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Performance of Infrastructure – Friendly Vehicles

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PERFORMANCE OF INFRASTRUCTURE - FRIENDLY VEHICLES

PERFORMANCE DE VÉHICULES FAVORABLE À L'INFRASTRUCTURE

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Project HV828

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ABSTRACT

This work used computer simulation to assess the dynamic performance of existing tractor-semitrailer configurations with eight or more axles that operate in Ontario and between Ontario and Michigan, and candidate tractor-semitrailers that could replace them. The existing configurations must raise rigid liftable axles to turn. The candidate configurations equalize the loads between all axles on the semitrailer, and use self-steering axles rather than rigid liftable axles, so may qualify as “infrastructure-friendly”. Vehicle performance was assessed against customary standards, and in comparison with the dynamic performance of existing tridem and self-steer quad semitrailer configurations.

This work also assessed the state of self-steering axle technology, and the drive traction of tractors that haul such trailers. It recommends regulatory principles for configuration and equipment of candidate configurations, and proposes tests that would address the performance issues and validate the computer simulations.

RÉSUMÉ

La présente évaluation a été faite par simulation informatique, dans le but de comparer la performance dynamique des configurations actuelles des tracteurs semi-remorques à huit essieux ou plus qui roulent en Ontario et entre l'Ontario et le Michigan à celle des tracteurs semi-remorques qui les remplaceront éventuellement. Les configurations actuelles doivent soulever les essieux relevables rigides pour faciliter les virages. Les configurations à venir doivent égaliser les charges entre tous les essieux de la semi-remorque et utiliser des essieux autovireurs plutôt que des essieux relevables rigides pour mériter d'être qualifiée de « favorable à l'infrastructure ». La performance des véhicules a été comparée aux normes en vigueur et à la performance dynamique des configurations des essieux tridem autovireurs actuels à celle des semi-remorques à quatre roues.

Cette évaluation s'est également penchée sur l'état de la technologie des essieux autovireurs et de la traction des tracteurs qui tirent de telles semi-remorques. Elle recommande des principes réglementaires en matière de configuration et d'équipement de configurations éventuelles, et propose des tests qui évalueraient la performance et valideraient les simulations par ordinateurs.

EXECUTIVE SUMMARY

Ontario Ministry of Transportation (MTO) began regulating the axle group weights and gross weight of heavy trucks by bridge formula in 1970, including a substantial increase in the maximum allowable gross weight, to 63,500 kg (140,000 lb). A variety of new vehicle configurations were developed to take advantage of the freedom offered by these rules, and additional configurations have emerged since from changes in allowable lengths. Many of these vehicle configurations have widely spaced axles, and include liftable axles which are raised so that the vehicle can make a turn at an intersection. MTO has recognized that heavy trucks that raise liftable axles when loaded cause significant road wear, and increase the risk of bridge failure, so embarked on a program to phase out use of liftable axles by heavy trucks. Phase 1 reduced the allowable gross weight of tri-axle semitrailers, and introduced the self-steer tri-axle and self-steer quad axle groups, with a single self-steering axle ahead of a fixed tandem or tridem axle group. The self-steering axle cannot be lifted from the cab, and must carry the same load as each fixed axle. The self-steer tri-axle and quad, and semitrailers with a fixed single, tandem or tridem axle were defined as “infrastructure-friendly”. Phase 2 reduced the allowable gross weight of end-dump and open-top hopper-dump semitrailers.

MTO was able to introduce the legislative and regulatory changes to implement Phases 1 and 2 based on existing research, in-house analysis, and extensive consultations with stakeholders. Phase 3 addresses multi-axle semitrailers and double trailer combinations. It is likely that many of the semitrailers will require two self-steering axles to come close to meeting customary standards for dynamic performance, so will be more complicated than existing vehicles, with the possibility of modes of instability that may not occur for existing vehicles with similar axle arrangements. A comprehensive analysis was required to ensure that any new “infrastructure-friendly” multi-axle semitrailer configuration that MTO will define in regulation will be at least as safe and productive as the vehicles it will replace, and will also be compatible with Michigan regulations. The dynamic performance of vehicles was assessed using procedures and standards similar to those used for the CCMTA/RTAC Vehicle Weights and Dimensions Study, a methodology now widely accepted by all provinces and other countries as a logical means to develop vehicle configuration specifications.

The dynamic performance of existing configurations that are principally used in Ontario was evaluated at Ontario weights, and the dynamic performance of existing configurations that are principally used between Ontario and Michigan was evaluated at Michigan weights. In each case, performance was evaluated with the liftable axles down, and with them raised as is commonly necessary to allow these vehicles to turn. A payload with a high centre of gravity is the critical load case for high-speed dynamic performance, and the following comments refer to this case. Payload centre of gravity height is not a factor for low-speed dynamic performance. All configurations fail the friction demand performance standard by a wide margin, and cannot make a turn with their liftable axles down. Most also fail this standard with their liftable axles raised, though they are able to make a turn. Two configurations with a large effective rear overhang fail the rear outswing performance standard, and one with a long semitrailer wheelbase fails the low-speed offtracking performance standard. Almost all configurations fail the high-speed offtracking and load transfer ratio performance standards by

a small margin, and the principal Ontario configurations fail the transient offtracking performance standard. All configurations also fail the static roll threshold when their liftable axles are raised. High-speed dynamic performance of these configurations is marginal with their liftable axles down. The problem is that none can turn with their liftable axles down, and must raise these axles in order to be able to turn. This significantly overloads the remaining axles, so none of these configurations could be considered "infrastructure-friendly".

The dynamic performance of a self-steer quad semitrailer as defined by Ontario Regulation 597 was evaluated for the range of self-steer axle location allowed by the regulation, and for self-steering axles with low, medium and high centring force characteristics. This configuration is already in regulation, so its performance may be considered as a baseline against which the dynamic performance of candidate "infrastructure-friendly" configurations may be measured. This configuration meets all performance standards, except for high-speed offtracking which it fails by about 0.02-0.05 m (1-2 in), and friction demand, where it is at the high end of the range for tridem semitrailers with a 3.66 m (144 in) spread tridem. 20 deg of self-steer angle should be sufficient for most turns, but the tightest turns, or turns through an angle greater than 90 deg may require a self-steer angle greater than 20 deg. Self-steer angle and friction demand are both minimized if the self-steering axle is as close to the tridem as possible. It is probably best to use as low a self-steering axle centring force characteristic as possible. An increase in centring force reduces the self-steer angle in a turn, but significantly increases friction demand.

None of the candidate "infrastructure-friendly" configurations meets all the performance standards. Configuration 13S13 came closest to meeting the performance standards. Tractor specifications for this configuration should be compatible with those of other provinces.

Configuration 12S113 comes close to meeting the performance standards if it is fitted with a 3.05 m (120 in) spread tridem, and the two self-steering axles are as close to each other and the tridem as possible. The foremost self-steering axle needs close to 25 deg of wheel cut, and the self-steering axles should have a low centring force characteristic. The self-steering axles do not apparently need to be locked at highway speed. Configuration 12S131 has difficulty with its large effective rear overhang, so the tridem must be positioned to the rear of centre between the two self-steering axles. It should be fitted with self-steering axles with a low centring force characteristic. Its self-steering axles should have at least 20 deg of wheel cut. The rearmost self-steering axle must lock automatically at highway speed. Configurations 12S114 and 12S141 are similar to configurations 12S113 and 12S131 respectively, but are more difficult to configure, have a lower payload in Ontario and will not be useful for operation into Michigan. They have no evident benefits over the five-axle semitrailer configurations. The pusher axle of configuration 112S13 causes particular difficulties. While the performance of this configuration is not bad, this configuration requires further work to define load control of the pusher axle.

The requirement for load equalization increases the spread of the fixed axles on candidate configuration 12S131 compared to the existing configuration, and the requirement for self-steering axles limits the spacing of these axles for configurations 12S113 and 12S113.

Existing configurations 12S114 and 12S141 have proven versatile alternatives to existing configurations 12S113 and 12S131 as a compromise for operation into Michigan, but this will no longer be the case as the axle spreads required for load equalization and the axle spacings required for self-steering axles will result in a much reduced payload in Michigan. Configurations 12S114 and 12S141 will have no evident benefits over the five-axle semitrailer configurations for operation in Ontario, and offer no benefit in performance. It will therefore be necessary to add two “invisible” liftable axles to candidate configurations 12S113 or 12S131 as a compromise for operation into Michigan, so there will be seven axles on these semitrailers.

No special requirements beyond those already used for the self-steer quad appear necessary for configurations 12S113 or 12S114. Configurations 12S131 and 12S141 require that the rearmost self-steering axle be locked at highway speed. This may be beyond the mandate of the Motor Vehicle Safety Act, but could be addressed within an Ontario Regulation, by an industry recommended practice, or by these two means together. A tridem drive tractor should be specified in a manner that is compatible with other provinces, and most especially Alberta and B.C. A tractor with a self-steering pusher axle should not equalize axle loads with the drive tandem. The issue of how the load on the pusher axle should be controlled is to be addressed in the next phase of MTO’s weight and dimension reform program.

Previous research and testing has not identified any hazard introduced by a self-steering axle in the belly position. However, a self-steering axle as the rear-most axle can introduce serious stability concerns that are addressed here by ensuring any such axle will be locked at highway speed.

A small number of carriers have successfully operated vehicles with self-steering axles for a long time, and each has worked with the axle and trailer manufacturers to identify a combination of axle, suspension, tire and set-up that works with controllable maintenance cost for their application. A much larger number of carriers have recently begun to operate vehicles with self-steering axles in accordance with the requirements of regulations in Ontario and Québec. They have certainly benefited from the experience of the pioneers, and many report satisfactory experience, possibly after learning the need to lubricate moving parts and maintain steering alignment. However, these carriers have a much wider range of applications, and some report troubles like excessive tire wear, insufficient steer angle and inadequate liftable axle clearance. These issues are gradually being resolved with improved understanding of operational needs and maintenance requirements. Québec carriers report a somewhat greater level of concern than Ontario carriers. Drivers generally report that a self-steering axle makes it easier to handle the vehicle. Taking the lift control out of the cab is not an issue for many drivers. There remain cases, like climbing hills on very slippery roads, and tight turns at low-speed where the self-steer axle bottoms, where there remains support for a cab lift control, with suitable interlocks.

The candidate configurations will require more than the 20 deg of steer commonly fitted to self-steer quads. At least one self-steering axle is available that provides 25 deg of steer, and at least one more is being developed. It may be possible to gain a degree or two of steer by modest adjustments to existing designs. A greater gain in steer that requires new components could be much more expensive.

Self-steering axles are still very much a work in progress. Manufacturers and carriers are gradually learning how to make them work for a wide range of applications, and they are proving cost-effective and reliable when the vehicles are operated within their capabilities. Some applications, like hoppers and log trucks, are still not amenable to the current self-steer configurations. Some carriers are waiting until the unknowns are better resolved. Depending on the perspective, the next step to two self-steering axles should not be a problem, or is premature.

The issue of additional drive traction from a fourth axle on the power unit is not easily separated from the additional weight that it accrues. If greater drive traction is required, then a 6 x 6 tractor can provide it. A tridem drive provides more consistent traction than fitting either a liftable pusher or liftable tag axle to a tandem drive tractor. Whatever drive arrangement is selected, optimum traction requires locking all axle and inter-axle differentials, to eliminate wheel spin. However, locking differentials greatly reduces the ability of a vehicle to turn. Alternatives are restrictive differentials, and traction control.

Self-steer quad semitrailers have better drive traction than 8-axle B-trains that do not have any liftable axles. If the self-steer quad semitrailer has traction problems, then the B-trains would be expected to have more severe traction problems. The candidate semitrailers considered here would have very similar drive traction characteristics to 8-axle B-trains. If these B-trains can operate satisfactorily in slippery conditions, then the tractor-semitrailers should also be able to operate in the same conditions without lifting any axles. It has been suggested that a driver of a tractor with a self-steer quad semitrailer should be able to lift the self-steer axle from the cab when necessary to maintain progress in slippery conditions. If the driver operates in the same manner as the driver of a B-train, then presumably traction should not be an issue. If it is, there are other options. A tridem drive, a driven front axle, or a traction control system available with all antilock brake systems all address the need for additional traction without the need to raise any liftable axle. A traction control works best if it is allied with an antilock brake system with a speed sensor and modulator for each wheel on the tractor.

A test program should demonstrate the effects of self-steering axles on vehicle dynamic performance. It will allow validation of simulations against test results, and demonstrate "normal" and "ultimate" dynamic performance for existing and proposed vehicle configurations. The self-steer quad semitrailers have little difference in response whether they are pulled by a three- or four-axle tractor, so there is little need to test them. Configurations 12S113 and 12S131 should be considered for testing, which will require outriggers to be fitted on the semitrailer to prevent rollover, and anti-jackknife cables to be fitted between the tractor and semitrailer to prevent jackknife. It would be desirable, though not necessary, to have a load equalizing suspension on each semitrailer, so it would be feasible to use existing semitrailers with a steel spring suspension on the tridem and an air suspension on the self-steering liftable axles. Whatever semitrailers are used, the self-steering axles should be fitted with a manual override to an automatic locking device, and with a device that allows the self-steer centring stiffness to be adjusted.

SOMMAIRE

Le ministère des Transports de l'Ontario (MTO) a commencé à réglementer les poids par groupe d'essieux ainsi que le poids total en charge des camions lourds, selon la méthode d'établissement des poids et mesure sur route (bridge formula), datant de 1970, autorisant notamment une augmentation marquée du poids total en charge permis, qui est passé à 63 500 kg (140 000 lb). Les configurations de nouveaux véhicules se sont multipliées, permettant de tirer avantage de la marge de manœuvre offerte par ces nouvelles règles, et d'autres configurations sont apparues depuis les changements de la longueur autorisée. Plusieurs configurations de véhicules présentent un large espacement entre les essieux et comportent des essieux relevables surélevés, afin de faciliter les virages aux intersections. Ayant reconnu que les camions lourds qui surélèvent les essieux relevables, une fois chargés, peuvent causer l'usure prématurée des routes et augmenter le risque de bris de différentiel, le MTO a lancé un programme d'élimination progressive des essieux relevables sur les camions lourds. L'étape 1 a réduit le poids total en charge autorisé des semi-remorques à essieu tridem pour chaque poids lourd et imposé l'essieu tridem autovireur et les groupes d'essieux autovireurs à quatre roues, pourvus d'un seul essieu autovireur situé en avant d'un essieu tandem fixe ou d'un groupe d'essieux tridem. Le levier de contrôle de l'essieu autovireur ne peut être enlevé de la cabine et doit faire porter la même charge que sur chaque essieu fixe. L'essieu autovireur à essieu tridem à quatre roues et les semi-remorques pourvues d'un essieu unique fixe, les essieux tandem ou tridem ont été décrits comme étant « favorables à l'infrastructure ». L'étape 2 a réduit le poids total en charge autorisé des semi-remorques à virage par l'arrière, à toit ouvert et à trémie.

Le MTO a pu faire adopter les lois et les règlements modifiant la mise en œuvre des étapes 1 et 2 en se fondant sur la recherche à jour, des analyses internes et une vaste consultation auprès des intervenants. L'étape 3 évaluera les semi-remorques à essieux multiples et les combinaisons de remorques doubles. Il est probable que plusieurs semi-remorques nécessiteront deux essieux autovireurs pour se rapprocher des normes usuelles de performance dynamique, ainsi elles seront plus complexes que les véhicules actuels, présentant en outre une possible instabilité qui ne peut pas toucher les véhicules actuels pourvus d'aménagements d'essieux semblables. Une analyse fouillée s'impose afin de s'assurer que toute nouvelle de configuration de semi-remorques à essieux multiples « favorable à l'infrastructure » que le MTO déterminera dans ses règlements est au moins aussi sûre et productive que celle des véhicules qu'elle va remplacer, et qu'elle est compatible avec les règlements du Michigan. La performance dynamique des véhicules a été évaluée en suivant les procédures et les normes semblables à celles retenues dans l'Étude des poids et des dimensions du Conseil des administrateurs en transport motorisé (CATM) et de l'Association des routes et des transports du Canada (ARTC), une méthodologie largement acceptée par toutes les provinces et les autres pays comme une façon logique d'élaborer des spécifications de configuration de véhicule.

La performance dynamique des configurations actuelles, qui est surtout utilisée en Ontario, a été évaluée selon les poids de l'Ontario; la performance dynamique des configurations actuelles surtout utilisées entre l'Ontario et le Michigan a été évaluée selon les poids du

Michigan. Dans chaque cas, la performance a été évaluée avec les essieux relevables non surélevés et avec les essieux relevables surélevés comme il est communément nécessaire pour permettre à ces véhicules d'effectuer des virages. La charge utile avec un centre de gravité élevé est un cas de charge crucial pour la performance dynamique à haute vitesse, et les commentaires suivants font référence à ce cas. Le centre de gravité élevé de la charge utile n'est pas un facteur à considérer en performance dynamique à faible vitesse. Toutes les configurations ont raté de très loin les normes de performance de la friction requise, et ne peuvent effectuer un virage avec leurs essieux autovireurs non surélevés. La plupart ont également raté cette norme avec leurs essieux autovireurs surélevés, bien qu'ils aient été capables d'effectuer un virage. Deux configurations présentant un porte-à-faux arrière vraiment large ont raté la norme de performance d'effet extérieur arrière et l'une d'elle, pourvue d'un empattement long de semi-remorque, a raté la norme de performance de dispositif de mise hors voie à faible vitesse. Presque toutes les configurations ont raté en regard du dispositif de mise hors voie à vitesse élevée et des normes de performance de ratio de transfert de charge par un faible écart, et les principales configurations de l'Ontario ont raté la norme de performance de dispositif de mise hors voie transitoire. Toutes les configurations ont également raté le seuil de roulement statique avec des essieux autovireurs surélevés. La performance dynamique à vitesse élevée de ces configurations est marginale avec les essieux autovireurs non surélevés. Le problème est qu'aucun véhicule ne peut effectuer un virage avec des essieux autovireurs non surélevés et doit donc surélever ces essieux afin de pouvoir le faire. Ce problème surcharge de façon importante les autres essieux, ainsi aucune de ces configurations ne pourrait être considérée comme « « favorable à l'infrastructure ».

On a évalué la performance dynamique d'une semi-remorque à essieu autovireur à quatre roues telle que définie par le règlement 597 de l'Ontario en regard de l'emplacement de l'essieu autovireur permis par le règlement, et en regard des essieux autovireurs présentant un centre de gravité bas, moyen ou élevé. Cette configuration fait déjà partie des règlements, ainsi sa performance peut être considérée comme une base de comparaison de la performance dynamique des configurations éventuelles dites « favorables à l'infrastructure ». Cette configuration satisfait à toutes les normes de performance, sauf pour les dispositifs de mise hors voie rapide qui ratent par presque 0,02-0,05 m (1-2 pouces) et la friction requise, qui se situe à la toute fin de la liste pour les semi-remorques à essieu tridem, avec un écartement des essieux tridem de 3,66 m (144 pouces). Vingt degrés d'angle d'autovirage devraient s'avérer suffisant pour la plupart des virages, mais les virages les plus serrés ou les virages présentant un angle de plus de 90 degrés peuvent nécessiter un angle d'autovirage de plus de 20 degrés. L'angle d'autovirage et la friction requise sont atténués si l'essieu autovireur est placé le plus près possible de l'essieu tridem. Il semble préférable de choisir un centre de gravité d'essieu autovireur le plus bas possible. Une élévation du centre de gravité réduit l'angle d'autovirage dans un virage, mais sollicite bien davantage la friction requise.

Aucune des configurations « favorables à l'infrastructure » éventuelles n'a satisfait à toutes les normes de performance. La configuration 13S13 a presque satisfait aux normes de performance. Les spécifications de tracteurs pour cette configuration devraient être compatibles avec celles des autres provinces.

La configuration 12S113 a presque satisfait aux normes de performance lorsqu'elle est installée avec un écartement de l'essieu tridem de 3,05 m (120 pouces), et que les deux essieux autovireurs sont presque aussi près l'un de l'autre et de l'essieu tridem que possible. L'essieu autovireur le plus en avant doit avoir près de 25 degrés d'angle de virage et les essieux autovireurs devraient avoir un centre de gravité bas. Les essieux autovireurs n'ont apparemment pas besoin d'être verrouillés à vitesse élevée. La configuration 12S131 a éprouvé des difficultés avec son large porte-à-faux arrière effectif; par conséquent, l'essieu tridem doit être situé à l'arrière du centre entre les deux essieux autovireurs. Il devrait être placé avec les essieux autovireurs présentant un centre de gravité bas. Ces essieux autovireurs devraient avoir au moins 20 degrés d'angle de virage. L'essieu autovireur le plus en arrière devrait verrouiller automatiquement à vitesse élevée. Les configurations 12S114 et 12S141 sont semblables aux configurations 12S113 et 12S131 respectivement, mais sont plus difficiles à configurer, ont une charge utile inférieure en Ontario et ne sont pas permises au Michigan. Elles ne présentent aucun avantage de prime abord par rapport aux configurations de semi-remorque à cinq essieux. L'essieu poussé de la configuration 112S13 pose des problèmes particuliers. Bien que la performance de cette configuration ne soit pas mauvaise, elle a besoin d'être améliorée pour déterminer le contrôle de charge de l'essieu poussé.

