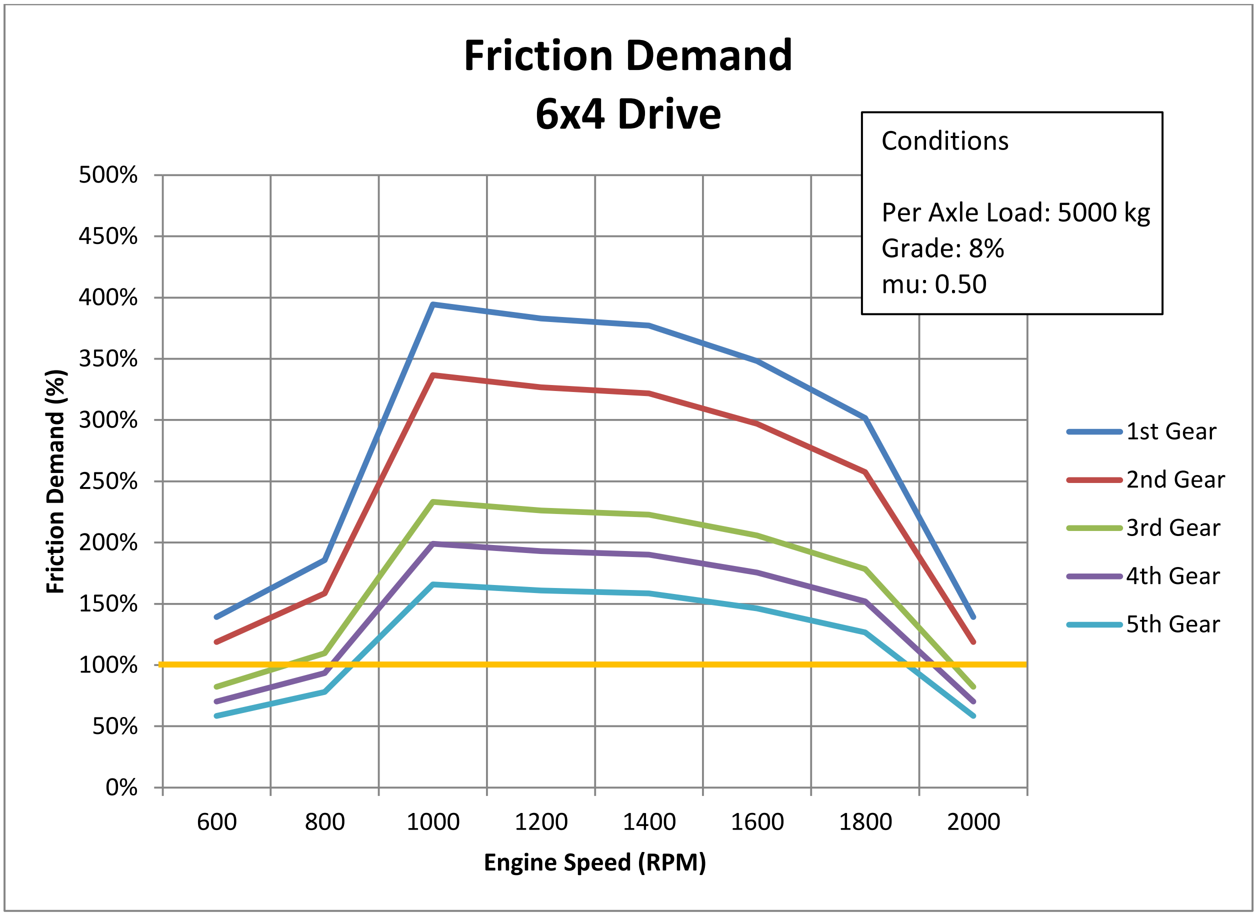

Figure 13: 6x4 friction demand (5,000 kg axle load, 8% grade, mu of 0.5)

Figure 13 shows the original conditions of 5,000 kg per axle, but for a 6x4 tractor. It can be seen that the 6x4 tractor and the 6x2 tractor with 9,100 kg on the drive axle (for the same axle group load of 10,000 kg) can be expected to have comparable traction. It should be clear from the above example that in order to restore the performance of 6x2 drive to a level comparable to a 6x4 drive, it would likely be necessary increase the drive axle load twofold. However, the mechanical limits of the axle would only permit a maximum of 1.2-1.3 times increase in load.