L'exigence d'égalisation de charge augmente l'écartement d'essieux, comparativement à certaines configurations actuelles, et les exigences en matière d'essieux autovireurs limitent l'espacement entre ces essieux. Il est également probable que la charge utile permise sera beaucoup plus proche de la somme du poids de charge des essieux permis pour les véhicules sur le marché, ce qui réduira la souplesse de placer une charge sur la semi-remorque sans dépasser aucun poids de charge permis pour un groupe d'essieux. Les configurations actuelles 12S114 et 12S141 se sont avérées être des choix souples pour les configurations actuelles 12S113 et 12S131 en tant que compromis pour les opérations au Michigan. Les compromis des configurations éventuelles nécessiteront un total de sept essieux sur les semi-remorques, ce qui les rendra plus compliquées et tendra à réduire leur charge utile, comparativement aux véhicules actuels.

Aucune exigence particulière au-delà de celles déjà en vigueur pour les essieux autovireurs à quatre roues ne semble nécessaire aux configurations 12S113 ou 12S114. Les configurations 12S131 et 12S141 exigent que l'essieu autovireur arrière soit verrouillé à vitesse élevée. Cette exigence peut outrepasser le mandat conféré par la *Loi sur la sécurité des véhicules automobiles*, mais devrait faire l'objet d'un règlement de l'Ontario, par une pratique recommandée par l'industrie ou par ces deux moyens réunis. Un tracteur à transmission par essieu tridem doit faire l'objet de spécifications compatibles avec celles des autres provinces, et tout particulièrement de l'Alberta et de la Colombie-Britannique. Un tracteur avec un essieu poussé autovireur ne devrait pas égaliser les charges par essieu avec la transmission par essieu tandem. La manière dont la charge sur l'essieu poussé devrait être contrôlée doit faire partie de la prochaine étape du programme de modernisation des poids et dimensions du MTO.

Les recherches et les essais antérieurs n'ont déterminé aucun danger découlant d'un essieu autovireur en position inférieure. Toutefois, un essieu autovireur comme l'essieu à l'arrière peut causer des problèmes graves d'instabilité qui sont résolus dans ce cas en s'assurant que tout essieu de cette sorte est verrouillé à vitesse élevée.

Un nombre restreint de transporteurs réussit à faire rouler des véhicules avec des essieux autovireurs pendant longtemps, et chacun d'eux a travaillé avec les fabricants d'essieux et de remorques afin de déterminer une combinaison d'essieux, de suspensions, de pneus et d'adapter ce travail à leur application, en maintenant des coûts d'entretien raisonnables. Un nombre beaucoup plus grand de transporteurs ont commencé dernièrement à faire rouler leurs véhicules avec des essieux autovireurs respectant les exigences des règlements de l'Ontario et du Québec. Ils ont certainement profité de l'expérience des pionniers, et plusieurs rapports dressent un bilan satisfaisant de l'expérience, peut-être après avoir compris qu'il est nécessaire de lubrifier les parties amovibles et d'entretenir l'alignement des essieux. Toutefois, ces transporteurs ont une plus vaste gamme d'applications, et font état d'ennuis comme l'usure excessive des pneus, l'insuffisance de l'angle d'essieu et un espace de dégagement d'essieu relevable inadéquat. Ces questions sont résolues petit à petit par une meilleure compréhension des besoins d'opération et d'entretien. Les transporteurs du Québec se montrent légèrement plus préoccupés que les transporteurs de l'Ontario. Les conducteurs rapportent en général que l'essieu autovireur rend plus facile la prise en main du véhicule. Sortir le levier de contrôle de la cabine n'est pas une solution aux yeux de plusieurs conducteurs. Certains cas, comme grimper des collines sur des routes très glissantes, prendre des virages serrés à faible vitesse, où l'essieu autovireur se trouve en bas, justifient la présence du levier de contrôle dans la cabine, munis de verrous internes convenables.

Les configurations éventuelles exigeront plus de 20 degrés de direction habituellement fixés aux essieux autovireurs à quatre roues. Au moins un essieu autovireur disponible doit fournir 25 degrés de direction et au moins un de plus est en cours d'élaboration. On pourrait gagner un degré ou deux de direction par des adaptations mineures aux concepts actuels. Vouloir gagner davantage en matière de direction exige de nouveaux composantes qui seraient plus coûteuses.

Les essieux autovireurs sont toujours un travail en pleine évolution. Les fabricants et les transporteurs apprennent graduellement la manière de faire leur travail en fonction d'une vaste gamme d'applications, et ils en prouvent le rendement et la fiabilité quand les véhicules roulent au mieux de leurs capacités. Certaines applications, comme les camions à trémie et les grumiers ne sont pas encore adaptables aux configurations actuelles avec essieu autovireur. Certains transporteurs attendent que les facteurs inconnus trouvent de meilleures solutions. Selon le point de vue, la prochaine étape des deux essieux autovireurs ne devraient pas causer de problèmes ni s'avérer prématurée.

La question d'un dispositif de transmission supplémentaire d'un quatrième essieu sur le bloc-moteur ne peut être considérée isolément du poids supplémentaire qu'elle occasionnerait. Si un dispositif de transmission plus important est nécessaire, alors un tracteur 6 x 6 peut le fournir. Une transmission à essieu tridem fournit une traction plus cohérente que d'ajuster soit un essieu poussé relevable ou un essieu traîné relevable à une transmission à essieu tandem. Peu importe l'arrangement de transmission choisi, la transmission optimale exige le verrouillage de tous les essieux et des différentiels interponts, afin d'éliminer le patinage. Toutefois, le verrouillage des différentiels réduit beaucoup la capacité d'un véhicule d'effectuer un virage. Les choix sont les différentiels restreints et le système d'antipatinage à l'accélération.

Les semi-remorques à essieux autovireurs à quatre roues ont une meilleure transmission que les trains doubles de type B à 8 essieux qui n'ont pas d'essieux relevables. Si la semi-remorque à essieux autovireurs à quatre roues a des problèmes de transmission, alors le train double de type B devrait présenter encore plus de problèmes de transmission graves. Les semi-remorques éventuelles, objets du présent document, devraient avoir des dispositifs de transmission très semblables aux trains doubles de type B à 8 essieux. Si ces trains doubles de type B peuvent rouler de façon satisfaisante dans des conditions glissantes, alors les tracteurs semi-remorques devraient également être capables de fonctionner dans les mêmes conditions sans relever aucun essieu. On a proposé que le conducteur d'un tracteur tirant une semi-remorque à essieux autovireurs à quatre roues doive être capable de relever l'essieu autovireur de la cabine si nécessaire pour continuer à progresser dans des conditions glissantes. Si ce conducteur conduit de la même manière que le conducteur d'un train double de type B, alors on suppose que la transmission ne sera pas un problème. Si cela se produit, il existe d'autres choix. Une transmission à essieu tridem, un essieu frontal directeur ou un système d'antipatinage à l'accélération muni d'un système de freinage antiblocage rendent tous inutile le besoin d'une transmission supplémentaire, sans le besoin de surélever tout essieu relevable. Un système d'antipatinage fonctionne mieux s'il est accompagné d'un système de freinage antiblocage avec un capteur de vitesse et de modulation pour chaque roue du tracteur.

Un programme d'essais devrait démontrer les effets des essieux autovireurs sur la performance dynamique des véhicules. Il permettra de valider les simulations par rapport aux résultats des tests et de démontrer la performance dynamique « normale » ou « extrême » des configurations de véhicules sur le marché ou en préparation. Les semi-remorques à essieux autovireurs à quatre roues montrent peu de différence dans leur réaction, qu'elles soient tirées par un tracteur à trois ou quatre essieux; il n'est donc pas vraiment nécessaire de les tester. Les configurations 12S113 et 12S131 devraient subir des tests, qui exigeront qu'on installe des stabilisateurs sur la semi-remorque de façon à prévenir le capotage et des câbles pour empêcher la mise en porte-feuille entre le tracteur et la semi-remorque afin de prévenir la mise en porte-feuille. Il serait souhaitable, bien que pas nécessaire, d'avoir une suspension égalisant la charge sur chaque semi-remorque, de façon à ce qu'il soit possible d'utiliser des semi-remorques actuelles munies d'une suspension à ressorts à lames d'acier sur l'essieu tridem et d'une suspension pneumatique sur les essieux autovireurs relevables. Peu importe la semi-remorque utilisée, les essieux autovireurs devrait être adaptés avec une supervision manuelle à un dispositif de verrouillage automatique, et avec un dispositif qui permet d'ajuster la rigidité du centrage d'autovirage.

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1. INTRODUCTION

1.1 Background

Ontario began regulating axle group and gross weights by bridge formula in 1970, which included a substantial increase in the maximum allowable gross weight, to 63,500 kg (140,000 lb). A wide variety of new vehicles quickly emerged to take advantage of the freedom offered by the new rules. Many of these vehicles had widely spaced axles, some of which were liftable axles which had to be raised so that the vehicle could turn at an intersection. The provinces began a program to establish greater uniformity in vehicle weights and dimensions in the late 1970's, and the first round dealt principally with bridge issues. After some bridge and highway strengthening, principally in western Canada, most provinces had gross weights in the range 53,500-56,500 kg (118,000-124,500 lb), though the vehicles used were still quite different between provinces. The provinces were not prepared to consider any further weight increases without dealing with vehicle issues, because other provinces did not want most of the vehicle configurations used for heavy haul in Ontario. The CCMTA/RTAC Vehicle Weights and Dimensions Study assessed the dynamic performance of trailers and the pavement effects of tridem axle groups. This landmark study proposed the first set of objective standards for the dynamic performance of heavy vehicles [1], and these served as the basis for the vehicle configuration and weight and dimension limits defined in the national Memorandum of Understanding on Vehicle Weights and Dimensions ("the M.o.U.") [2]. The M.o.U. was initially signed in 1988, and defined the most common configurations used in inter-provincial commerce. It was subsequently amended in 1991, to add straight trucks and truck-trailer combinations, and has since been amended twice to refine details.

The four western provinces immediately adopted the M.o.U. as the basis for their regulations. However, Ontario maintained its prior semitrailer length of 14.65 m (48 ft) and overall length limit of 23 m (75 ft 6 in) until 1994, when Regulation 32/94 allowed the respective M.o.U. standards of 16.2 m (53 ft) and 25 m (82 ft). Québec and the Atlantic provinces were then able to bring their regulations more closely in line with the M.o.U.

Québec had been allowing 4- and 5-axle semitrailers of Ontario configuration to operate into that province at Ontario weights by special permit. Administration of the permit program became increasingly onerous, and when Québec reviewed the implications of the M.o.U., it found the weights allowed on these vehicles were somewhat above the capacity of their bridges, and substantially above that when liftable axles were raised. Consequently, in 1991 Québec:

- Cancelled the permit program;
- Defined quad-axle groups B.44 and B.45 in regulation at an allowable axle group weight of 32,000 kg (70,547 lb);
- Restricted all other groups of four or more axles to 30,000 kg (66,138 lb); and
- Reduced the weight allowed on a tri-axle to 26,000 kg (57,320 lb), though the 2.44-2.44 m (96-96 in) spread tri-axle was overlooked.

This quickly established the so-called “Québec quad” as the principal semitrailer for heavy haul between Québec and Ontario. Other multi-axle semitrailer configurations essentially disappeared from this market.

A series of discussions between Ontario, Québec and the Atlantic provinces in 1995 attempted to harmonize their weight and dimension regulations for common configurations beyond the scope of the M.o.U., but the effort failed, and the provinces continued to act independently. Québec reduced the allowable weight on all tri-axles to 18,000 kg (39,683 lb), though vehicles built before 1 November 1998 are still allowed 26,000 kg (57,319 lb) until 31 December 2009. It also required that the axle loads equalize between the four axles of a quad-axle group, and that the single axle should be self-steering, from 1 January 2003. The Atlantic provinces developed an agreement to harmonize their regulations, which became effective 10 October 2002 [3]. Ontario Ministry of Transportation (MTO) conducted two significant studies on the impacts of various regulatory scenarios, one on pavements and bridges [4], and the other on the economic implications for carriers and shippers [5]. This work allowed MTO to identify the risks and costs associated with continued operation of vehicles with liftable axles. MTO concluded it needed to constrain use of uncontrolled liftable axles, and developed a four-phase program of vehicle weight and dimension reforms to address this. Phase 1, implemented on 1 January 2001, had the following features:

- A “single semitrailer” was defined as a semitrailer towed by a tractor, so excludes all double trailer combinations, and truck-trailer combinations.
- The self-steer tri-axle semitrailer and self-steer quad semitrailer were introduced, with specific weight and dimension specifications and certain equipment and operational requirements.
- The concept of an “infrastructure-friendly” vehicle was introduced, to include a single semitrailer that is:
    - operating on a single axle;
    - operating on a tandem axle;
    - operating on a tridem axle;
    - a self-steer triaxle semitrailer; or
    - a self-steer quad semitrailer.
- The following allowable axle group weights were increased, effective immediately:
    - 18,000 kg (39,682 lb) on a tandem axle with a spread from 1.2 to 1.6 m (47 to 63 in) if the tandem axle is the drive tandem of a 3-axle tractor, or on a single semitrailer with no other axles deployed, or on a self-steer tri-axle semitrailer; and
    - 25,500 kg (56,217 lb) on a tridem axle with a spread from 3.6 to 3.7 m (142 to 146 in) on a single semitrailer with no other axles deployed, or on a self-steer quad semitrailer.
- The following allowable axle group weights were increased, effective 1 January 2006:
    - 24,000 kg (52,910 lb) on a tridem axle with a spread from 3.0 to 3.6 m (118 to 142 in) if the tridem axle is on a single semitrailer with no other axles deployed; and
    - 26,000 kg (57,319 lb) on a tridem axle with a spread from 3.6 to 3.7 m (142 to

146 in) if the tridem axle is on a single semitrailer with no other axles deployed.

- The allowable gross weight will be reduced by 3,000 kg (6,613 lb) for any 3-axle single semitrailer not fitted with a tridem axle or a self-steer tri-axle that is not a specialized tank or end dump semitrailer, effective 1 January 2006.
- The allowable gross weight will be reduced by 4,500 kg (9,921 lb) for any 3-axle single semitrailer that is not fitted with a tridem axle or a self-steer tri-axle, or is not an end dump semitrailer, effective 1 January 2011, and this weight reduction will also apply to any tank semitrailer, effective 1 January 2021.
- An additional fine was introduced if the setting of a liftable axle contributes to an overweight infraction.
- The minister was given limited authority to issue a Special Vehicle Configuration Permit for a vehicle not in compliance with provisions of the Act and regulations. Previously, permits were only available for specialized vehicles or indivisible loads that were oversize or overweight. A Special Vehicle Configuration Permit is generally only available for a vehicle that meets specified standards for dynamic performance, and where there is a clear economic benefit to the province. The vehicle may carry a divisible load.
- An agreement was concluded with Québec that provided equal treatment of various types of quad-axle semitrailer at lengths of 14.65, 15.5 and 16.2 m (48 ft, 50 ft 10 in and 53 ft) in both provinces, under regulation or by permit.

Phase 2, implemented on 1 July 2002, addressed end dump and open-top hopper dump semitrailers as follows:

- The list of vehicles exempted from the Phase 1 triaxle gross weight reductions was expanded to include open-top hopper dump semi-trailers.
- The allowable gross weight of an end dump or open-top hopper dump semitrailer built from 1 January 2003 was reduced by 4,500 kg (9,920 lb) if the semitrailer was not an "infrastructure friendly" configuration, or 9,000 kg (19,841 lb) if the semitrailer had two or more liftable axles.
- The allowable gross weight of an end dump or open-top hopper dump semitrailer built prior to 2003 will be reduced by 4,500 kg (9,920 lb) on 1 January 2011, or 9,000 kg (19,841 lb) if the semitrailer has two or more liftable axles. An end dump semitrailer built from 1996 through 2002, and an open-top hopper dump semitrailer built from 1991 through 2002, will be eligible for a special permit exempting it from this reduction until it reaches an age of 15 or 20 years, respectively.
- The special method of calculating allowable gross weight and the 1,500 kg (3,307 lb) gross weight reduction was eliminated for "infrastructure-friendly" aggregate vehicles, but continues to apply to all other aggregate vehicles, including those subject to the allowable gross weight reductions given above.

Phase 1 allows a self-steer quad semitrailer, but does not require it to the exclusion of other 4-axle configurations, though it is required by Québec if the semitrailer was built after 1 January 2003. Phase 2 effectively restricts the configuration of an end dump or open-top hopper dump semitrailer built after 1 January 2003 to a tridem, self-steer tri-axle or self-steer quad semitrailer. Because no 5-axle “infrastructure-friendly” semitrailers have been defined yet, industry cannot build this class of vehicle for end dump or open-top hopper dump applications, though such vehicles can still be built in other body styles for other applications. Phase 3 addresses semitrailers with more than four axles, so will remove this restriction. It also addresses double trailer combinations. Phase 4 will address straight trucks, truck-trailer combinations, and tractors with more than three axles, subsequent to implementation of Phase 3.

1.2 Issues

MTO has embarked on a program to phase out use of liftable axles by heavy trucks that operate within Ontario. Phases 1 and 2 of this program have addressed tri-axle and quad-axle semitrailers, and end- and open-top hopper-dump semitrailers, by allowing self-steer tri-axle and self-steer quad axle groups, where a single self-steering axle is placed ahead of a fixed tandem or tridem axle group, cannot be lifted from the cab, and each axle carries an equal load. MTO was able to introduce the legislative and regulatory changes to implement Phases 1 and 2 based on existing research, including the CCMTA/RTAC Vehicle Weights and Dimensions Study [1], major MTO studies completed in 1996 and 1997 [4], [5], in-house research and analysis, and extensive consultations with stakeholders.

Phase 3 addresses multi-axle semitrailers and double trailer combinations. It is likely that many of the semitrailers will require two self-steering axles if they are to come close to meeting customary standards for dynamic performance. However, these vehicles will be more complicated than existing vehicles, which introduces the possibility of modes of instability that may not occur for existing vehicles with similar axle arrangements. A comprehensive and thorough analysis will be required to ensure that any new multi-axle semitrailer configurations that MTO will define in regulation will be at least as safe as the vehicles they replace. MTO is undertaking this work to develop suitable “infrastructure-friendly” multi-axle semitrailers in cooperation with the Canadian Transportation Equipment Association (CTEA), whose members build the vehicles, and Transport Canada.

1.3 Objectives

The objectives of this work are to define “infrastructure-friendly” vehicle configurations, equipment and operational requirements so that:

- The vehicles are at least as safe as the vehicles they will replace;
- The vehicles are at least as productive as the vehicles they will replace;
- Configurations are compatible with the regulations and weight of neighboring jurisdictions; and
- The process is well documented and transparent to stakeholders.

1.4 Scope

Phase 3 addresses multi-axle tractor-semitrailers and double trailer combinations. It is envisaged that it will proceed in four stages:

1. Preliminary assessments of:
    a. Impact of proposed vehicles on roads and bridges;
    b. Self-steering axle technology, application and experience; and
    c. Vehicle dynamic performance by computer simulation;
2. Full-scale testing to:
    a. Validate computer simulations; and
    b. Demonstrate vehicle dynamic performance characteristics;
3. Stakeholder consultation; and
4. Regulatory development.

This work addresses tractor-semitrailers for items 1 b and 1 c above. It must produce specific recommendations that allow stages 2, 3 and 4 to follow. It does not address double trailer combinations, as it is believed that the existing Ontario Regulation 32/94 already provides the required “infrastructure-friendly” vehicle options.

1.5 Approach

The multi-axle semitrailers were assessed by computer simulation to determine the dynamic performance of:

- Existing configurations with rigid liftable axles;
- The self-steer quad semitrailer, a baseline “infrastructure-friendly” configuration; and
- Candidate “infrastructure-friendly” configurations using self-steering axles rather than rigid liftable axles.

These were supported by assessments of:

- Self-steering axle technology;
- Drive options for four-axle tractors;
- The need for a cab lift control on “infrastructure-friendly” configurations;
- The need for regulatory principles for “infrastructure-friendly” multi-axle semitrailers; and
- The need for a full-scale test program for “infrastructure-friendly” multi-axle semitrailers.

This report presents the findings of the computer simulations and assessments.

2. ASSESSMENT OF DYNAMIC PERFORMANCE

2.1 Approach

This work used the same approach to assess vehicle dynamic performance as the CCMTA/RTAC Vehicle Weights and Dimensions Study [6], [7]. This approach has served as the basis for all new vehicle weight and dimension regulations since 1985, and for evaluation of many special permit applications, for all provinces.