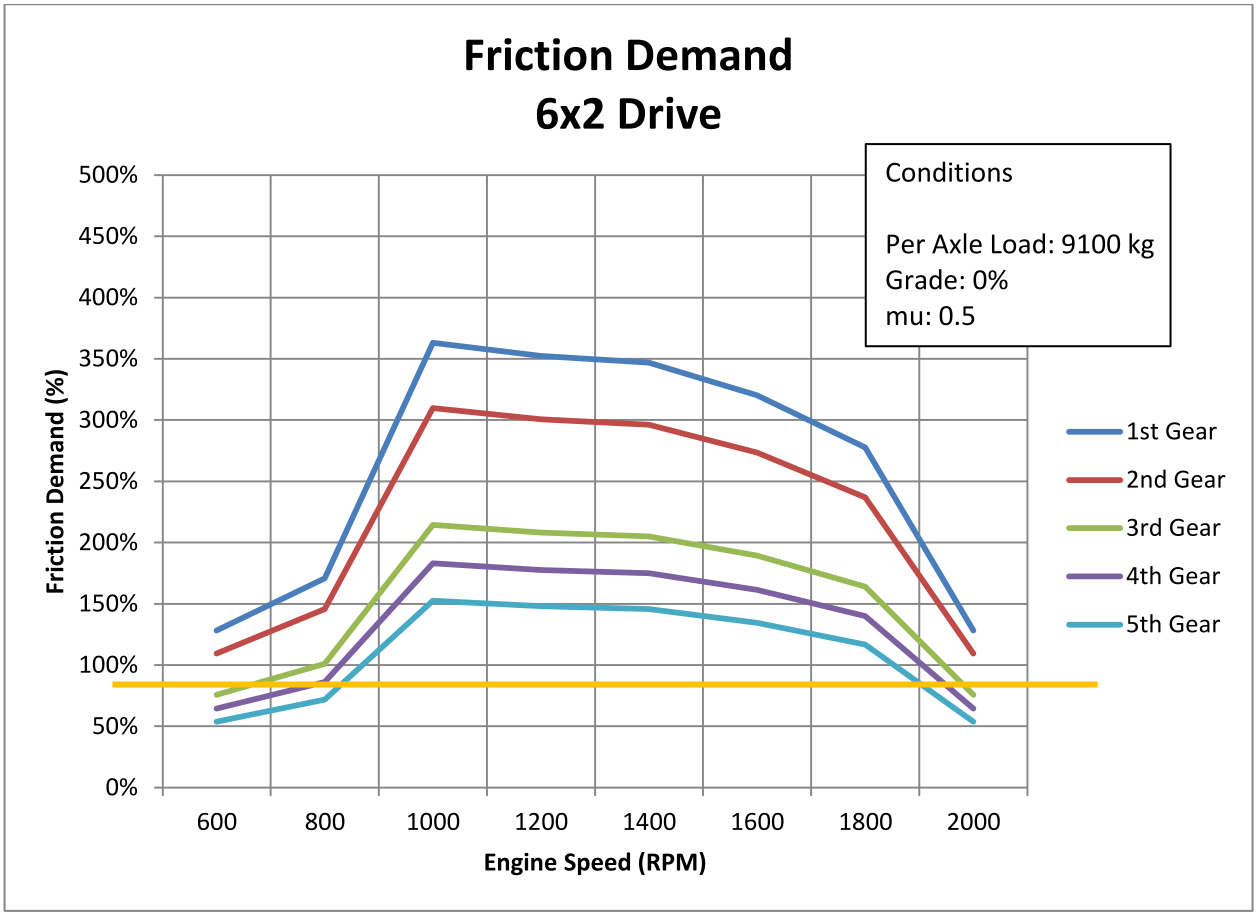

Figure 14: 6x2 friction demand (9,100 kg axle load, 0% grade, mu of 0.5)

Figure 14 shows the conditions of 9,100 kg per axle, which is more typical for Canadian trucking. In all cases, it can be seen that regardless of the axle load for a 6x2 or 6x4 tractor, the overall shape of the friction demand curves is unchanged. Only the magnitude is different.