A performance measure is some response of a system to a standardized input. The input is standardized so that responses of different systems can be compared to each other. The performance standard is the criterion or boundary between satisfactory and unsatisfactory performance. Evaluating vehicle performance consists of three steps:

1. Subject the vehicle to a standardized input;
2. Evaluate the performance measure; then
3. Compare the performance measure to the performance standard.

The evaluation process requires standardized inputs, performance measures and performance standards to be defined in a consistent and coherent manner.

This work examines vehicles at "normal" and "ultimate" performance levels. The "normal" performance level is designed to keep a vehicle upright on its wheels and within its customary space envelope on the highway. This is the procedure that evolved from the CCMTA/RTAC Vehicle Weights and Dimensions Study. The "ultimate" performance level is a new concept, used here for the first time. It evaluates a vehicle in a very aggressive manoeuvre at a lateral acceleration close to its rollover threshold, and allows the vehicle to intrude on the space of other vehicles. It is intended to assess the ultimate lateral/directional response of a new vehicle, to determine whether it has potential crash characteristics that differ from those of existing vehicles of similar configuration.

2.2 "Normal" Performance

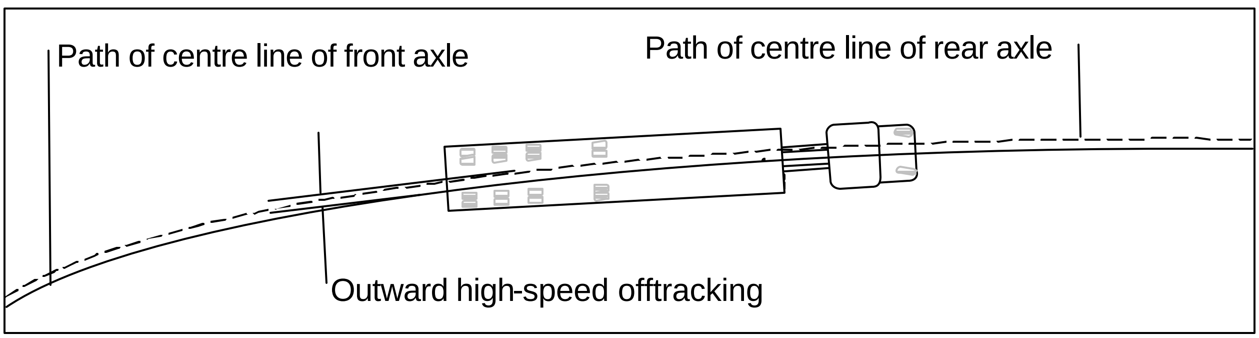
The "normal" performance was assessed using the so-called "RTAC" performance measures, developed during the CCMTA/RTAC Vehicle Weights and Dimensions Study [1], [6]. These are also consistent with performance measures proposed for vehicles that might operate North America-wide under possible future provisions of the North American Free Trade Agreement [8]. This study principally examined the dynamic performance of trailers, so these performance measures were primarily aimed at characterizing the performance of the trailer within the whole vehicle. The RTAC performance measures were supplemented with others that address particular aspects of the tractor-semitrailers that were the subject of this work. The proposed "normal" performance measures were all determined by computer simulation using five manoeuvres that produce all the required responses to compute the performance measures.

A high-speed turn, made at 100 km/h (62.1 mi/h) on a high-friction surface, was used to evaluate the high-speed offtracking and static rollover performance measures. The turn starts with a short tangent segment, and is followed by a spiral entry to a curve of radius 393.3 m (1290.3 ft), which corresponds to a lateral acceleration of 0.2 g. This curve is held until 15 s into the run, to allow steady state offtracking to be achieved, and then steering wheel angle is increased at a steady rate of 2 deg/s until rollover occurs. The performance measures are:

- **Static Rollover Threshold**, which is the lateral acceleration, in g, at which a vehicle just rolls over in a steady turn. This measure is known to correlate well with the incidence of single vehicle truck rollover accidents in highway service. The static rollover threshold desirably should not be less than 0.4 g.

- **High-Speed Offtracking**, which is the lateral offset between the path of the steer axle of the tractor and the path of the last axle of the vehicle in a steady turn of 0.2 g lateral acceleration, as shown in Figure 1. Since the driver guides the tractor along a desired path, there is a clear safety hazard if the trailer tires follow a more outboard path that might intersect a curb or other roadside obstacle, or intrude into an adjacent lane of traffic. High-speed offtracking should not exceed 0.46 m (18 in) outboard of the path of the tractor. This is a particularly significant performance measure for a long semitrailer equipped with self-steering axles.

Figure 1: High-speed Turn

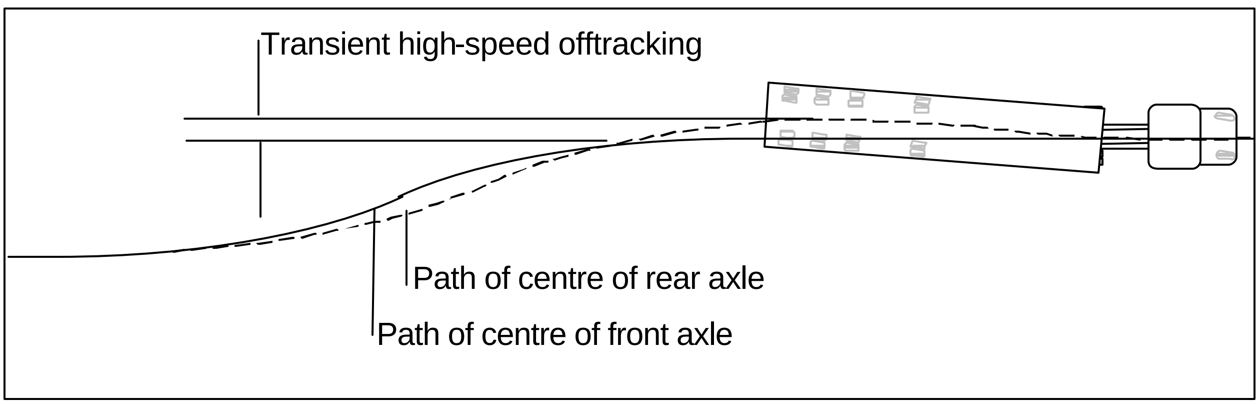


A high-speed lane change, made at 100 km/h (62.1 mi/h) on a high-friction surface, was used to evaluate the load transfer ratio and transient high-speed offtracking performance measures. The path was a side-step of 2.11 m (6.92 ft), which corresponds to a single cycle sinusoidal lateral acceleration of 0.15 g with a period of 3.0 s at the tractor front axle, and represents the manoeuvre made to avoid an obstacle in the path of the vehicle [9]. This manoeuvre is sufficiently gentle that it does not cause the rearmost trailer of a multi-trailer combination to roll over. The period corresponds to that at which the greatest response occurred for most trucks in the simulations for the CCMTA/RTAC Vehicle Weights and Dimensions Study [6], but is not necessarily the period at which greatest response would actually occur for any particular vehicle. The two performance measures are not particularly strongly dependent upon steer period for tractor-semitrailers, whereas they usually are for multi-trailer combinations. The performance measures are:

- **Load Transfer Ratio**, which is the fractional change in load between left- and right-hand side tires of the vehicle in an obstacle avoidance manoeuvre. It indicates how close the vehicle came to lifting off all of the tires on one side, a precursor to rollover. The load transfer ratio should not exceed 0.6, which is equivalent to an 80%-20% left-right division of wheel loads.

- **Transient High-Speed Offtracking**, which is the peak overshoot in the lateral position of the rearmost trailer axle from the path of the tractor front axle in an obstacle avoidance manoeuvre, as shown in Figure 2. It is an indication of potential for side-swipe of a vehicle in an adjacent lane, or for impact-induced rollover due to a curb strike. This measure quantifies the "tail-wagging" response to a rapid steer input. The transient high-speed offtracking should not exceed 0.8 m (31.5 in).

Figure 2: High-speed Lane Change

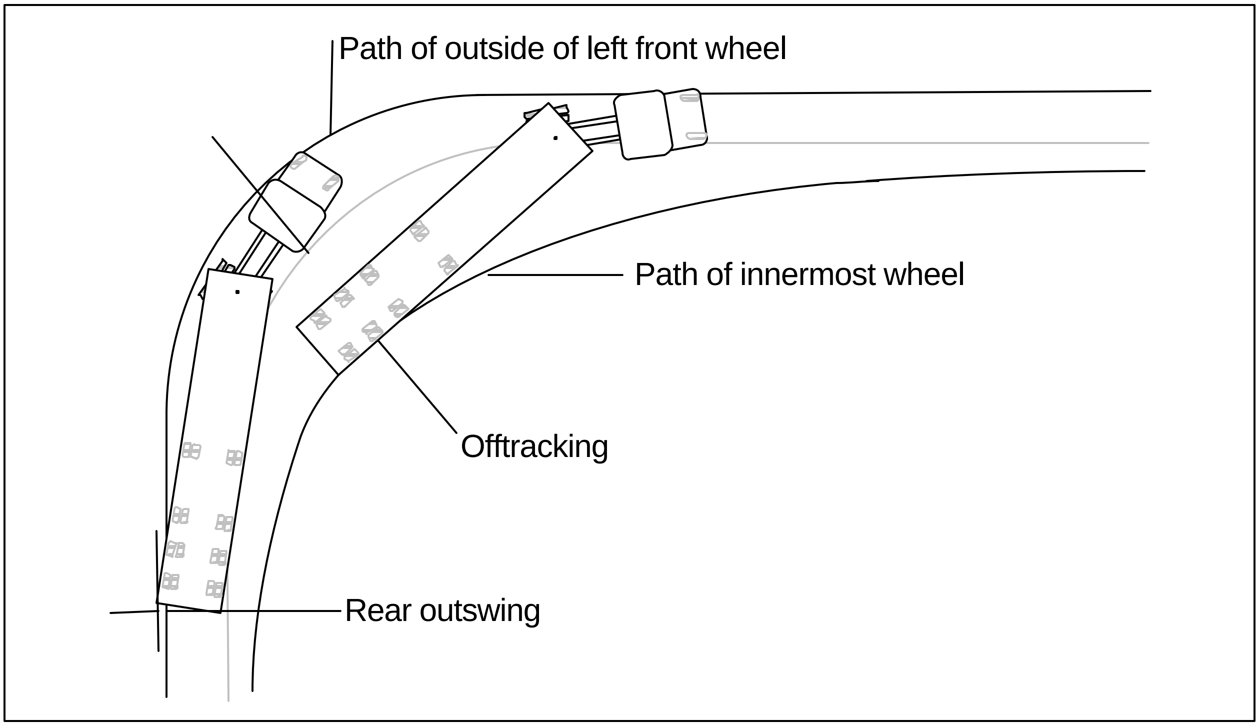


A low-speed 90 degree right-hand turn, made at a speed of 8.8 km/h (5.5 mi/h) on a high-friction surface, was used to evaluate the low-speed offtracking, rear outswing, friction demand and lateral friction utilization performance measures. The simulations for the CCMTA/RTAC Vehicle Weights and Dimensions Study used a turn radius of 10.97 m (36 ft) at the outside of the left front wheel of the power unit [6]. However, not all long wheelbase power units can turn so tightly, and a vehicle can only be evaluated in a turn that it can make. Some previous studies have used a turn radius of 14 m (46 ft) at the outside of the left front wheel of the power unit, because that is the turn radius that MTO used to establish the geometry of the two-centred compound circular curves used for the curb line of open throat intersections. This radius has recently also been recommended as the basis for assessment of vehicle configurations to be agreed under provisions of the North American free Trade Agreement (NAFTA) [8]. It is proposed to use this turn radius to evaluate the performance measures.

The performance measures are:

- **Low-Speed Offtracking**, which is the extent of inboard offtracking of the rearmost trailer from the tractor front axle in a 90 degree right-hand turn at a typical intersection, as shown in Figure 3. This property is of concern to the "fit" of the vehicle on the road system, and has implications for safety as well as abuse of roadside appurtenances. The low-speed offtracking performance standard of 6 m (19.7 ft) for a turn with 11 m (36 ft) radius at the tractor left front wheel [1] is not practical for a vehicle which cannot turn so tightly, which includes tractors addressed by this study. It is more practical to ensure that the offtracking of another vehicle is no greater than that of the configuration with the greatest offtracking allowed by the M.o.U., which is a tractor with 6.20 m (244 in) wheelbase towing a semitrailer with 12.50 m (41 ft) wheelbase, in a turn that both vehicles can make. The NAFTA proposal sets the low-speed offtracking at 5.60 m (18.4 ft) in a turn of 14.00 m (46 ft) radius [8], based on the turning performance of this vehicle. Low-speed offtracking is not expected to be critical for the candidate vehicles.

Figure 3: Low-speed Right-hand Turn



- **Rear Outswing**, which is the extent of intrusion of any left-hand side corner of the vehicle into the lane to the left of that occupied by the vehicle as it makes a right-hand turn, as shown in Figure 3. The left rear corner especially becomes a potential obstacle to another vehicle traveling in that lane, and offers the possibility of a high-speed collision. Rear outswing should be less than 0.20 m (8 in). It is a particular issue for semitrailers with a long effective rear overhang.

- **Friction Demand in a Tight Turn**, which is a measure of the resistance of multiple axles to travel around a tight-radius turn, such as at an intersection. It results in a "demand" for tire side force at the tractor's drive axles. When the pavement friction level is low, a vehicle whose friction demand exceeds that which is available will produce a jackknife-type response of the tractor. The friction demand measure describes the minimum tire-pavement friction necessary for the vehicle to negotiate an intersection turn without suffering such loss of control. The friction demand should be less than 0.1. It is expected to be a significant issue for the candidate vehicles.

A low-speed 90 degree right-hand turn, made at a speed of 8.8 km/h (5.5 mi/h) on a low-friction surface, was used to evaluate the lateral friction utilization performance measure for a turn radius of 14.00 m (46 ft) at the outside of the left front wheel of the power unit. The performance measure is:

- **Lateral Friction Utilization**, which is a measure of the effort required by the steer axle to turn the vehicle. It results in a "demand" for tire side force at the tractor's front axle, and this must be comfortably within the friction available from the tire-pavement interface for the vehicle to be able to turn. If the lateral friction utilization reaches 1.0, the limit of control has been reached and the tractor will tend to plough out of the turn. Lateral friction utilization should not exceed 0.8. This performance measure is particularly significant for tridem drive tractors [10].

A low-speed 90 degree right-hand turn, made at a speed of 8.8 km/h (5.5 mi/h) on a high-friction surface, was used to evaluate the maximum self-steer angle of a self-steering axle for a turn radius of 12 m (39.4 ft) at the outside of the left front wheel of the power unit. This is close to the minimum turning radius of many of the tractors that are likely to be used with the semitrailers that are the subject of this study. The amount of steer required from a self-steering axle increases as the self-steering axle moves further away from the turn centre of a semitrailer, as the turn radius decreases, and as the turn angle increases. There is no limit on amount of steer required by such an axle, because it is always possible for the tractor to get to an articulation angle of 90 deg, when it simply pulls the semitrailer sideways. However, such manoeuvres generally take place in a yard, when self-steering axles may be lifted. The performance measure is:

- **Maximum Self-steer Angle**, for a vehicle with one or more self-steering axles, is the maximum self-steer angle that is required during a low-speed turn at an intersection. The maximum self-steer angle should not exceed the maximum wheel cut provided by the self-steering axle. Ontario Regulation 597 requires 20 deg wheel cut for a self-steer axle fitted to a self-steer tri-axle or self-steer quad semitrailer. This performance measure is only significant for a vehicle fitted with a self-steering axle.

2.3 Other Performance Measures

Braking efficiency was one of the original RTAC performance measures, which assessed how effectively the braking system could use available tire-road friction to stop a vehicle. An antilock brake system (ABS) has been required on tractors since 1997, and on trailers since 1998. An ABS automatically ensures the braking efficiency performance standard should be met over a much wider range of road and load conditions than the original RTAC performance measure. This performance measure is therefore no longer relevant, and was not evaluated.

Australia is considering introducing a parallel system of regulation that would qualify vehicles based on compliance with a comprehensive set of performance standards, rather than to conventional prescriptive weight and dimension standards. The current proposal has 20 performance measures, listed in Table 1 [11]. These performance measures are the survivors from an initial list of over 100 candidates, culled by a thorough process of rigorous analysis.

Six performance measures are related to the longitudinal performance of vehicles. There are no differences expected between candidate vehicles and existing vehicles in this regard, so there would be no need to consider any of these six performance measures. The issue of drive traction on slippery road surfaces is discussed in Chapter 9.

Four performance measures are related to the low-speed directional performance of vehicles. Low-speed offtracking, tail swing and steer tire friction demand are included above, but frontal swing is not included. This was excluded as a performance measure in the CCMTA/RTAC Vehicle Weights and Dimensions Study, because it was not an evident safety issue. There are also no differences expected between the frontal swing of candidate vehicles and existing vehicles, so again this does not need to be considered.

Six performance measures are related to the high-speed directional performance of vehicles. The static rollover threshold and high-speed transient offtracking are included above. Rearward amplification is included as a surrogate for load transfer ratio, because it can be measured in a test following a standard procedure [9]. The yaw damping coefficient is the rate of decay of trailer oscillation after a sinusoidal steer. It is an issue for combinations with two or more articulation points, but is not a significant issue for tractor-semitrailers. Handling performance is clearly a safety issue, but it is not clear how it affects safety performance on the highway. In most cases, if a driver gets into a region where the handling is so degraded that the driver has difficulty controlling the vehicle, then it is likely that the driver would be going to crash anyway. Braking stability in a turn is automatically addressed when a vehicle is fitted with ABS. Tractors have been fitted with ABS since 1997, and trailers since 1998.

Four performance measures are related to the infrastructure, and are beyond the scope of this report. The gross (or payload) weight per standard axle repetition is a measure of the productivity of the roadway, and may be of interest to MTO in other parts of its assessment. Horizontal tire force is a surrogate for friction demand, which is effectively addressed in Australia by a prescriptive restriction on semitrailer axle spread. Tire contact pressure is extremely difficult to deal with, and there would be no difference in this regard between candidate vehicles and existing vehicles, so this also does not need to be considered.

Table 1: Performance Standards Proposed for Australia

Low Speed Longitudinal Performance	
1	Startability
2	Gradability
3	Acceleration Capability
High Speed Longitudinal Performance	
4	Overtaking Time
5	Tracking Ability on a Straight Path
6	Ride Quality (Driver Comfort)
Low Speed Directional Performance	
7	Low-Speed Offtracking
8	Frontal Swing
9	Tail Swing
10	Steer Tire Friction Demand
High Speed Directional Performance	
11	Static Rollover Threshold
12	Rearward Amplification
13	High-Speed Transient Offtracking
14	Yaw Damping Coefficient
15	Handling (Understeer/Oversteer)
16	Braking Stability in a Turn
Infrastructure Performance	
17	Gross Weight per Standard Axle Repetition
18	Horizontal Tire Force
19	Tire Contact Pressure Distribution
20	Maximum Effect Relative to Reference Vehicle

Maximum effect relative to reference vehicle is the Australian method for assessment of the effect of vehicles on bridges, using a methodology that may be different from, but is likely equivalent to, that used by MTO.

Performance standards have been established for 12 of the vehicle safety performance measures, for each of four different road classes. Overtaking time, ride quality, handling and braking stability in a turn are all on hold at this time, because they are difficult to define or evaluate, or because it is difficult to define in an objective fashion how they relate to road safety.

High-speed offtracking and friction demand are performance measures used for this work that did not survive in Australia. High-speed offtracking survived the original culling stages, but has now been dropped, possibly because Australia has a limited freeway network, and this measure is most critical on freeway ramps. Friction demand is redundant, because it was allegedly dealt with by a pavement horizontal tire force performance measure. However, a vestigial prescriptive requirement remains, which limits the maximum spread of an axle group to 3.05 m (120 in), and it is this which effectively eliminates friction demand as an issue.

2.4 "Ultimate" performance

When the first C-trains were introduced, the role of the C-dolly self-steering axle in vehicle stability was not well-understood, and the methods of analysis used during the CCMT/RTAC Vehicle Weights and Dimensions Study were not available [6]. Specific characteristics of the C-dolly resulted in types of crash that did not exist for A- or B-trains. After further analysis and testing during the CCMTA/RTAC Vehicle Weights and Dimensions Study [7], [13], it was clear that the properties of the C-dolly governed the dynamic performance of a C-train, and a wide range of performance was possible depending on the type of C-dolly and the steer properties of its self-steering axle [6], [7], [14]. The initial version of the M.o.U. therefore capped the C-train gross weight at 53,500 kg (117,946 lb), pending development of the necessary performance requirements for a C-dolly. This work determined that a C-dolly and its self-steering axle both need very specific properties to ensure the C-train can meet standards for its dynamic performance [15]. This was codified as Canadian Motor Vehicle Safety Standard (CMVSS) 903 [16] and 904 [17]. Once these standards were in place, the M.o.U. was amended to increase the allowable gross weight of a C-train to 58,500 kg (128,969 lb) [2].

It is known that the dynamic performance of vehicles with one self-steering axle in the belly position is not significantly affected by the steer-characteristics of the self-steering axle [6], [18]. However, the candidate vehicles considered here may have two self-steering axles, and in some configurations one of those self-steering axles may be the last axle on the vehicle. It is known that vehicles with a self-steering axle as the rearmost axle may be prone to lateral/directional instability, which could result in a single unit vehicle spinning out, or a semitrailer swinging across the road [19]. It may be possible to configure such a vehicle to meet the "normal" dynamic performance standards, which attempt to keep the vehicle upright and within its space on the highway at lateral accelerations in the range 0.15-0.20 g. However, a more aggressive manoeuvre could still result a type of crash that would not occur in a vehicle with rigid liftable axles. It was therefore considered necessary to assess the modes of instability of the proposed vehicles under more aggressive manoeuvres, in the range 0.25-0.30 g, just below the rollover threshold of such a vehicle carrying a payload with a high centre of gravity.

The "ultimate" performance measures were designed to explore the types of crash that a vehicle might manage to achieve. A vehicle with multiple self-steering axles may have adequate "normal" performance. However, for example, if one of the self-steering axles is the last axle on the semitrailer, it is possible that at the "ultimate" performance level, the trailer may swing substantially more than the equivalent existing configuration that has only rigid liftable axles. This will expose the vehicle with the self-steering axles to potential sideswipe or run-off-road conditions that might not arise for the existing vehicle. It does not matter that the steer inputs necessary to evaluate “ultimate” performance might be expected to result in a crash. The issue is not whether the vehicle will crash, but rather whether it could crash in a manner that is both different and potentially more severe than the vehicles they will replace. “Ultimate” performance need only be evaluated for loaded vehicles. When a vehicle is empty, it operates with its self-steering liftable axles raised, so they do not influence the dynamic performance of the vehicle. The configuration of each candidate vehicle in this condition is likely to be close to the configuration of an existing vehicle, so similar “ultimate” performance would be expected for each. Since the performance of empty candidate vehicles will be essentially the same as for existing vehicles, the candidate vehicles will not introduce any mode of crash that does not already occur for an existing vehicle when empty.

Two performance measures were used to evaluate “ultimate” lateral/directional performance of the vehicles, load transfer ratio and transient offtracking. These were evaluated using a high-speed lane change made at 100 km/h (62.1 mi/h), similar to that used to evaluate the “normal” load transfer ratio and transient high-speed offtracking performance measures, using a path that resulted in a lateral acceleration of 0.30 g, just below the rollover threshold of a vehicle with a high centre of gravity.

The “ultimate” performance measures were a new concept for this study, intended to provide qualitative insights into the relative performance of candidate and existing configurations. For example, if several configurations have similar “normal” performance, but one has distinctly poorer “ultimate” performance, then that one might be expected to have a higher risk or severity of crash. On this basis, that one might be considered a less preferred candidate than other configurations. The limited intent of the “ultimate” performance measures means that it is not necessary to consider performance standards. Indeed, an appropriate basis for setting such standards is not clear at this time.

3. COMPUTER SIMULATIONS

3.1 Simulation Model

The dynamic performance of vehicles has always been evaluated by computer simulation. While it is possible to determine some performance measures in a full-scale test, there is no practical way to measure friction demand or load transfer ratio in a test.

The simulation study was conducted using the Yaw/roll model [19]. The Yaw/roll model is a dynamic simulation of moderate complexity that represents the combined lateral, yaw and roll response of heavy articulated vehicles as a result of either closed or open loop steering input with relatively simple input data. The model can represent vehicle combinations with up to six vehicle units and eleven axles, with up to eight axles on any vehicle unit. Up to five axles (besides the front axle) at any location may be self-steering or forced steering. The model is structured so that any specific limit can easily be changed if necessary. Fifth wheel, turntable, pintle hook, C-dolly and other couplings allow representation of A-, B- and C-train combinations, and others. The non-linear characteristics of tires, suspensions and self-steering axles are represented by lookup tables of input data. The non-linear characteristics of coupling devices are represented directly by the model. The model does not represent longitudinal tire forces needed for drive and brake torque, so is restricted to travel at constant longitudinal velocity on a smooth, level road surface with uniform frictional characteristics. The model operates either in closed loop mode by defining a specific steer input, either at the steering wheel or the steering axle, or in open loop mode, by defining a path that the vehicle should follow and using a driver model to cause the vehicle to follow that path. The steer input is defined in the closed loop mode, and the vehicle does not follow any specific path on the ground, it goes where it wants to, depending on its own dynamic characteristics. Two different vehicles subjected to the same closed loop input may follow quite different paths on the ground. The path to be followed is defined in the open loop mode, and choice of parameters in a driver model determines how closely the specified path is actually followed. These are normally chosen to represent an alert driver so that the vehicle follows the path closely.

The Yaw/roll simulation program had been used extensively in previous simulation studies [7], and has been shown to provide reasonable agreement with test results for a large number of vehicle configurations [14]. The program has subsequently been extended by NRC/CSTT to represent the log truck configurations peculiar to B.C. and Alberta [21], and additional validation has been conducted [22].

The absolute accuracy of a vehicle simulation depends critically both on how well the model represents the vehicle system, and how accurately the component data is known. Previous work has addressed the accuracy of the model [14], [19]. The relative accuracy, for purposes of comparison of similar vehicles, is less dependent upon the accuracy of component data. The simulation can be expected to provide a proper ranking of vehicles in a comparison as long as the data are reasonably representative.

The "normal" performance measures were obtained from the five manoeuvres described in

Chapter 2.2, which were designed to provide the necessary responses. This procedure is completely consistent with that used in the CCMTA/RTAC Vehicle Weights and Dimensions Study and other studies conducted for a variety of purposes, including some supporting applications to MTO for Special Vehicle Configuration Permits.

The “ultimate” performance measures were obtained from the two manoeuvres described in Chapter 2.4, which were designed to provide the necessary responses. This procedure is new, and is intended to assess the potential modes of instability of the vehicles.

In each case, a computer simulation run is made that computes the time history of basic simulation variables, linear and angular displacements, velocities and accelerations, and derived variables like spring forces, tire forces and slip angles. The value of each performance measure is determined by an appropriate algorithm that scans the basic and derived variables to determine the key location for that performance measure, and then computes it. The suspension, tire and self-steering axle models are all non-linear, and the suspension and self-steering axle models both include Coulomb friction elements. These introduce some noise into the time history responses. While the simulation program produces repeatable results for the exact same run, a small change in inputs may produce different noise characteristics depending on exactly where Coulomb friction break points occur during the run. There are large numbers of these break points, which cannot be tracked in any meaningful way. The algorithms used to determine performance measures include some level of smoothing to reduce the influence of noise on the performance measures. While it is certain that the simulation program predicts large differences between performance measures, and trends in performance, quite reliably, it is not certain that small differences between performance measures are necessarily real. This is not inherently a problem in this study, where it is likely that policy decisions will only be justified on the basis of significant differences in performance.

3.2 Tractors

This work used two generic tandem drive tractors, one for Ontario and Ontario-Michigan configurations, and another for pure Michigan configurations. The Ontario tractor has a 6.20 m (244 in) wheelbase, with a 1.52 in (60 in) drive axle spread for existing vehicles, or a 1.42 m (56 in) spread for new vehicles. The Michigan tractor has a 5.28 m (208 in) wheelbase and a 1.37 in (54 in) drive axle spread. Both tractors have a tare weight of 8,164 kg (18,000 lb). The fifth wheel is generally placed 0.20 m (8 in) ahead of the centre of the drive tandem, though its location may be adjusted when necessary to balance the axle weights. The front axle is assumed to weigh 680 kg (1,500 lb), with a rating of 5,443 kg (12,000 lb), and a tare load of 4,536 kg (10,000 lb). Each drive axle is assumed to weigh 1,134 kg (2,500 lb). Moments of inertia for these tractors were generated in the same way as during the CCMTA/RTAC Vehicle Weights and Dimensions Study [6].

The four-axle tractors were specialized vehicles developed specifically for the configurations requiring them, based on the 6.20 m (244 in) wheelbase Ontario tractor described above.

3.3 Semitrailers

This work used a generic 14.65 m (48 ft) flatbed semitrailer, shortened where necessary to represent existing Michigan configurations with a length of 12.80 or 13.72 m (42 or 45 ft). The kingpin setback was 0.46 m (18 in) when the semitrailer was pulled by a 3-axle tractor, or 0.91 m (36 in) when it was pulled by a 4-axle tractor. The rearmost axle was placed 0.71 m (28 in) from the rear of the semitrailer, which is about the minimum possible, unless a greater spacing was beneficial for load distribution. This axle location was used to maximize the base length for Ontario configurations, and to maximize the space for axles for Michigan configurations. Each semitrailer was assumed to have the same frame, deck and equipment. The sprung weight of the semitrailer was 495.4 kg/m (333.3 lb/ft), distributed uniformly along the length of the semitrailer. The unsprung weight of each fixed axle was 771 kg (1,700 lb) and the unsprung weight of each liftable axle was 907 kg (2,000 lb). Moments of inertia for these semitrailers were generated in the same way as during the CCMTA/RTAC Vehicle Weights and Dimensions Study [6].

Semitrailers have a great variety of body styles, and each body style may have a different tare weight from the baseline flatbed. However, the difference in weight between body styles is generally distributed over approximately the same height and length as the payload. There is generally little difference in the overall weight and centre of gravity of a semitrailer in a vehicle loaded to its allowable gross weight, whatever its body style, though the actual payload weight will vary depending on the actual tare weight of the semitrailer.

3.4 Load Distribution

Vehicles were loaded with a solid block of payload of uniform density over a width of 2.44 m (96 in) and the maximum possible length of the deck. A payload density of 545 kg/cu m (34 lb/cu ft) was used to generate a high centre of gravity. This density represents a payload like dressed lumber, products packed 1.52-1.83 m (60-72 in) high on a pallet and weighing 1,000-1,500 kg (2,204-3,306 lb), municipal waste, and many other commodities of moderate density. This is the same payload density used for the simulations conducted for the CCMTA/RTAC Vehicle Weights and Dimensions Study [6]. It results in a centre of gravity height about 2.28-2.41 m (90-95 in) above the ground for the vehicles considered here. The maximum possible centre of gravity height is about 2.74 m (108 in), for a uniform payload reaching the overall height limit of 4.15 m (163 in). A payload density of 1,603 kg/cu m (100 lb/cu ft) was used to generate a low centre of gravity, which represents a dense payload like metal billets or ingots. This does not represent the inherent density of any particular commodity. It is simply an equivalent density that results in a block of payload about one third the height of that produced by the lower payload density. The low payload density, which results in a high centre of gravity, tends to promote a rolling response of the vehicle, while the high payload density tends to promote a sliding response.

The payload weight was the difference between the allowable gross weight and the tare weight of the vehicle, rounded down to the nearest thousand pounds. The simulation program uses Imperial inch and pound dimensions. Payload was distributed on the semitrailer depending on whether the allowable gross weight:

- Equaled the sum of allowable axle weights; or
- Exceeded the sum of allowable axle weights.

When the allowable gross weight was equal to the sum of allowable axle weights, the payload centre of gravity is fixed. The block of payload is generally shorter than the length of the semitrailer, and was rounded down to the nearest 0.15 m (6 in) in length. The block of payload was positioned to one end or other of the semitrailer to ensure proper distribution of weight to the axles. If the payload centre of gravity was ahead of the mid-point of the semitrailer, there was open space at the back of the semitrailer, and vice versa.

When the sum of allowable axle weights exceeds the allowable gross weight, the payload centre of gravity can vary. The block of payload may equal the length of the semitrailer, or may be shorter, depending on the available axle capacity. If the axle capacity is within 1,000 kg (2,204 lb) of the gross weight, the payload was arranged so that the tractor drive and semitrailer axles were each at the same percentage of their allowable weights. If the axle capacity was more than 1,000 kg (2,204 lb) higher than the gross weight, the payload was arranged so that the tractor drive axles were loaded within 500 kg (1,102 lb) of their allowable axle group weight, and the semitrailer axles were under-loaded. This ensured adequate mobility for the vehicle.

4. EXISTING CONFIGURATIONS

4.1 Introduction

This work addressed heavy haul tractor-semitrailers with eight or more axles that operate within Ontario, or between Ontario and Michigan. These vehicles haul dense or bulk commodities like logs, lumber, metals, waste, liquids, aggregates and others. Existing vehicle configurations use semitrailers with five to eight axles that almost universally include rigid liftable axles that must be lifted when the vehicle makes a low-speed turn. Table 2, provided by MTO, shows 31 tractor-semitrailer configurations with eight or more axles that were encountered in the 1999 Commercial Vehicle Survey [23]. Vehicles are described by a vehicle configuration code, which consists of a configuration code for each vehicle unit from the power unit to the rearmost trailer. A vehicle unit configuration code simply consists of the number of axles in each axle group, from the front to the rear of the vehicle unit, followed by a code that describes the hitch by which one vehicle unit tows another. For example, the vehicle unit configuration code **12S** describes a tractor with a single front axle **1** and a tandem drive axle **2**, and **S** represents the fifth wheel it uses to tow a semitrailer. The vehicle unit configuration code **131** describes a semitrailer with a single axle, a tridem and another single axle. When these two vehicle units are coupled together, the vehicle configuration code is **12S131**. The vehicle configuration code addresses all configurations, but other features are not described here as this work only addresses tractor-semitrailers.

The results in Table 2 are sorted by number of tractor axles, number of trailer axles, then by number of vehicles. The number of vehicles is a weighted estimate of the actual number of vehicles on the highway during the time of the survey. The weighting process accounts for differences between the proportion of trucks surveyed and total truck counts at the various survey sites. The configurations in Table 2 can be broken into three groups:

- Vehicles configured to Ontario rules for use within Ontario;
- Vehicles configured as a compromise between the rules of Ontario and Michigan for use between Ontario and Michigan; and
- Vehicles configured to Michigan rules for use within Michigan and between Michigan and Ontario.

The term “rules” is used here to include all legislation, regulations, permits and policies of a jurisdiction that govern vehicle weights and dimensions in that jurisdiction.

The following are the principal axle configurations for vehicles configured to Ontario rules for use primarily within Ontario:

- 12S131, about 48.5% of all vehicles; and
- 12S113 and 12S23, almost 26% of all vehicles.

Table 2: Heavy Haul Tractor-Semitrailer Configurations Operating in Ontario

Configuration	Tractor axles	Semitrailer axles	Total axles	Count	%
12S131	3	5	8	1,142	48.5%
12S113	3	5	8	573	24.3%
12S23	3	5	8	34	1.4%
12S14	3	5	8	33	1.4%
12S5	3	5	8	4	0.2%
12S1121	3	5	8	1	0.0%
12S122	3	5	8	1	0.0%
12S141	3	6	9	295	12.5%
12S114	3	6	9	128	5.4%
12S15	3	6	9	31	1.3%
12S6	3	6	9	23	1.0%
12S1113	3	6	9	9	0.4%
12S1131	3	6	9	6	0.2%
12S132	3	6	9	3	0.1%
12S222	3	6	9	1	0.0%
12S1311	3	6	9	0	0.0%
12S24	3	6	9	0	0.0%
12S33	3	6	9	0	0.0%
12S7	3	7	10	14	0.6%
12S115	3	7	10	10	0.4%
12S322	3	7	10	0	0.0%
12S8	3	8	11	16	0.7%
12S143	3	8	11	12	0.5%
13S4	4	4	8	7	0.3%
112S4	4	4	8	2	0.1%
13S13	4	4	8	1	0.0%
112S22	4	4	8	0	0.0%
13S113	4	5	9	4	0.1%
13S221	4	5	9	0	0.0%
13S15	4	6	10	2	0.1%
13S233	4	8	12	0	0.0%

Vehicles of configuration 12S113 and 12S131 invariably have a base length just over 19.25 m (758 in), to maximize allowable gross weight. The semitrailer usually has minimum kingpin setback, and the last axle is right at the rear of the semitrailer. A long wheelbase tandem drive tractor may be required to achieve the base length, which may result in a wheelbase in the range 6.60-6.86 m (260-270 in). A tractor with a front axle gross axle weight rating (GAWR) of 5,443 kg (12,000 lb) and an actual front axle load over 5,000 kg (11,023 lb) allows a gross weight of 61,800 kg (136,244 lb), regardless of axle configuration. An actual front axle load over 5,500 kg (12,125 lb), and sufficient front axle GAWR, allows a gross weight of 62,300 kg (137,346 lb). These axle arrangements provide an axle capacity of 23,500-24,000 kg (51,808 to 52,910 lb) on the tractor, and an axle capacity of 41,300 to 44,400 kg (91,050 to 97,884 lb) on the semitrailer, for a total axle capacity in the range 64,800 to 68,400 kg (142,858 to 150,794 lb) under Ontario rules. The excess of axle capacity over gross weight gives carriers flexibility to distribute load on the semitrailer without risking an axle overload, as long as the liftable axles carry an appropriate share of the load.

The following are the principal axle configurations of vehicles configured as a compromise between the rules of Ontario and Michigan that are in use between Ontario and Michigan:

- 12S141, 12.5% of all vehicles;
- 12S114, 5.4% of all vehicles; and
- 12S1112, recently appeared, so not in Table 2.

Vehicles of these configurations are generally as described above if they operate both within Ontario and between Ontario and Michigan. However, a vehicle dedicated to operation between Ontario and Michigan, such as those that haul Toronto's municipal waste, operates only at Michigan weights. The above configurations have gross weights of 56,246 and 59,874 kg (124,000 and 132,000 lb) in Michigan, so only need sufficient base length and inter-vehicle unit distance to achieve this gross weight in Ontario.

The following are the principal axle configurations of vehicles configured to Michigan rules that are in use between Ontario and Michigan:

- 12S14;
- 12S15
- 12S6;
- 12S7; and
- 12S8, which together make up about 5% of all vehicles

Vehicles of these configurations are strictly configured to Michigan rules. Some are based in Ontario and are dedicated to operation between Ontario and Michigan. Those based in Michigan may operate occasionally into Ontario, or between Michigan and New York through Ontario. The base length of these vehicles is generally well under 19.25 m (758 in), so is too short to achieve the maximum gross weight in Ontario. The allowable gross weight under Ontario rules for some of these vehicles with an inter-vehicle-unit distance less than 3.60 m (142 in) may increase if the first axle on the semitrailer is raised.

The 10 configurations identified above represent almost 96% of the heavy haul tractor-semitrailers with 8 or more axles in use in Ontario, or between Ontario and Michigan.

Other configurations with a 3-axle tractor and eight or more axles are about 3.5% of all vehicles. Almost all of these are configured to Michigan rules, and many are also domiciled in the U.S. Each is generally equivalent to one or other of the vehicles listed above. The remaining configurations have a 4-axle tractor, and are less than 1% of all vehicles. Some of these are general freight vehicles with a long wheelbase tractor of configuration 112S, operated by one specific carrier. Almost all the rest are specialized vehicles that haul indivisible oversize or overweight loads by special permit, and are beyond the scope of this work.

MTO has provided an estimate that about 277,000 semitrailers operate in Ontario. From above, if 2% of these have five or more axles, then about 5,550 semitrailers should be directly affected by this work.

4.2 Simulation Schedule for Existing Configurations

Simulations for existing vehicles determined “normal” and “ultimate” performance for low and high centres of gravity, with liftable axles down, and also with liftable axles raised.

Each existing configuration is defined in detail, and the simulation results are presented, in the following sections. A diagram shows the axle arrangement and dimensions of the vehicle. The symbol **L** in a diagram indicates that the axle is a liftable axle. The semitrailer is shown as a flatbed, which is probably the most common body style for these configurations. However, semitrailers also exist in tank, hopper, dump, stake and rack, curtain-side, log, van and other body styles. A table shows the allowable axle weights for the vehicle under Ontario and under Michigan rules, and also shows the actual axle weights used for the simulation runs with the liftable axles both down and raised. The actual weights are Ontario weights for configurations that primarily operate within Ontario, and Michigan weights for configurations that primarily operate between Ontario and Michigan. A subsequent table then presents the “normal” performance measures derived from the simulation runs. The performance measure column headings as abbreviated in this table for each configuration are as follows:

- SRT =static roll threshold;
- HSOT =high-speed offtracking;
- LTR =load transfer ratio;
- TOT =transient offtracking;
- LSOT =low-speed offtracking;
- RO =rear outswing;
- FD =friction demand;
- LFU =lateral friction utilization; and
- MSSA =maximum self-steer angle.