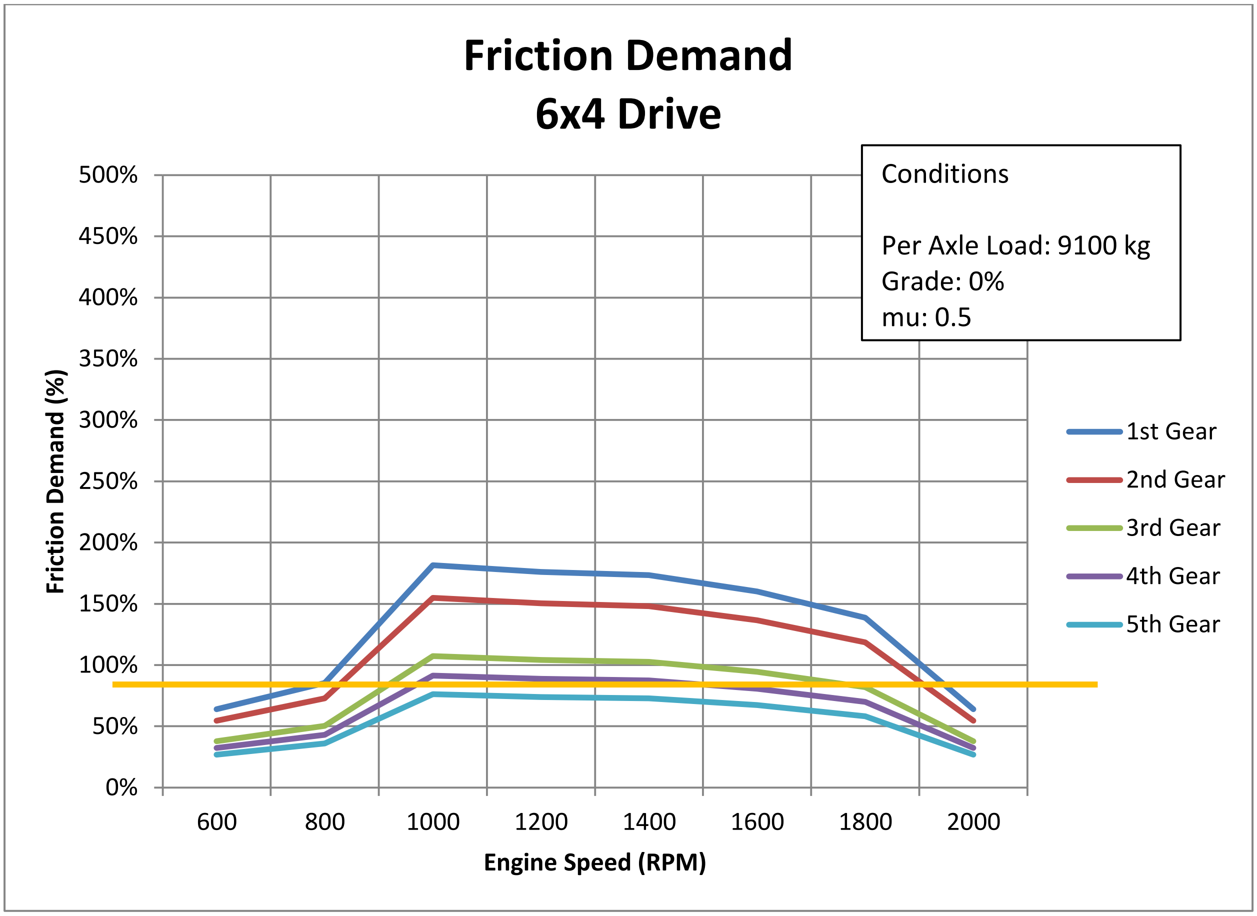

Figure 15: 6x4 friction demand (9,100 kg axle load, 0% grade, mu of 0.5)

Figure 15 shows the same load conditions as Figure 14, but for a 6x4 tractor. Comparing with previous examples using 7,700 kg and it is clear that the general shape does not change appreciably. Only the magnitudes are different.