Any performance measure that failed the applicable performance standard is highlighted in bold.

4.3 Existing Configuration 12S113

Figure 4 shows the most common typical dimensions for this configuration, as determined from the 1999 Commercial Vehicle Survey [23]. The configuration shown is predominantly used to haul tree-length and 2.44 m (8 ft) long logs in northern Ontario, and for this application the foremost liftable axle is often equipped with single 275 or 295 mm (11 or 12 in) tires. The vehicle as used here has a single 275 mm (11 in) tire on this axle.

Table 3 shows the allowable gross and axle weights under Ontario and Michigan rules. The allowable weight shown under Michigan rules assumes that the tridem spread is no more than 3.05 m (120 in), so that the single axle spacings can be at least 2.77 m (109 in) and the inter-vehicle-unit distance exceeds 3.60 m (142 in). This configuration may operate into Michigan, but is not very useful, because other configurations have an allowable gross weight in Michigan much closer to its allowable gross weight in Ontario. This configuration is therefore primarily used for domestic traffic within Ontario. The table also shows the actual gross and axle weights used in the simulation, with all liftable axles down, and with them all raised, with a payload of 42,184 kg (93,000 lb) uniformly distributed along the entire length of the semitrailer.

Table 4 presents the performance measures derived from the simulation runs. This configuration fails the high-speed offtracking and friction demand performance standards for all four conditions, it fails static rollover threshold with a high centre of gravity payload, and it just fails load transfer ratio and transient offtracking with a high centre of gravity payload and its liftable axles down. Even though the simulation was able to compute numbers, the vehicle would almost certainly be unable to make the low-speed right-hand turn with its liftable axles down, whereas it is readily able to do this with them raised, even though the remaining axles are significantly overloaded. While the performance standard is exceeded in this case, it is in the range typical for a tridem semitrailer.

Figure 4: Existing Configuration 12S113

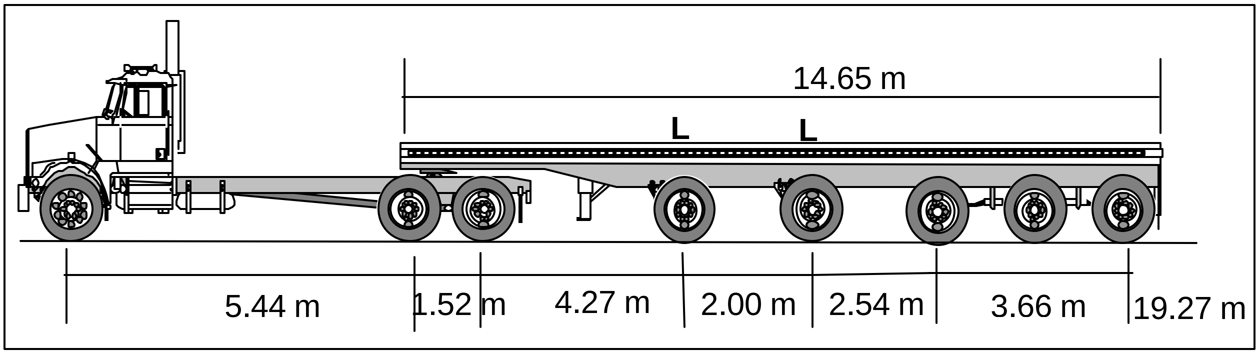


Table 3: Weights for Existing Configuration 12S113

Rules	Gross	Front	Drive	Single	Single	Tridem
Ontario Allowable	61,800 kg (136,244 lb)	5,443 kg (12,000 lb)	18,000 kg (39,684 lb)	10,000 kg (22,046 lb)	10,000 kg (22,046 lb)	24,400 kg (53,792 lb)
Michigan Allowable	53,978 kg (119,000 lb)	5,443 kg (12,000 lb)	14,515 kg (32,000 lb)	8,164 kg (18,000 lb)	8,164 kg (18,000 lb)	17,690 kg (39,000 lb)
Actual Lifts Down	61,508 kg (135,600 lb)	5,369 kg (11,836 lb)	17,313 kg (38,168 lb)	4,990 kg (11,000 lb)	9,979 kg (22,000 lb)	23,857 kg (52,596 lb)
Actual Lifts up	61,508 kg (135,600 lb)	5,741 kg (12,658 lb)	23,433 kg (51,661 lb)			32,333 kg (71,281 lb)

Table 4: Performance Measures for Existing Configuration 12S113

CG	Lift	Performance Measure								
		SRT (g)	**HSOT (m)**	**LTR**	**TOT (m)**	**LSOT (m)**	**RO (m)**	**FD**	**LFU**	**MSSA (deg)**
		>0.400	**<0.460**	**<0.600**	**<0.800**	**<5.600**	**<0.200**	**<0.100**	**<0.800**	**<20.0**
Low	Down	0.596	**0.492**	0.391	0.691	4.018	0.098	**0.677**	NA	NA
Low	Up	0.538	**0.532**	0.350	0.589	5.188	0.027	**0.143**	NA	NA
High	Down	**0.392**	**0.529**	**0.601**	**0.813**	4.005	0.102	**0.675**	NA	NA
High	Up	**0.355**	**0.638**	0.570	0.757	5.165	0.033	**0.143**	NA	NA

4.4 Existing Configuration 12S131

Figure 5 shows typical dimensions for this configuration, as determined from the 1999 Commercial Vehicle Survey [23]. This configuration is often preferred over configuration 12S113 for hauling heavy dense cargo like metal coils, because the tridem is well-located to carry a single heavy article, and because it has a relatively short wheelbase so can be turned more tightly than the other configuration. It is also found in a variety of other body styles.

Table 5 shows the allowable gross and axle weights under Ontario and Michigan rules. The allowable weight shown under Michigan rules assumes that the single axle spacings are at least 2.77 m (109 in). This configuration may operate into Michigan, but is not very useful, because other configurations have an allowable gross weight in Michigan much closer to its allowable gross weight in Ontario. This configuration is therefore primarily used for domestic traffic within Ontario. The table also shows the actual gross and axle weights used in the simulation, with all liftable axles down, and with them all raised, for a payload of 42,184 kg (93,000 lb) uniformly distributed along the entire length of the semitrailer.

Table 6 presents the performance measures derived from the simulation runs. This configuration fails the high-speed offtracking and friction demand performance standards for all four conditions, it fails static rollover threshold with a high centre of gravity payload, it fails load transfer ratio and transient offtracking with a high centre of gravity payload and its liftable axles up, and it fails rear outswing with its liftable axles up. Even though the simulation was able to compute numbers, the vehicle would almost certainly be unable to make the low-speed right-hand turn with its liftable axles down, whereas it is readily able to do this with them raised, even though the tridem is significantly overloaded.

Figure 5: Existing Configuration 12S131

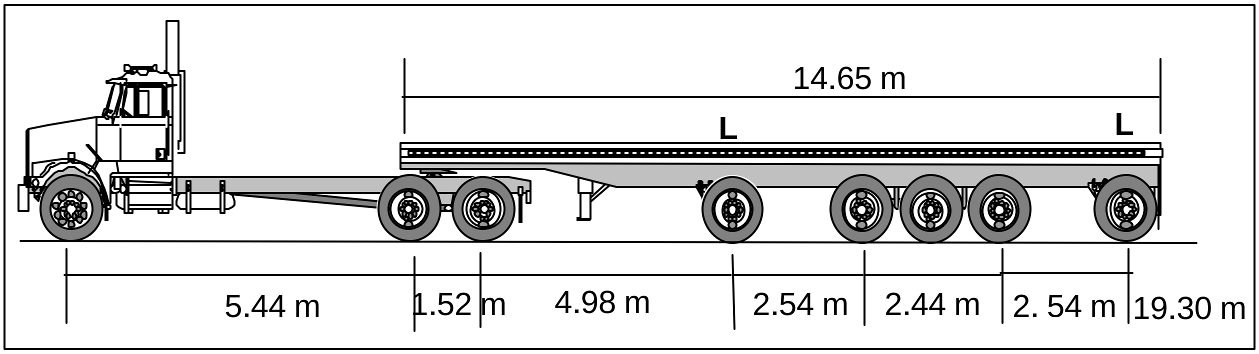


Table 5: Weights for Existing Configuration 12S131

Rules	Gross	Front	Drive	Single	Tridem	Single
Ontario	61,800 kg (136,244 lb)	5,443 kg (12,000 lb)	18,000 kg (39,684 lb)	10,000 kg (22,046 lb)	21,300 kg (46,958 lb)	10,000 kg (22,046 lb)
Michigan	53,978 kg (119,000 lb)	5,443 kg (12,000 lb)	14,515 kg (32,000 lb)	8,164 kg (18,000 lb)	17,690 kg (39,000 lb)	8,164 kg (18,000 lb)
Actual Lifts Down	61,735 kg (136,100 lb	5,368 kg (11,834 lb)	17,293 kg (38,124 lb)	9,526 kg (21,000 lb)	20,023 kg (44,142 lb)	9,526 kg (21,000 lb)
Actual Lifts up	61,735 kg (136,100 lb	5,368 kg (11,834 lb)	17,293 kg (38,124 lb)		39,074 kg (86,142 lb)	

Table 6: Performance Measures for Existing Configuration 12S131

CG	Lift	Performance Measure								
		SRT (g)	HSOT (m)	LTR	TOT (m)	LSOT (m)	RO (m)	FD	LFU	MSSA (deg)
		>0.400	<0.460	<0.600	<0.800	<5.600	<0.200	<0.100	<0.800	<20.0
Low	Down	0.611	**0.509**	0.375	0.686	4.019	0.087	**0.610**	NA	NA
Low	Up	0.571	**0.499**	0.434	0.746	4.193	**0.215**	**0.112**	NA	NA
High	Down	**0.398**	**0.557**	0.580	0.793	4.003	0.091	**0.611**	NA	NA
High	Up	**0.335**	**0.607**	**0.705**	**0.910**	4.177	**0.254**	**0.112**	NA	NA

4.5 Existing Configuration 12S114

Figure 6 shows the most common typical dimensions for this configuration, as determined from the 1999 Commercial Vehicle Survey [23]. There is almost no variation in dimensions for this configuration, because it is very tight to fit all the axles under the semitrailer. An inter-vehicle-unit distance of 3.6 m (142 in) is usually not achieved unless the axle spacings in the four axle group are less than 1.22 m (48 in), or the semitrailer is actually longer than 14.65 m (48 ft). Michigan allows a semitrailer length of 15.24 m (50 ft). The configuration is a compromise between Ontario and Michigan rules, and is predominantly used to haul logs, wood chips, municipal waste and metal between Ontario and Michigan. Michigan weights govern, so this configuration is customarily operated at Michigan weights when in Ontario. Because the allowable gross weight in Michigan is less than in Ontario, it is not always critical for the inter-vehicle-unit distance to reach 3.60 m (142 in), or for the base length to reach 19.25 m (758 in), for maximum allowable gross weight in Ontario. Vehicles dedicated to cross-border traffic, such as those hauling municipal waste, tend to operate with shorter wheelbase tractors than used on the corresponding domestic Ontario configurations 12S113 and 12S131. The four axle group at the rear of the semitrailer usually consists of a fixed tridem and a single liftable axle, which may be either the first axle or the last axle. This axle is usually deployed when the vehicle operates in Ontario, so it is not an “invisible” liftable axle which is lifted when the vehicle operates in Ontario.

Table 7 shows the allowable gross and axle weights under Ontario and Michigan rules. The table also shows the actual gross and axle weights used in the simulation, with all liftable axles down, and with them all raised, for a payload of 39,009 kg (86,000 lb) set back 0.40 m (16 in) from the front of the semitrailer, but otherwise uniformly distributed along the entire length of the semitrailer. Note that the four-axle group becomes a tridem when the liftable axles are raised.

Table 8 presents the performance measures derived from the simulation runs. This configuration fails the high-speed offtracking performance standard for all four conditions, it fails the friction demand performance standard with the liftable axles down, and it fails static rollover threshold with a high centre of gravity payload. Even though the simulation was able to compute numbers for the low-speed right-hand turn with its liftable axles down, the values are not meaningful, and are not presented, because the vehicle would certainly be unable to make the turn. It is readily able to make this turn with the liftable axles raised, even though the remaining axles are significantly overloaded.

Figure 6: Existing Configuration 12S114

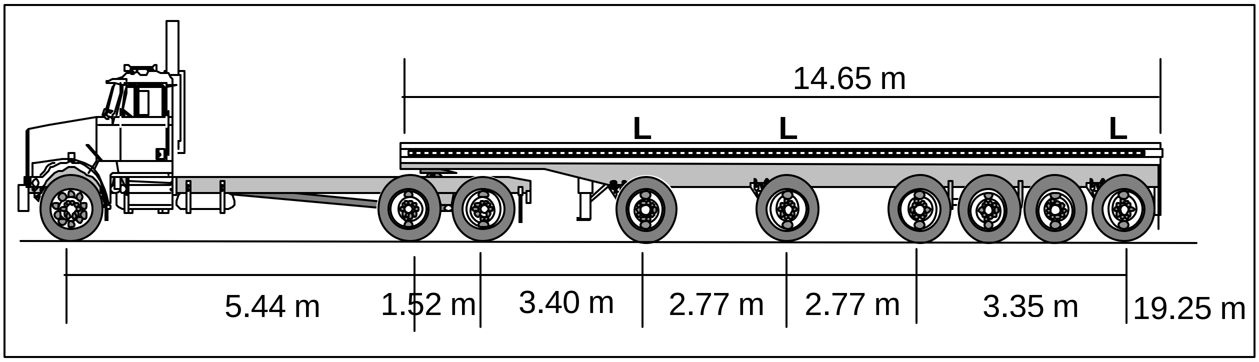


Table 7: Weights for Existing Configuration 12S114

Rules	Gross	Front	Drive	Single	Single	4-axle group
Ontario	61,300 kg (135,142 lb)	5,443 kg (12,000 lb)	18,000 kg (39,684 lb)	10,000 kg (22,046 lb)	10,000 kg (22,046 lb)	23,500 kg (51,808 lb)
Michigan	59,874 kg (132,000 lb)	5,443 kg (12,000 lb)	14,515 kg (32,000 lb)	8,164 kg (18,000 lb)	8,164 kg (18,000 lb)	23,587 kg (52,000 lb)
Actual Lifts Down	59,466 kg (131,100 lb)	5,289 kg (11,659 lb)	14,354 kg (31,644 lb)	8,164 kg (18,000 lb)	8,164 kg (18,000 lb)	23,495 kg (51,797 lb)
Actual Lifts up	59,466 kg (131,100 lb)	5,714 kg (12,598 lb)	20,420 kg (45,018 lb)			33,332 kg (73,485 lb)

Table 8: Performance Measures for Existing Configuration 12S114

CG	Lift	Performance Measure								
		SRT (g)	**HSOT (m)**	**LTR**	**TOT (m)**	**LSOT (m)**	**RO (m)**	**FD**	**LFU**	**MSSA (deg)**
		>0.400	**<0.460**	**<0.600**	**<0.800**	**<5.600**	**<0.200**	**<0.100**	**<0.800**	**<20.0**
Low	Down	0.607	**0.476**	0.387	0.699				NA	NA
Low	Up	0.580	**0.493**	0.342	0.554	4.991	0.055	0.070	NA	NA
High	Down	0.427	**0.480**	0.594	0.785				NA	NA
High	Up	**0.378**	**0.571**	0.539	0.690	4.977	0.059	0.070	NA	NA

4.6 Existing Configuration 12S141

Figure 7 shows the most common typical dimensions for this configuration, as determined from the 1999 Commercial Vehicle Survey [23]. There is almost no variation in dimensions, because it is very tight to fit all the axles under the semitrailer. An inter-vehicle-unit distance of 3.6 m (142 in) is usually not achieved unless the axle spacings in the four axle group are less than 1.22 m (48 in), or the semitrailer is actually longer than 14.65 m (48 ft). Michigan allows a semitrailer length of 15.24 m (50 ft). The configuration is a compromise between Ontario and Michigan rules, and is predominantly used to haul metals and municipal waste between Ontario and Michigan, and construction materials within Ontario. Michigan weights govern, so this configuration is customarily operated at Michigan weights when in Ontario. Because the allowable gross weight in Michigan is less than in Ontario, it is not always critical for the inter-vehicle unit distance to reach 3.6 m (142 in), or for the base length to reach 19.25 m (758 in), for maximum allowable gross weight in Ontario. Vehicles dedicated to cross-border traffic, such as those hauling municipal waste, tend to operate with shorter wheelbase tractors than used on the corresponding domestic Ontario configurations 12S113 and 12S131. The four axle group on the semitrailer usually consists of a single liftable axle ahead of a fixed tridem. This axle may be lifted when the vehicle operates in Ontario, because lifting it does not sacrifice base length. This configuration is often preferred over configuration 12S114 for hauling heavy dense cargo like metal coils, because the four axle group is well-located to carry a single heavy article, and because it has a relatively short wheelbase so can be turned more tightly than the other configuration.

Table 9 shows the allowable gross and axle weights under Ontario and Michigan rules. The table also shows the actual gross and axle weights used in the simulation, with all liftable axles down, and with them all raised, for a payload of 39,009 kg (86,000 lb) uniformly distributed along all but the last 0.15 m (6 in) of the semitrailer. Note that the four-axle group becomes a tridem when the liftable axles are raised.

Table 10 presents the performance measures derived from the simulation runs. This configuration fails the high-speed offtracking performance standard for all four conditions. It fails all high-speed performance standards with a high centre of gravity payload, except for static rollover threshold with its liftable axles down. It fails the friction demand performance standard with its liftable axles down, and it fails rear outswing with its liftable axles up. Even though the simulation was able to compute numbers for the low-speed right-hand turn with its liftable axles down, the values are not meaningful, and are not presented, because the vehicle would certainly be unable to make the turn. It is able to make this turn with the liftable axles raised, even though the four-axle group is significantly overloaded.

Figure 7: Existing Configuration 12S141

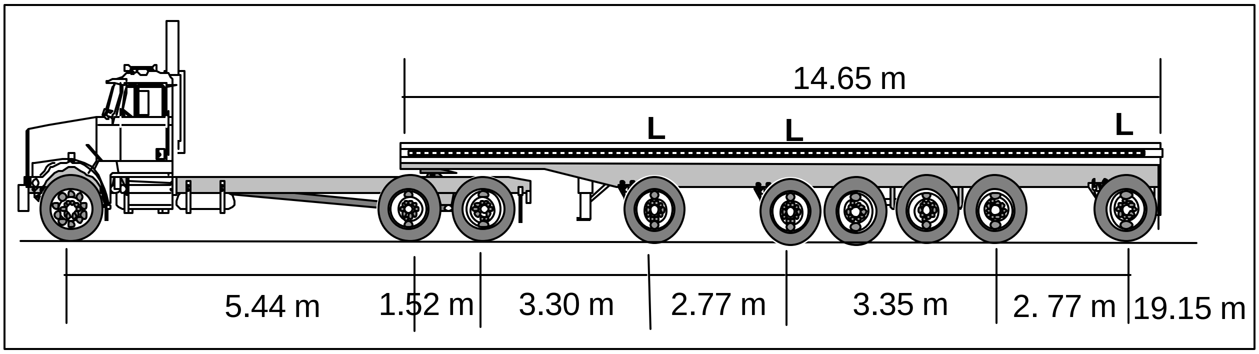


Table 9: Weights for Existing Configuration 12S141

Rules	Gross	Front	Drive	Single	4-axle group	Single
Ontario	60,900 kg (134,260 lb)	5,443 kg (12,000 lb)	18,000 kg (39,684 lb)	10,000 kg (22,046 lb)	23,500 kg (51,808 lb)	10,000 kg (22,046 lb)
Michigan	59,874 kg (132,000 lb)	5,443 kg (12,000 lb)	14,515 kg (32,000 lb)	8,164 kg (18,000 lb)	23,587 kg (52,000 lb)	8,164 kg (18,000 lb)
Actual Lifts Down	59,466 kg (131,100 lb)	5,393 kg (11,889 lb)	14,387 kg (31,717 lb)	8,164 kg (18,000 lb)	23,357 kg (51,494 lb)	8,164 kg (18,000 lb)
Actual Lifts up	59,466 kg (131,100 lb)	5,567 kg (12,274 lb)	16,579 kg (31,928 lb)		37,320 kg (82,275) lb)	

Table 10: Performance Measures for Existing Configuration 12S141

CG	Lift	Performance Measure								
		SRT (g)	HSOT (m)	LTR	TOT (m)	LSOT (m)	RO (m)	FD	LFU	MSSA (deg)
		>0.400	**<0.460**	**<0.600**	**<0.800**	**<5.600**	**<0.200**	**<0.100**	**<0.800**	**<20.0**
Low	Down	0.610	**0.474**	0.406	0.775				NA	NA
Low	Up	0.598	**0.465**	0.420	0.714	4.066	**0.241**	0.098	NA	NA
High	Down	0.429	**0.511**	**0.612**	**0.859**				NA	NA
High	Up	**0.366**	**0.549**	**0.666**	**0.856**	4.059	**0.235**	0.099	NA	NA

4.7 Existing Configuration 12S1112

Figure 8 shows typical dimensions for this recent configuration, which did not appear in the 1999 Commercial Vehicle Survey [23]. It is very tight to fit all the axles under the semitrailer. An inter-vehicle-unit distance of 2.8 m (110 in) can just be achieved. The configuration is a compromise between Ontario and Michigan rules, and is predominantly used to haul municipal waste between Ontario and Michigan. Michigan weights govern, so this configuration is customarily operated at Michigan weights when in Ontario. Because the allowable gross weight in Michigan is less than in Ontario, it is not critical for the inter-vehicle unit distance to reach 3.60 m (142 in), or for the base length to reach 19.25 m (758 in), for maximum allowable gross weight in Ontario. The semitrailer has a wheelbase of about 12.9 m (508 in), which exceeds the limit of 12.5 m (492 in) imposed of 16.20 m (53 ft) semitrailers under Ontario Regulation 32/94. However, it does not require a tractor with as long a wheelbase as shown here.

Table 11 shows the allowable gross and axle weights under Ontario and Michigan rules. The table also shows the actual gross and axle weights used in the simulation, with all liftable axles down, and with them all raised, for a payload of 36,287 kg (80,000 lb) uniformly distributed along the most forward 13.72 m (45 ft) of the length of the semitrailer.

Table 12 presents the performance measures derived from the simulation runs. This configuration fails the high-speed offtracking performance standard for all four conditions, it fails static rollover threshold with a high centre of gravity payload and the liftable axles raised, it just fails load transfer ratio and transient offtracking with a high centre of gravity payload and its liftable axles down, and it fails low-speed offtracking with its liftable axles raised. It would meet the low-speed offtracking performance standard if a tractor with wheelbase shorter than that used in the simulation would be used. Even though the simulation was able to compute numbers for the low-speed right-hand turn with its liftable axles down, the values are not meaningful, and are not presented, because the vehicle would certainly be unable to make the turn. It is able to make this turn with the liftable axles raised, even though the remaining axles are significantly overloaded. The friction demand in this case is typical for a tandem semitrailer.

Figure 8: Existing Configuration 12S1112

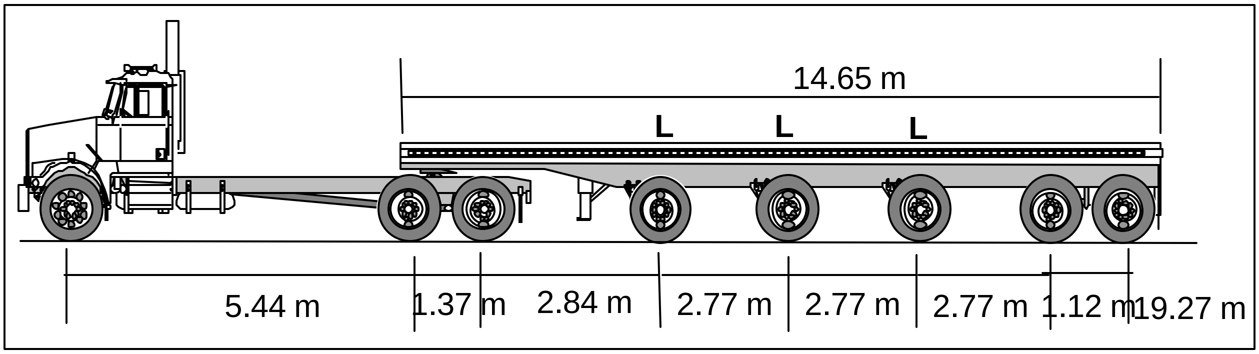


Table 11: Weights for Existing Configuration 12S1112

Rules	Gross	Front	Drive	Single	Tandem
Ontario	59,200 kg (130,512 lb)	5,443 kg (12,000 lb)	18,000 kg (39,684 lb)	10,000 kg (22,046 lb)	15,400 kg (33,950 lb)
Michigan	56,246 kg (124,000 lb)	5,443 kg (12,000 lb)	14,515 kg (32,000 lb)	8,164 kg (18,000 lb)	11,793 kg (26,000 lb)
Actual Lifts Down	55,974 kg (123,400 lb)	5,198 kg (11,459 lb)	14,504 kg (31,975 lb)	8,164 kg (18,000 lb)	11,778 kg (25,966 lb)
Actual Lifts up	55,974 kg (123,400 lb)	5,870 kg (12,941 lb)	25,542 kg (56,310 lb)		24,562 kg (54,149 lb)

Table 12: Performance Measures for Existing Configuration 12S1112

CG	Lift	Performance Measure								
		SRT (g)	HSOT (m)	LTR	TOT (m)	LSOT (m)	RO (m)	FD	LFU	MSSA (deg)
		>0.400	<0.460	<0.600	<0.800	<5.600	<0.200	<0.100	<0.800	<20.0
Low	Down	0.613	**0.487**	0.409	0.774				NA	NA
Low	Up	0.582	**0.526**	0.323	0.538	**5.768**	0.021	0.043	NA	NA
High	Down	0.431	**0.495**	**0.613**	**0.869**				NA	NA
High	Up	**0.371**	**0.632**	0.516	0.695	**5.832**	0.007	0.034	NA	NA

4.8 Existing Configuration 12S14

Figure 9 shows the most common typical dimensions for this configuration, as determined from the 1999 Commercial Vehicle Survey [23]. The semitrailers are typically 10.97 to 14.65 m (36 to 48 ft) long, and the most common length is 12.80 m (42 ft). The semitrailers are mostly flatbeds for hauling metals, tankers for hauling bulk liquids, hoppers or dumps for hauling scrap, agricultural produce or animal feed, or vans. The 4-axle group consists of a fixed tridem followed by a liftable axle.

Table 13 shows the allowable gross and axle weights under Ontario and Michigan rules. The table also shows the actual gross and axle weights used in the simulation, with all liftable axles down, and with them all raised, for a payload of 33,112 kg (73,000 lb) set back 0.61 m (24 in) from the front of the semitrailer but otherwise uniformly distributed along the entire length of the semitrailer.

Table 14 presents the performance measures derived from the simulation runs. This configuration fails the static rollover threshold and load transfer ratio performance standards with a high centre of gravity payload and its liftable axle raised, and it fails the friction demand performance standard with its liftable axles down. Even though the simulation was able to compute numbers, the vehicle would almost certainly be unable to make the low-speed right-hand turn with its liftable axles down, whereas it is readily able to do this with them raised, even though the semitrailer tridem is significantly overloaded.

Figure 9: Existing Configuration 12S14

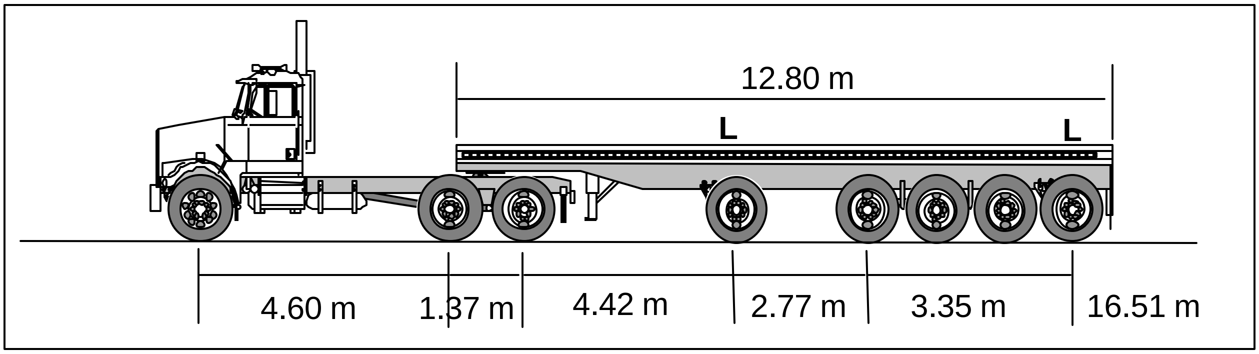


Table 13: Weights for Existing Configuration 12S14

Rules	Gross	Front	Drive	Single	4-axle group
Ontario	56,600 kg (124,780 lb)	5,443 kg (12,000 lb)	18,000 kg (39,684 lb)	10,000 kg (22,046 lb)	23,500 kg (51,808 lb)
Michigan	51,710 kg (114,000 lb)	5,443 kg (12,000 lb)	14,515 kg (32,000 lb)	8,164 kg (18,000 lb)	23,587 kg (52,000 lb)
Actual Lifts Down	51,483 kg (113,300 lb)	5,130 kg (11,309 lb)	14,442 kg (31,838 lb)	8,164 kg (18,000 lb)	23,561 kg (51,942 lb)
Actual Lifts up	51,483 kg (113,300 lb)	5,449 kg (12,013 lb)	16,282 kg (35,896 lb)		29,752 kg (65,591 lb)

Table 14: Performance Measures for Existing Configuration 12S14

CG	Lift	Performance Measure								
		SRT (g)	HSOT (m)	LTR	TOT (m)	LSOT (m)	RO (m)	FD	LFU	MSSA (deg)
		>0.400	<0.460	<0.600	<0.800	<5.600	<0.200	<0.100	<0.800	<20.0
Low	Down	0.610	0.377	0.392	0.552	3.458	0.060	**0.504**	NA	NA
Low	Up	0.586	0.398	0.387	0.541	3.773	0.063	0.095	NA	NA
High	Down	0.424	0.380	0.591	0.628	3.452	0.057	**0.507**	NA	NA
High	Up	**0.383**	0.455	**0.606**	0.673	3.764	0.067	0.095	NA	NA

4.9 Existing Configuration 12S15

Figure 10 shows the most common typical dimensions for this configuration, as determined from the 1999 Commercial Vehicle Survey [23]. The semitrailers are typically 13.72 to 14.65 m (45 to 48 ft) long, and the most common length is 13.72 m (45 ft). The semitrailers are flatbeds for hauling metals, tankers for hauling bulk liquids or dumps for hauling scrap, agricultural produce or animal feed. There are a variety of axle arrangements on such semitrailers. The 5-axle group considered here has a fixed tridem with a single liftable axle ahead of and behind the tridem.

Table 15 shows the allowable gross and axle weights under Ontario and Michigan rules. The Ontario allowable weight on the 5-axle group is simply based on the weight allowed on a 4-axle group for an axle group with the same spread. This is the current method used by MTO for evaluating groups of more than four axles. In this case, it allows sufficient weight that the allowable gross weight is not limited by the sum of axle weights. The table also shows the actual gross and axle weights used in the simulation, with all liftable axles down, and with them all raised, for a payload of 37,648 kg (83,000 lb) set back 0.15 m (6 in) from the front of the semitrailer, but otherwise uniformly distributed along the length of the semitrailer.

Table 16 presents the performance measures derived from the simulation runs. This configuration fails the load transfer ratio performance standard with a high centre of gravity payload and its liftable axles down, and it also fails the static rollover threshold and transient offtracking performance standards with its liftable axles raised. Even though the simulation was able to compute numbers for the low-speed right-hand turn with its liftable axles down, the values are not meaningful, and are not presented, because the vehicle would certainly be unable to make the turn. It is able to make this turn with the liftable axles raised, even though the remaining axles are significantly overloaded, and the friction demand just exceeds the performance standard, though is well below the levels typical of a tridem semitrailer.

Figure 10: Existing Configuration 12S15

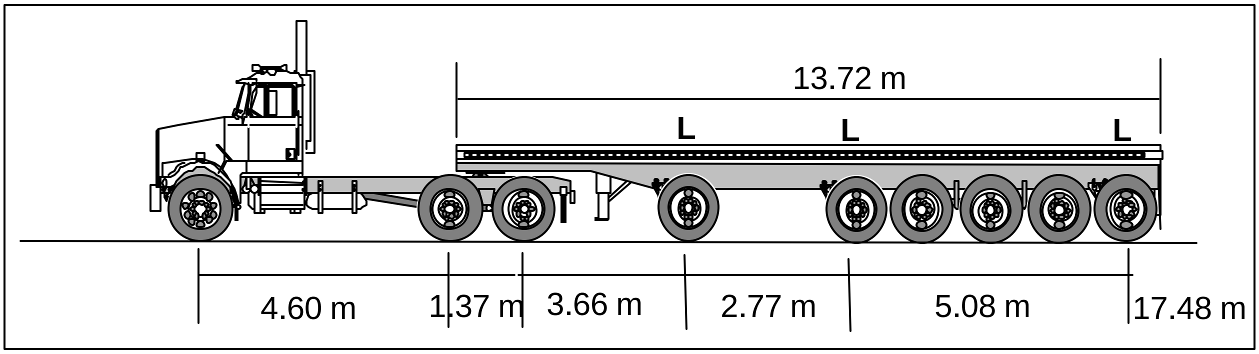


Table 15: Weights for Existing Configuration 12S15

Rules	Gross	Front	Drive	Single	5-axle group
Ontario	58,100 kg (128,087 lb)	5,443 kg (12,000 lb)	18,000 kg (39,684 lb)	10,000 kg (22,046 lb)	28,900 kg (63,713 lb)
Michigan	59,874 kg (127,000 lb)	5,443 kg (12,000 lb)	14,515 kg (32,000 lb)	8,164 kg (18,000 lb)	29,483 kg (65,000 lb)
Actual Lifts Down	57,380 kg (126,500 lb)	5,317 kg (11,721 lb)	14,446 kg (31,848 lb)	8,164 kg (18,000 lb)	29,453 kg (64,931 lb)
Actual Lifts up	57,380 kg (126,500 lb)	5,608 kg (12,364 lb)	18,485 kg (40,753 lb)		33,286 kg (73,383 lb)

Table 16: Performance Measures for Existing Configuration 12S15

CG	Lift	Performance Measure								
		SRT (g)	**HSOT (m)**	**LTR**	**TOT (m)**	**LSOT (m)**	**RO (m)**	**FD**	**LFU**	**MSSA (deg)**
		>0.400	**<0.460**	**<0.600**	**<0.800**	**<5.600**	**<0.200**	**<0.100**	**<0.800**	**<20.0**
Low	Down	0.607	0.408	0.420	0.676				NA	NA
Low	Up	0.597	0.457	0.382	0.595	4.070	0.081	**0.105**	NA	NA
High	Down	0.419	0.420	**0.639**	0.753				NA	NA
High	Up	**0.366**	**0.522**	**0.614**	0.743	4.058	0.090	**0.106**	NA	NA

4.10 Existing Configuration 12S6

Figure 11 shows the most common typical dimensions for this configuration, as determined from the 1999 Commercial Vehicle Survey [23]. The semitrailers are typically 12.29 to 12.80 m (36 to 42 ft) long, and the most common length is 12.80 m (42 ft). The semitrailers are flatbeds for hauling metals, tankers for hauling bulk liquids or dumps for hauling scrap, agricultural produce or animal feed. There are a variety of axle arrangements on such semitrailers. The 6-axle group considered here has a fixed tridem, with two liftable axles ahead of it and one behind.

Table 15 shows the allowable gross and axle weights under Ontario and Michigan rules. The Ontario allowable weight on the 6-axle group is simply based on the weight allowed on a 4-axle group for an axle group with the same spread. This is the current method used by MTO for evaluating groups of more than four axles. In this case, it allows sufficient weight that the allowable gross weight is not limited by the sum of axle weights. The table also shows the actual gross and axle weights used in the simulation, with all liftable axles down, and with them all raised, for a payload of 35,834 kg (79,000 lb) set back 0.23 m (9 in) from the front of the semitrailer, but otherwise uniformly distributed along the length of the semitrailer.

Table 16 presents the performance measures derived from the simulation runs. This configuration fails the load transfer ratio performance standard with a high centre of gravity payload and its liftable axles down, and it also fails the static rollover threshold and transient offtracking performance standards with its liftable axles raised. Even though the simulation was able to compute numbers for the low-speed right-hand turn with its liftable axles down, the values are not meaningful, and are not presented, because the vehicle would certainly be unable to make the turn. It is able to make this turn with the liftable axles raised, even though the remaining axles are significantly overloaded, and the friction demand just exceeds the performance standard.

Figure 11: Existing Configuration 12S6

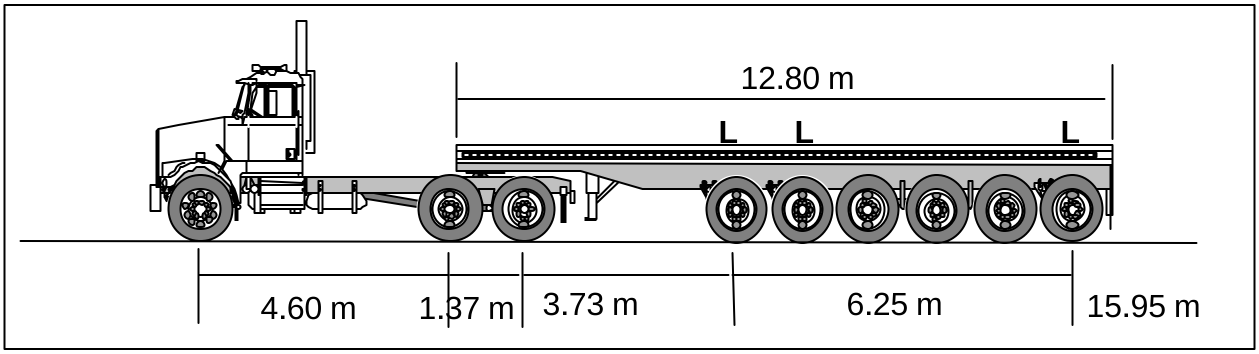


Table 17: Weights for Existing Configuration 12S6

Rules	Gross	Front	Drive	6-axle group
Ontario	55,200 kg (121,693 lb)	5,443 kg (12,000 lb)	18,000 kg (39,684 lb)	33,200 kg (73,192 lb)
Michigan	55,338 kg (122,000 lb)	5,443 kg (12,000 lb)	14,515 kg (32,000 lb)	35,380 kg (78,000 lb)
Actual Lifts Down	55,112 kg (121,500 lb)	5,318 kg (11,724 lb)	14,467 kg (31,893 lb)	35,328 kg (77,883 lb)
Actual Lifts up	55,112 kg (121,500 lb)	5,484 kg (12,091 lb)	16,771 kg (36,973 lb)	32,857 kg (72,436 lb)

Table 18: Performance Measures for Existing Configuration 12S6

CG	Lift	Performance Measure								
		SRT (g)	**HSOT (m)**	**LTR**	**TOT (m)**	**LSOT (m)**	**RO (m)**	**FD**	**LFU**	**MSSA (deg)**
		>0.400	**<0.460**	**<0.600**	**<0.800**	**<5.600**	**<0.200**	**<0.100**	**<0.800**	**<20.0**
Low	Down	0.625	0.380	0.421	0.621				NA	NA
Low	Up	0.598	0.428	0.411	0.615	3.612	0.085	**0.122**	NA	NA
High	Down	0.422	0.403	**0.629**	0.690				NA	NA
High	Up	**0.371**	**0.494**	**0.659**	0.766	3.602	0.089	**0.122**	NA	NA

4.11 Existing Configuration 12S7

Figure 12 shows the most common typical dimensions for this configuration, as determined from the 1999 Commercial Vehicle Survey [23]. The semitrailers are typically 12.29 to 14.65 m (40 to 48 ft) long. The most common length is 12.80 m (42 ft), and the semitrailers are mostly flatbeds for hauling steel, tankers for hauling bulk liquids, dumps for hauling scrap, agricultural produce or animal feed, or vans. An inter-vehicle-unit distance of 3.6 m (142 in) is usually not achieved, and the allowable gross weight in Ontario is maximized by raising the first axle on the semitrailer, as shown in the diagram. There are a variety of axle arrangements on such semitrailers. The 7-axle group considered here has a fixed tridem, with three liftable axles ahead of it and one behind it.

Table 19 shows the allowable gross and axle weights under Ontario and Michigan rules. The allowable weights in Ontario assume the first axle on the semitrailer is raised. The allowable weight on the 7-axle group, which is actually a 6-axle group when the first axle is lifted, is simply based on the weight allowed on a 4-axle group for an axle group with the same spread. This is the current method used by MTO for evaluating groups of more than four axles. It allows sufficient weight that the allowable gross weight in Ontario is not limited by the sum of axle weights. The table also shows the actual gross and axle weights used in the simulation, with all but the foremost liftable axle down, and with them all raised, for a payload of 36,287 kg (80,000 lb) uniformly distributed along the entire length of the semitrailer.