5.6 Lateral Stability

Although there would likely be less traction available with the use of a 6x2 drive tractor in place of a 6x4 drive tractor, there have been claims that 6x2 tractors have additional lateral stability which could be beneficial in certain specific circumstances [3].

Figure 16 shows a simplified force diagram for the contact patches of two tires: a drive tire on the left, a non-powered tire on the right. Assuming that the two tires are identical in form and loading, each tire may only impart a specific maximum force, F_R, between the vehicle and the road before the tire reaches its maximum static friction capacity and starts to slip. With the tire on the left of Figure 16, a portion of F_R is used to provide a tractive force, F_T, to propel the vehicle forward leaving the remainder of the available F_R to provide lateral stability to the vehicle, F_L. For the unpowered tire on the right of Figure 16, there is no tractive force imparted between the tire and the road, leaving all of F_R to be available for F_L, theoretically increasing the lateral stability of the vehicle.

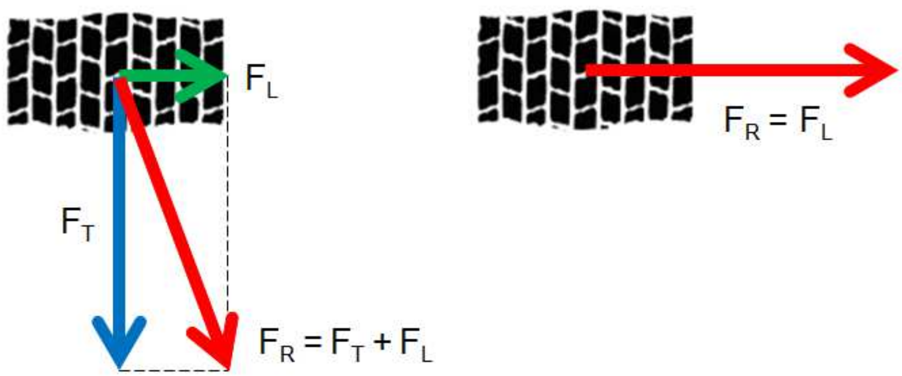

Figure 16: Available lateral stability between powered and non-powered tire

The circumstance in which the additionally available lateral force of a non-powered tire may become beneficial is a jackknifing event. Jackknifing is generally initiated while braking or turning, or a combination of both, causing the tractor to rotate to such a degree that the trailer exacerbates the tractor rotation to the point where contact between the two occur. The additionally available lateral force may decrease the propensity of the tractor to begin rotation, thereby reducing the expected number of jackknifing events. However, this is dependent upon the specific circumstances in which the tractor begins to rotate. In the unlikely event that rotation initiates when the vehicle is accelerating or traveling at constant velocity, the additional lateral stability of an unpowered axle may mitigate jackknifing. If tractor rotation initiates while the vehicle is braking, there will be a braking force applied between the road surface and both powered and non-powered tires alike, thereby eliminating any possible increased lateral stability of non-powered tires. However, the majority of jackknifing events are initiated while the vehicle is braking, it is unlikely 6x2 tractors would reduce the likelihood or severity of such events occurring.

There have been reports by certain fleets that their 6x2 tractors have experienced fewer jackknife events as a result of the additional lateral stability afforded by the tires on an unpowered 6x2 axle [13]. However, that has not been corroborated by any controlled tests.

6 DISCUSSION

6.1 Enforcement

Since 6x2 tractors are permitted in the US, there is the increasing probability that some U.S. 6x2 tractors could be entering Canada as part of their route. Unless the jurisdiction explicitly prohibits 6x2 tractors (for example in B.C.) a U.S. 6x2 could potentially find itself on Canadian highways. Even if 6x2 tractors are prohibited, identifying 6x2 tractors for enforcement may prove problematic. Visually, a 6x4 tractor and a 6x2 tractor are almost indistinguishable from the outside without looking under the frame or side skirting/fairing.

A knowledgeable inspector would have to look at the tractor's rear two axles for the presence of an inter axle driveshaft and two differential housings in order to confirm the drive type. A cursory glance at the rear-most axle from most available angles does not guarantee positive identification of the drive type. The Dana EconoTrek 6x2 axle set in particular uses the housing of a standard drive axle; only the internal components have been removed. Externally it looks nearly identical to a 6x4 drive.

Not all 6x2 configurations have the lead axle as the drive axle. It is possible to have the trailing axle as the drive axle. In that case, it may be possible to mistake the drive shaft for the inter-axle drive shaft and assume a 6x4 configuration. It may be necessary for additional training of inspectors in order to ensure consistent identification.

Typical axle load enforcement is done with weigh stations. A truck pulling through a weigh station's scales will not necessarily show the higher axle loads caused through weight shifting. Most probably, the weigh station results will show properly distributed axle loads as the suspension system always seeks to maintain load equalization. Identifying the operating parameters of load shifting system would require electronic inspection aids to be developed in order to determine the compliance of a tractor.

Weigh-in-motion has also been discussed as a potential means of detecting the presence of load shifting suspensions; however this would not be practical to accomplish. In order to detect the load shift, the vehicle suspension must be induced to transfer weight to the driven axle and the only way to do this for advanced 6x2 systems is to induce wheel slippage. Also, the scales would have to read the driven and dead axles simultaneously while the vehicle was in motion in order to compare the two values as the transfer is not instantaneous. Finally, externally inducing wheel slip would involve maintaining a low-friction surface at the scale year round and could only be conducted at low speeds as most 6x2 systems lock out the weight transfer functions at higher speeds.

6.2 Regulation Friendly Technological Enhancements

Based on the analysis from section 3 and assuming that provinces amend their legislation to allow 6x2 drives, there are some technological enhancements that may make 6x2 drives more acceptable to the various departments responsible for roads and infrastructure.

At its simplest, an additional requirement can be imposed that prohibits a driver override of the weight shifting at low speed. Some trucks are equipped with a driver override that allows the driver to manually initiate a load shift for instances where the driver knows, or anticipates traction issues. These systems generally disengage automatically as speeds increase above a certain threshold [19] and would only pose a potential issue in low speed areas such as access ramps, loading docks, intersections, and the like.

Another option for technology to assist in regulating the use of 6x2 drives is to allow the temporary exceeding of axle load limits, up to a limit (mechanical or legislated), but with strict electronic supervision by the controller. The controller would be required to keep track of the amount of weight shifted and for how long, and disengage the system temporarily based on some kind of algorithm. This would require further study and significant consultation with industry in order to determine the most practical solution.

6.3 Summary

There are gaps in the publicly available understanding of 6x2 performance versus their 6x4 counterparts. The current state of information regarding 6x2 traction performance in North America is limited and needs to be expanded beyond anecdotal evidence from operators.

Class 8 tractor manufacturers have implemented a variety of technological contrivances in order to mitigate any potential traction loss in typical low-traction driving conditions that may be encountered.

Performance testing of actual production 6x2 vehicles with their equally configured 6x4 counterparts is necessary to examine whether the ability of a 6x2 tractor to provide a comparable level of traction of a 6x4 tractor is compromised, and if so, to what degree.

7 RECOMMENDATIONS

In order to evaluate the use of 6x2 drive tractors in Canada NRC-AST provides the following recommendations:

1. A test program should be undertaken for as many 6x2/6x4 matching pair tractors as possible. Only through a rigorous evaluation of the traction control load shifting suspension will regulatory bodies be ultimately convinced to, or deterred from fully accepting 6x2 drive tractors.
2. Publically available and unbiased calculators should be developed and provided to fleet operators considering incorporating 6x2 drive tractors in their fleets. The benefits of 6x2 drive tractors are highly sensitive to the environments in which they are meant to operate and great care should be taken when considering the use of such a technology.

8 ACRONYMS, ABBREVIATIONS, AND UNITS

8.1 Acronyms and Abbreviations

AST	Automotive and Surface Transportation
EPA	U.S. Environmental Protection Agency
GHG	Greenhouse Gas
GVW	Gross Vehicle Weight
NACFE	North American Council for Freight Efficiency
NRC	National Research Council Canada

8.2 Units and Symbols

ft	Foot
kg	Kilogram
km	Kilometres
km/h	Kilometres Per Hour
L	Litre
lb	Pound
mi	Miles
mpg	Miles Per Gallon
mph	Miles Per Hour
RPM	Revolutions Per Minute
%	percent

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