Table 20 presents the performance measures derived from the simulation runs, conducted with the foremost axle on the semitrailer raised, at Ontario allowable weights. This configuration fails the load transfer ratio performance standard with a high centre of gravity payload and its liftable axles down, and it also fails the static rollover threshold and transient offtracking performance standards with its liftable axles raised. Even though the simulation was able to compute numbers for the low-speed right-hand turn with its liftable axles down, the vehicle would certainly be unable to make the turn. It is able to make this turn with the liftable axles raised, even though the remaining axles are significantly overloaded, and the friction demand just exceeds the performance standard.

Figure 12: Existing Configuration 12S7

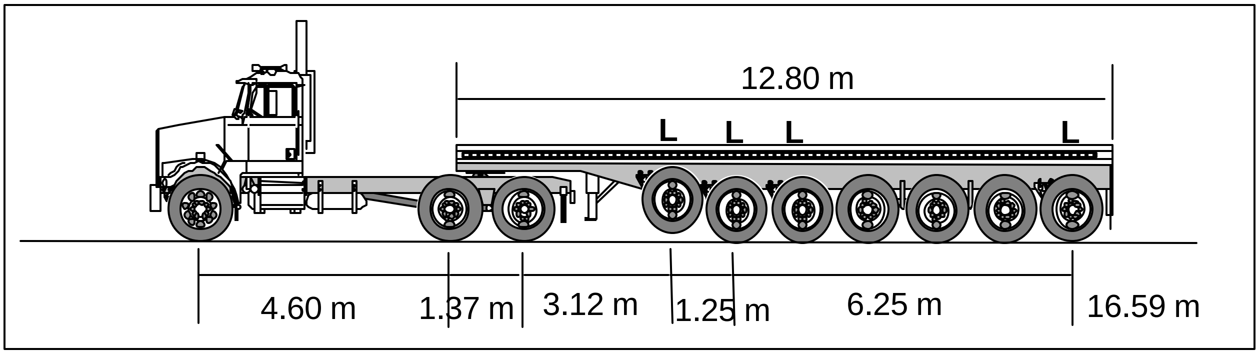


Table 19: Weights for Existing Configuration 12S7

Rules	Gross	Front	Drive	6-axle group
Ontario	56,600 kg (124,780 lb)	5,443 kg (12,000 lb)	18,000 kg (39,684 lb)	33,200 kg (73,192 lb)
Michigan	61,235 kg (135,000 lb)	5,443 kg (12,000 lb)	14,515 kg (32,000 lb)	41,277 kg (91,000 lb)
Actual Lifts Down	56,337 kg (124,200 lb)	5,433 kg (11,977 lb)	16,056 kg (35,398 lb)	34,848 kg (76,825 lb)
Actual Lifts up	56,337 kg (124,200 lb)	5,595 kg (12,334 lb)	18,302 kg (40,349 lb)	32,440 kg (71,517 lb)

Table 20: Performance Measures for Existing Configuration 12S7

CG	Lift	Performance Measure								
		SRT (g)	**HSOT (m)**	**LTR**	**TOT (m)**	**LSOT (m)**	**RO (m)**	**FD**	**LFU**	**MSSA (deg)**
		>0.400	**<0.460**	**<0.600**	**<0.800**	**<5.600**	**<0.200**	**<0.100**	**<0.800**	**<20.0**
Low	Down	0.609	0.377	0.409	0.597	3.135	0.086	**0.507**	NA	NA
Low	Up	0.591	0.433	0.401	0.607	3.644	0.081	**0.108**	NA	NA
High	Down	0.418	0.403	**0.624**	0.668	3.134	0.093	**0.514**	NA	NA
High	Up	**0.373**	**0.497**	**0.631**	0.749	3.633	0.089	**0.109**	NA	NA

4.12 Existing Configuration 12S8

Figure 13 shows the most common typical dimensions for this configuration, as determined from the 1999 Commercial Vehicle Survey [23]. The semitrailers are typically 12.19 to 13.72 m (40 to 45 ft) long, and are mostly flatbeds for hauling steel, dumps for hauling agricultural produce, animal feed or scrap, or vans. An inter-vehicle-unit distance of 3.60 m (142 in) is usually not achieved, and the allowable gross weight in Ontario is maximized by raising the first axle on the semitrailer, as shown in the diagram. There are a variety of axle arrangements on such semitrailers. The 8-axle group considered here has a fixed tridem, with four liftable axles ahead of it and one behind it.

Table 21 shows the allowable gross and axle weights under Ontario and Michigan rules. The allowable weights in Ontario assume the first axle on the semitrailer is raised. The allowable weight on the 8-axle group, which is actually a 7-axle group when the first axle is raised, is simply based on the weight allowed on a 4-axle group for an axle group with the same spread. This is the current method used by MTO for evaluating groups of more than four axles. It allows sufficient weight that the allowable gross weight in Ontario is not limited by the sum of axle weights. The table also shows the actual gross and axle weights used in the simulation, with all but the foremost liftable axle down, and with them all raised, for a payload of 36,741 kg (81,000 lb) uniformly distributed along the entire length of the semitrailer.

Table 22 presents the performance measures derived from the simulation runs, conducted with the foremost axle on the semitrailer raised, at Ontario allowable weights. This configuration fails the load transfer ratio performance standard with a high centre of gravity payload and its liftable axles down, and it also fails the static rollover threshold and transient offtracking performance standards with its liftable axles raised. Even though the simulation was able to compute numbers for the low-speed right-hand turn with its liftable axles down, the values are not meaningful, and are not presented, because the vehicle would certainly be unable to make the turn. It is able to make this turn with the liftable axles raised, even though the remaining axles are significantly overloaded, and the friction demand just meets the performance standard.

Figure 13: Existing Configuration 12S8

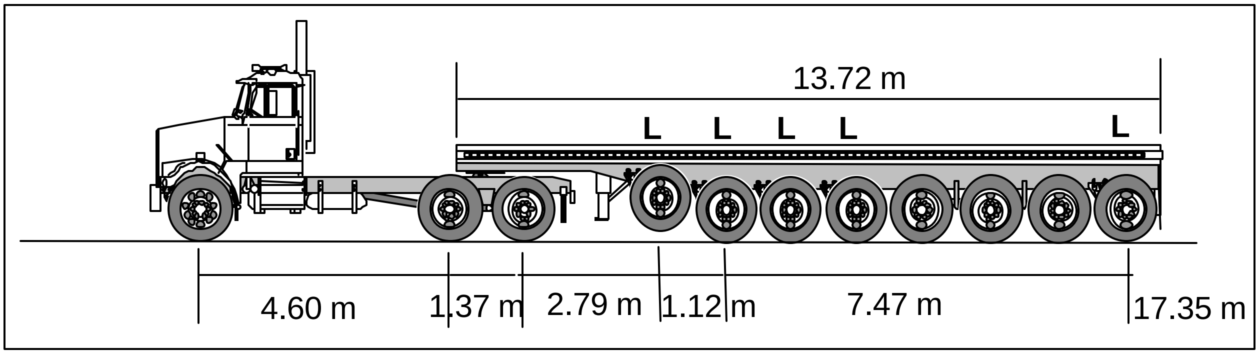


Table 21: Weights for Existing Vehicle Configuration 12S8

Rules	Gross	Front	Drive	7-axle group
Ontario	58,100 kg (128,087 lb)	5,443 kg (12,000 lb)	18,000 kg (39,684 lb)	37,600 kg (82,892 lb)
Michigan	67,132 kg (148,000 lb)	5,443 kg (12,000 lb)	14,515 kg (32,000 lb)	47,174 kg (104,000 lb)
Actual Lifts Down	58,015 kg (127,900 lb)	5,341 kg (11,774 lb)	14,780 kg (32,585 lb)	37,894 kg (83,541 lb)
Actual Lifts up	58,015 kg (127,900 lb)	5,684 kg (12,532 lb)	19,544 kg (43,087 lb)	32,786 kg (72,281 lb)

Table 22: Performance Measures for Existing Vehicle Configuration 12S8

CG	Lift	Performance Measure								
		SRT (g)	**HSOT (m)**	**LTR**	**TOT (m)**	**LSOT (m)**	**RO (m)**	**FD**	**LFU**	**MSSA (deg)**
		>0.400	**<0.460**	**<0.600**	**<0.800**	**<5.600**	**<0.200**	**<0.100**	**<0.800**	**<20.0**
Low	Down	0.660	0.400	0.402	0.667				NA	NA
Low	Up	0.611	0.450	0.364	0.578	4.099	0.080	0.097	NA	NA
High	Down	0.445	0.414	0.591	0.727				NA	NA
High	Up	**0.383**	**0.513**	0.574	0.715	4.089	0.084	0.097	NA	NA

4.13 Summary of Performance of Existing Configurations

Table 23 summarizes the performance measures for all the existing configurations for liftable axles both down and raised and a high centre-of-gravity payload. A high centre-of-gravity is the critical case for high speed performance measures. Centre-of-gravity height is not a significant factor for the low-speed performance measures.

All configurations fail the static roll threshold performance standard with their liftable axles raised, as they must be to allow the vehicle to turn. All 14.65 m (48 ft) semitrailers fail the high-speed offtracking performance standard, and the shorter Michigan semitrailers also fail it when their liftable axles are raised. Most semitrailers only fail this performance standard by a small margin.

Table 23: Summary of Performance of Existing Vehicle Configurations

Conf	Lift	Performance Measure						
		SRT (g)	HSOT (m)	LTR	TOT (m)	LSOT (m)	RO (m)	FD
		>0.400	<0.460	<0.600	<0.800	<5.600	<0.200	<0.100
12S113	Down	**0.392**	**0.529**	**0.601**	**0.813**	4.005	0.102	**0.675**
12S113	Up	**0.355**	**0.638**	0.570	0.757	5.165	0.033	**0.143**
12S131	Down	**0.398**	**0.557**	0.580	0.793	4.003	0.091	**0.611**
12S131	Up	**0.335**	**0.607**	**0.705**	**0.910**	4.177	**0.254**	**0.112**
12S114	Down	0.427	**0.480**	0.594	0.785			
12S114	Up	**0.378**	**0.571**	0.539	0.690	4.977	0.059	0.070
12S141	Down	0.429	**0.511**	**0.612**	**0.859**			
12S141	Up	**0.366**	**0.549**	**0.666**	**0.856**	4.059	**0.235**	0.099
12S1112	Down	0.431	**0.495**	**0.613**	**0.869**			
12S1112	Up	**0.371**	**0.632**	0.516	0.695	**5.832**	0.007	0.034
12S14	Down	0.424	0.380	0.591	0.628	3.452	0.057	**0.507**
12S14	Up	**0.383**	0.455	**0.606**	0.673	3.764	0.067	0.095
12S15	Down	0.419	0.420	**0.639**	0.753			
12S15	Up	**0.366**	**0.522**	**0.614**	0.743	4.058	0.090	**0.106**
12S6	Down	0.422	0.403	**0.629**	0.690	3.032	0.094	**0.619**
12S6	Up	**0.371**	**0.494**	**0.659**	0.766	3.602	0.089	**0.122**
12S7	Down	0.418	0.403	**0.624**	0.668	3.134	0.093	**0.514**
12S7	Up	**0.373**	**0.497**	**0.631**	0.749	3.633	0.089	**0.109**
12S8	Down	0.445	0.414	0.591	0.727			
12S8	Up	**0.383**	0.513	0.574	0.715	4.089	0.084	0.097

All configurations except 12S8 also fail the load transfer ratio performance standard by a small margin, and all 14.65 m (48 ft) semitrailers except 12S114 fail the transient offtracking performance standard.

The semitrailers in these existing configurations all have at least five axles spread over a distance of 6.10 m (20 ft) or more, and a relatively short wheelbase. A 16.20 m (53 ft) semitrailer with a 3.66 m (144 in) spread tridem has a friction demand in the range 0.15-0.20. These configurations all have such high friction demand that it is virtually impossible to turn the vehicle when all the liftable axles are down. Even though the simulation may be able to evaluate the performance measures in this situation, the values are not meaningful, and some are not shown for this reason. The designers of these vehicles have chosen the number and location of liftable axles so that when they are raised, only a tandem or tridem remains on the ground, and the friction demand is reduced to the range 0.03 to 0.15 or so, typical for a tandem or tridem semitrailer. However, the tractor drive and remaining semitrailer axles may be severely overloaded, which increases road wear and the risk of failure of roadway structures. In addition, configurations 12S131 and 12S141, which have large effective rear overhangs, fail the rear outswing performance standard.

5. BASELINE CONFIGURATION

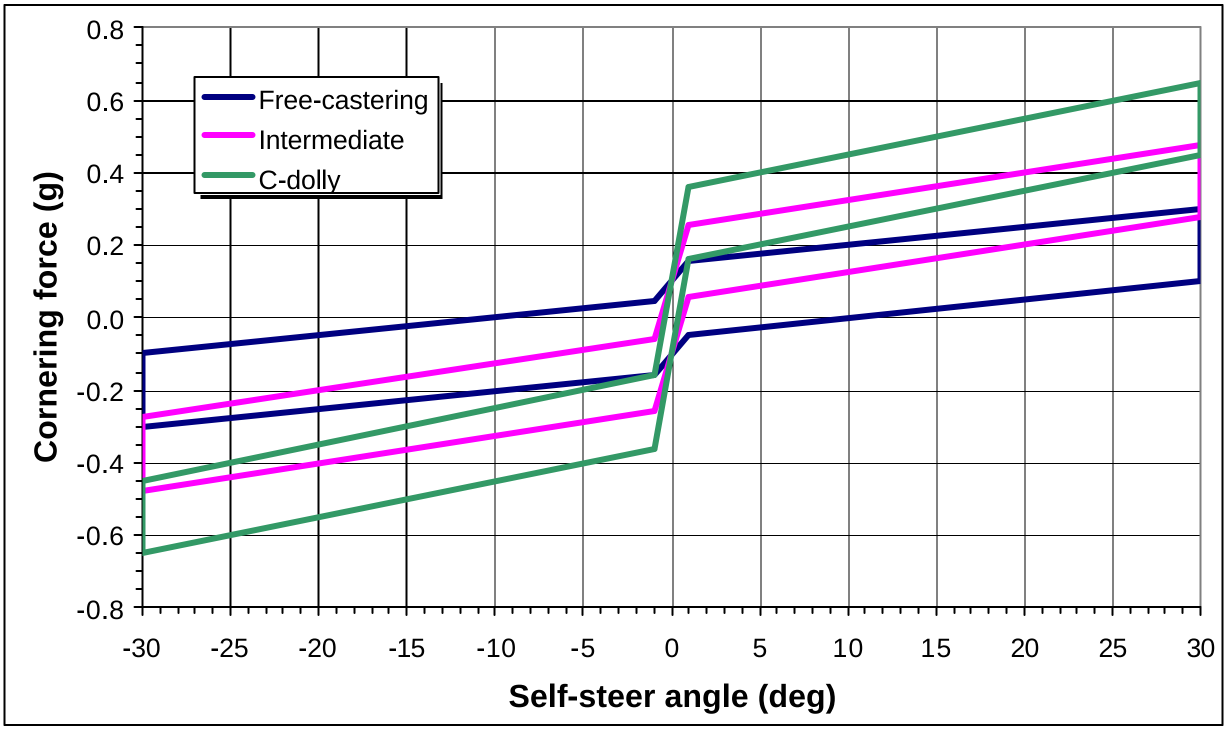
The self-steer quad semitrailer as defined in Ontario and Québec rules has been accepted as a heavy haul “infrastructure-friendly” vehicle. The performance of this configuration does push the performance standards discussed in Chapter 2, but that performance has been accepted by MTO, so it can serve as a baseline against which the performance of the candidate vehicles can be measured.

Figure 15 shows the dimensions for a typical self-steer quad semitrailer as defined in Ontario and Québec rules. The symbol **S** indicates the liftable self-steering axle. The load must be equalized between the four axles on the semitrailer, but the semitrailer may be fitted with a switch that allows load equalization to be disabled for operation outside Ontario and Québec. This configuration is primarily useful for domestic traffic within Ontario and Québec, and for traffic between these provinces. The location of a possible “invisible” liftable axle to allow a compromise for use in Michigan is shown by a ghost image. The self-steering axle must be at least 2.77 m (109 in) ahead of the tridem to maximize allowable gross weight in Michigan, and the “invisible” liftable axle must be at least 2.77 m (109 in) ahead of the self-steering axle, and down. A 14.65 m (48 ft) semitrailer allows sufficient space to achieve an inter-vehicle-unit distance of 2.77 m (109 in).

The location and self-steer characteristics of the self-steering axle affects certain of the performance measures. Table 24 identifies a number of variations in the dimension A shown in Figure 15 that should allow the effect of self-steer axle location and steer characteristics on self-steer angle to be determined. Each of these was evaluated for the three self-steer characteristics shown in Figure 14. A free-castering self-steer characteristic is typical of many axles used in the pusher position on straight trucks. At the other end of the range, CMVSS 903 requires very high on-centre stiffness for a C-dolly [16], but once the axle starts to steer, it may steer quite freely. This self-steer characteristic ensures that the C-dolly axle does not steer significantly in a moderate evasive or turning manoeuvre, which allows a C-train to approximate the dynamic performance of a B-train. However, if the manoeuvre is so aggressive that the axle does steer, then large high-speed or transient offtracking is possible, which can result in the trailers running off the road or into an adjacent traffic lane. CMVSS 903 addresses this by allowing, but not requiring, a speed-sensitive lock that prevents the axle from steering at highway speed [16]. . When the vehicle makes a low-speed turn, the forces induced by turning quickly become very high, overcome the high on-centre stiffness, and the much lower off-center stiffness allows the axle to steer easily. The medium characteristic is simply set half way between the free castering and C-dolly levels, to show trends relative to the self-steer characteristic, and to allow interpolation of results. The loop formations seen in Figure 14 are due to Coulomb friction in the steering system. The simulation does not limit the self-steer angle, but allows it to increase as necessary, so that the maximum necessary self-steer angle can be determined.

The simulation used a single tire on the self-steering axle. The choice of a single tire or dual tires, and tire size, is not particularly relevant for dynamic performance of the vehicle, as long as the self-steer limit is not reached. The self-steering axle simply aligns itself with the local

Figure 14: Self-steering Axle Steer Characteristics



direction of travel against the resistance provided by the stiffness and friction of the self-steering system. Any choice of tire size or arrangement allows the axle to steer properly, and the lateral force capacity of the tires will only be challenged if the steer limit is reached in a tight turn. The choice of tire size and arrangement is much more significant to geometric clearances within the self-steering system, which determine the maximum self-steer angle, and to management of the vehicle within a carrier's fleet.

Table 25 shows the allowable gross and axle weights under Ontario and Michigan rules. The self-steering axle must be at least 2.77 m (109 in) ahead of the tridem to achieve the Michigan weights shown in the table, and the "invisible" liftable axle must be at least 2.77 m (109 in) ahead of the self-steering axle, and down. The table also shows the actual gross and axle weights for each location of the self-steering axle, for a payload of 38,555 kg (85,000 lb) uniformly distributed along the entire length of the semitrailer.

Table 26 presents the performance measures derived from the simulation runs using a self-steering axle. The payload with a high centre of gravity is the critical case for the high-speed performance measures. The centre of gravity height has little effect on the low-speed performance measures. All axle configurations fail the high-speed offtracking performance measure for a payload with a high centre of gravity, but by less than 0.05 m (2 in). All vehicles also fail friction demand, but a friction demand around 0.2 is common for many tridem semitrailers that operate freely in all provinces under the M.o.U. Table 27 shows the friction demand for the standard heavy haul container chassis developed from the M.o.U., which has a trombone frame to accommodate containers from 12.19 m to 16.2 m (40 to 53 ft) in length, and a sliding 3.66 m (144 in) spread tridem bogie to ensure proper distribution of the payload to the axle groups. Friction demand was computed for this chassis with 12.19 m, 13.71 m, 14.65 m and 16.20 m (40 ft, 45 ft, 48 ft and 53 ft) containers, each grossing 30,480 kg (67,200 lb), for a gross vehicle weight of about 45,400 kg (100,000 lb). It is seen that the friction demand diminishes as the trailer wheelbase increases, but is in the range 0.16-0.20, and always exceeds the performance standard. Early versions of the M.o.U. required a wheelbase of at least 9.5 m (374 in) on a 3.66 m (144 in) spread tridem semitrailer, to control friction demand. This would be equivalent to about a 12.8 m (42 ft) container in Table 27, if such a container existed. Ontario and Québec have only imposed M.o.U. limits on semitrailers longer than 14.65 m (48 ft). The 9.5 m wheelbase limit was irrelevant for such long semitrailers, where the 35% rear overhang limit controls minimum wheelbase. The 9.5 m (374 in) limit does not appear in the 1997 M.o.U., so presumably has been dropped.

Friction demand and maximum self-steer angle both increase as single axle spacing and self-steer centring force characteristic increase. The static roll threshold, high-speed offtracking, load transfer ratio, transient offtracking, rear outswing and lateral friction utilization performance measures are hardly affected by the range of variation in single axle spacing and self-steer characteristic shown in Table 24.

Figure 16 shows that the maximum self-steer angle in a low-speed right-hand turn with a 12.00 m (39.4 ft) radius at the left front wheel increases as single axle spacing increases, and increases as self-steer centring stiffness decreases. The 12.00 m (39.4 ft) turn radius is close to full lock for the 6.20 m (244 in) wheelbase tractor used here.

Figure 17 shows that the friction demand in a low-speed right-hand turn with a 14.00 m (46 ft) radius at the left front wheel increases slightly as single axle spacing increases, and increases as self-steer centring stiffness increases.

Figure 18 shows that offtracking in a low-speed right-hand turn with a 14.00 m (46 ft) radius at the left front wheel is hardly affected by the single axle spacing, but decreases as self-steer centring stiffness increases, because this provides a small increase in turning resistance, which is equivalent to a small reduction in the equivalent wheelbase of the semitrailer. However, the low-speed offtracking is well within the performance standard for the range of parameters covered.

It appears preferable to use a self-steering axle with the minimum practical centring stiffness to reduce friction demand, and with the minimum practical single axle spacing to reduce self-steer angle. The minimum practical centring stiffness is that which is just sufficient to cause the steer to centre when the axle is raised, as long as the mechanical trail provided by the rearward setting of the axle spindle behind the vertical steer axis is sufficient to ensure dynamic tracking stability, so that the axle is free of shimmy.

Figure 15: Baseline Configuration 12S13

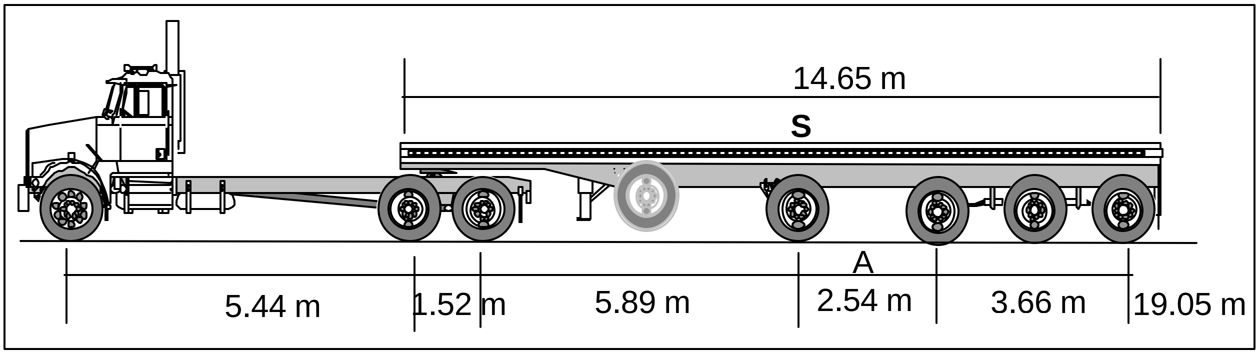


Table 24: Parametric Variations for Baseline Configuration 12S13

Case	A	Self-steer
1a	2.54 m	Low
1b	2.54 m	Medium
1c	2.54 m	High
2a	2.77 m	Low
2b	2.77 m	Medium
2c	2.77 m	High
3a	3.00 m	Low
3b	3.00 m	Medium
3c	3.00 m	High

Table 25: Weights for Baseline Configuration 12S13

Rules	Gross	Front	Drive	Single	Single	Tridem
Ontario allowable	57,500 kg (126,764 lb)	5,443 kg (12,000 lb)	18,000 kg (39,684 lb)		8,500 kg (17,636 lb)	25,500 kg (52,910 lb)
Michigan allowable	53,978 kg (119,000 lb)	5,443 kg (12,000 lb)	14,515 kg (32,000 lb)	8,164 kg (18,000 lb)	8,164 kg (18,000 lb)	17,690 kg (39,000 lb)
Actual Case 1	57,199 kg (126,100 lb)	5,412 kg (11,932 lb)	18,024 kg (39,735 lb)		8,543 kg (18,883 lb)	25,220 kg (55,600 lb)
Actual Case 2	57,199 kg (126,100 lb)	5,402 kg (11,910 lb)	17,863 kg (39,380 lb)		8,585 kg (18,927 lb)	25,348 kg (55,882 lb)
Actual Case 3	57,199 kg (126,100 lb)	5,392 kg (11,889 lb)	17,700 kg (39,022 lb)		8,629 kg (19,022 lb)	25,477 kg (56,167 lb)

Table 26: Performance Measures for Baseline Configuration 12S13

CG	Case	Performance Measure								
		SRT (g)	HSOT (m)	LTR	TOT (m)	LSOT (m)	RO (m)	FD	LFU	MSSA (deg)
		>0.400	<0.460	<0.600	<0.800	<5.600	<0.200	<0.100	<0.800	<20.0
Low	1a	0.621	0.450	0.344	0.566	4.972	0.044	**0.185**	0.606	17.13
Low	1b	0.628	0.440	0.348	0.568	4.893	0.052	**0.231**	0.598	15.31
Low	1c	0.643	0.434	0.350	0.568	4.808	0.062	**0.267**	0.585	14.04
Low	2a	0.602	0.459	0.346	0.574	4.975	0.044	**0.199**	0.617	18.09
Low	2b	0.640	0.442	0.350	0.575	4.890	0.055	**0.245**	0.591	16.41
Low	2c	0.620	0.436	0.352	0.576	4.805	0.059	**0.278**	0.586	15.01
Low	3a	0.625	0.456	0.348	0.581	4.971	0.047	**0.206**	0.593	18.83
Low	3b	0.627	0.443	0.352	0.583	4.887	0.052	**0.247**	0.600	17.12
Low	3c	0.623	0.439	0.355	0.585	4.792	0.059	**0.292**	0.573	15.71
High	1a	0.429	**0.496**	0.515	0.654	4.972	0.045	**0.199**	0.605	17.06
High	1b	0.431	**0.481**	0.514	0.645	4.887	0.054	**0.233**	0.600	15.33
High	1c	0.428	**0.474**	0.517	0.646	4.804	0.065	**0.267**	0.585	13.84
High	2a	0.435	**0.498**	0.517	0.666	4.971	0.046	**0.190**	0.609	18.37
High	2b	0.428	**0.483**	0.516	0.654	4.889	0.054	**0.237**	0.601	16.60
High	2c	0.428	**0.476**	0.519	0.655	4.795	0.063	**0.276**	0.578	14.85
High	3a	0.429	**0.499**	0.510	0.654	4.971	0.044	**0.195**	0.606	18.89
High	3b	0.433	**0.485**	0.519	0.663	4.880	0.053	**0.251**	0.585	17.15
High	3c	0.430	**0.479**	0.523	0.664	4.792	0.060	**0.290**	0.571	15.65

Table 27: Friction Demand for Tridem Semitrailers

Vehicle	Friction demand
Container chassis – 40 ft container	0.202
Container chassis – 45 ft container	0.175
Container chassis – 48 ft container	0.174
Container chassis – 53 ft container	0.165

Figure 16: Effect of Single Axle Spacing and Self-steer Characteristic on Maximum Self-steer Angle, 12 m Radius Turn

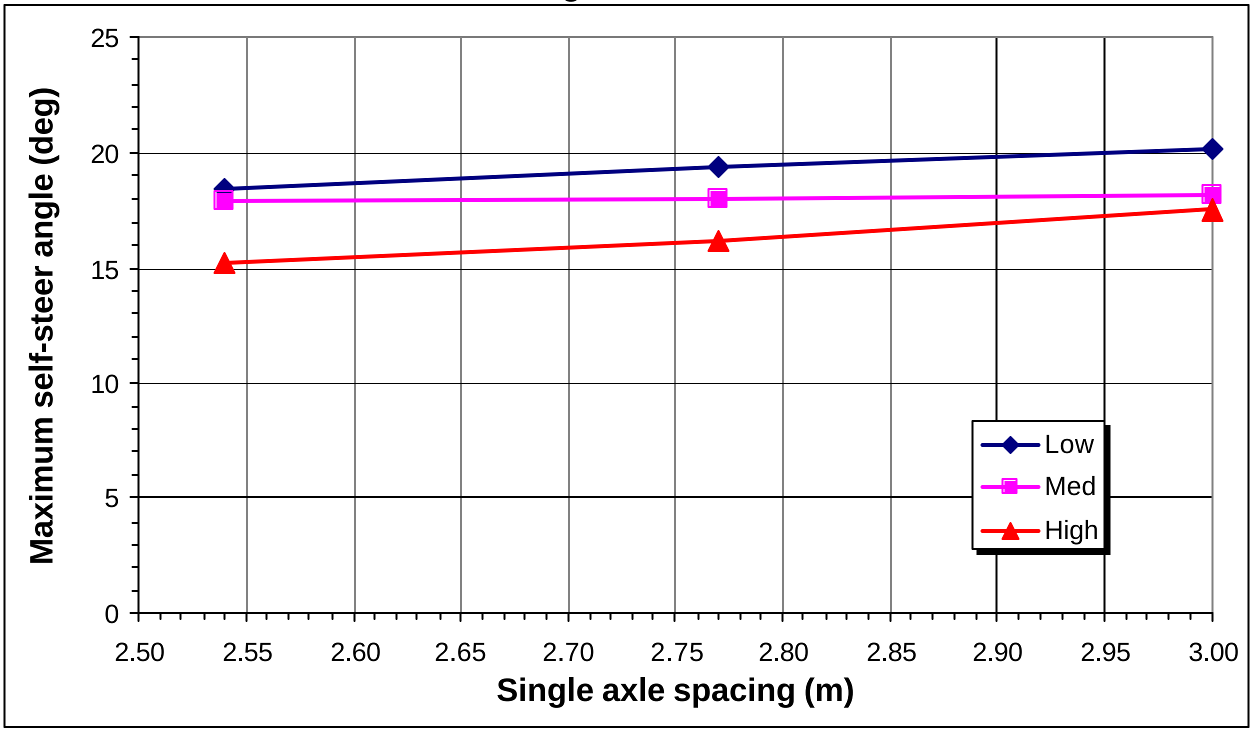


Figure 17: Effect of Single Axle Spacing and Self-steer Characteristic on Friction Demand, 14 m Radius Turn

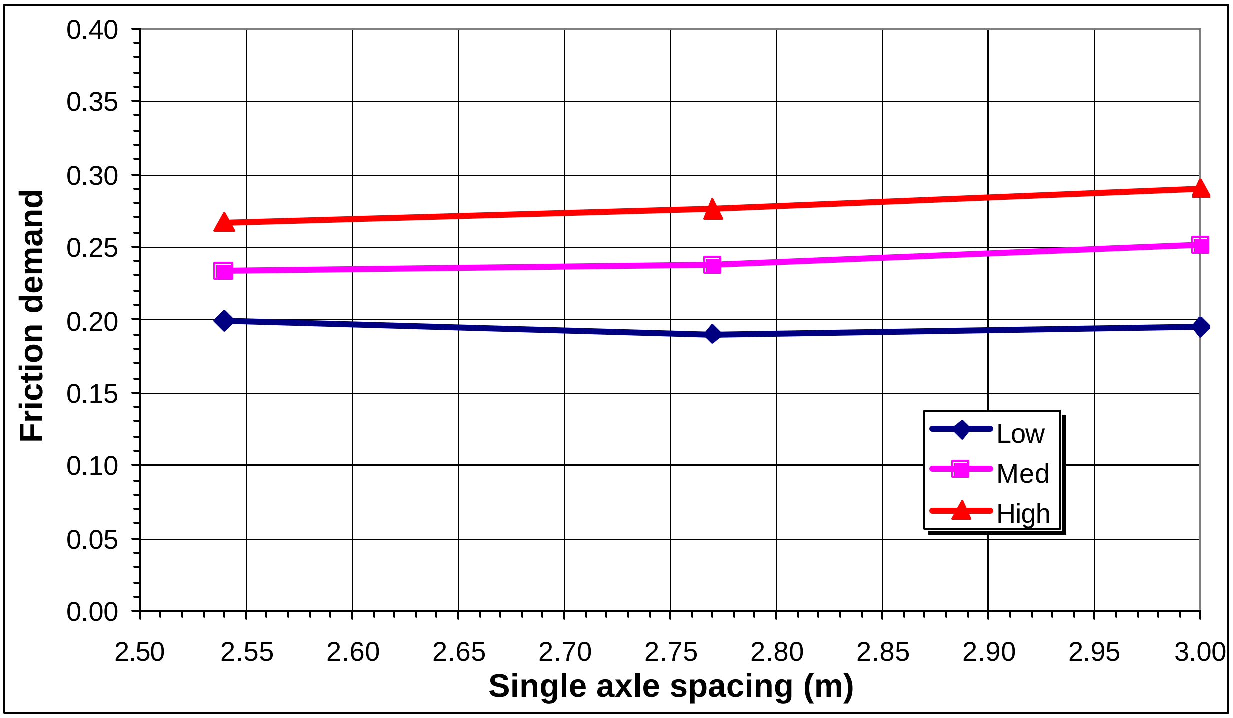
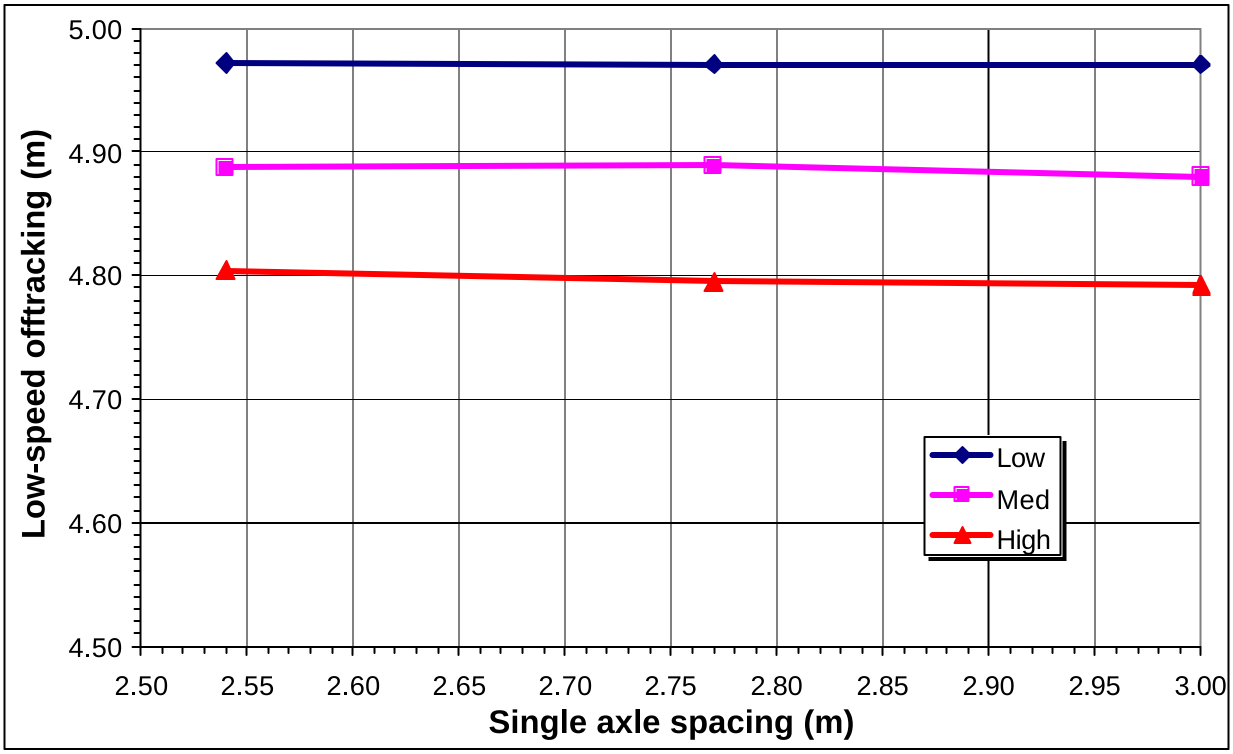


Figure 18: Effect of Single Axle Spacing and Self-steer Characteristic on Low-speed Offtracking, 14 m Radius Turn



6. CANDIDATE CONFIGURATIONS

6.1 Principles for Configuration of "Infrastructure-friendly" Vehicles

The existing semitrailers designated as "infrastructure-friendly" have been configured generally according to the following principles:

- The load carried by all axles on a semitrailer must be shared equally among those axles when the semitrailer is operated in Ontario;
- The axles of a self-steer quad semitrailer must have a device that allows the load on those axles to be determined;
- Self-steering axles may be used in Ontario, provided they have sufficient steer capability for their location on the semitrailer;
- A semitrailer must have more fixed axles than self-steering axles;
- A self-steering axle may be fitted with single or dual tires;
- A self-steering axle may be liftable, but any lift or axle load dump control must not be accessible to a driver in the cab;
- A self-steering axle may lift automatically only when the driver reverses the vehicle;
- Rigid "invisible" liftable axles may be fitted for use in another jurisdiction, as long as they are always raised in Ontario; and
- Load equalization may be disabled for operation in other jurisdictions.

These principles were suitable to develop the axle configuration of candidate "infrastructure-friendly" multi-axle semitrailers for this work. They do not address some of the issues that are likely to arise from use of two self-steering axles. The intention is that these issues should be addressed by this work.

6.2 Introduction

MTO identified the following primary candidate configurations:

- 12S113;
- 12S131;
- 12S114;
- 12S141;
- 13S13;
- 112S13; and
- 22S13.

These configurations were selected based on prior work that established that it might be possible to configure them to meet the performance standards outlined in Chapter 2 [18]. The axle configurations of the candidate configurations were adjusted from those of existing vehicles as necessary to achieve a gross weight comparable to that of existing configurations while equalizing the weight on each axle on the semitrailer. In each case, the symbol **S** in a diagram indicates a liftable self-steering axle. Other existing configurations were not considered as candidates, in the certain expectation that the work would show there would be no feasible adjustment that would allow them to meet the performance standards, or because the axle capacity and gross weight would be significantly less than that of a comparable existing configuration.

The following tridem axle weights were used for this work:

- 22,500 kg (49,603 lb) for 2.8 to less than 3.0 m (110 to 118 in) spread;
- 24,000 kg (52,910 lb) for 3.0 to less than 3.1 m (118 to 122 in) spread; and
- 25,500 kg (56,217 lb) for 3.6 to 3.7 m (142 to 146 in) spread.

The first of these is new, and the other two are consistent with weights allowed on the corresponding tridem on a self-steer quad. These allow 7,500, 8,000 and 8,500 kg (16,534, 17,636 and 18,739 lb) respectively on a single axle when the load is equalized between all axles in the group. A weight of 26,000 kg (57,319 lb) is also used on a four axle group with a 3.90 to 4.00 m (153 to 157 in) spread. The tridem axle weights were developed on the assumption that the tridem would be alone, or the tridem would be part of a self-steer quad. Bridge loading considerations may require a minimum spacing when a tridem or four axle group at one of these weights is placed next to a tandem axle. If this results in a vehicle that does not have acceptable dynamic performance, the bridge loading considerations may limit the weight on those axle spacings that do provide acceptable dynamic performance.

The axle arrangements and spacings of each vehicle defined below maximize allowable gross weight either within Ontario, or as a compromise for operation between Ontario and Michigan. Each vehicle is also configured as closely as possible so that it can be loaded with cargo distributed uniformly along the full length of its deck, so that the configuration will be useful for cargo like municipal waste, liquids, logs, lumber, and long metal articles. Any of the vehicles can be loaded with heavy dense articles like metal coils or billets.

The same tractor is used for all configurations that use a tandem drive. This tractor has a 6.20 m (244 in) wheelbase and a 1.42 m (56 in) drive tandem spread. This makes use of the opportunity to close up the drive tandem spread, now that 18,000 kg (39,682 lb) is allowed on a drive tandem from 1.20 to less than 1.60 m (47 to 63 in) spread for a standard tractor pulling a single semitrailer. Closing up the drive tandem spread from 1.52 to 1.42 m (60 to 56 in) allows an extra 0.05 m (2 in) of inter-vehicle-unit distance, which may be helpful for some of these configurations. The tractor fifth wheel location is adjusted as necessary to ensure proper front axle loading.

6.3 Simulation Schedule for Candidate Configurations

Simulations of candidate configurations were conducted to assess “normal” and “ultimate” performance for payloads with a low and a high centre of gravity. The baseline configuration for each vehicle was as shown in Figure 19, Figure 27, Figure 35, Figure 43, Figure 51, and Figure 55.

Simulations were conducted for each vehicle as follows:

- With all self-steering axles on the vehicle assumed to have the same characteristics, as follows:
  - Essentially free-castering, with just sufficient centering force to centre the axle when it is lifted;
  - A self-steer characteristic meeting the CMVSS 903 C-dolly standard; and
  - A self-steer characteristic somewhere between these levels, as shown in Figure 14;
- With each self-steering axle individually locked for the high-speed manoeuvres;
- With all self-steering axles locked for the high-speed manoeuvres; and
- With each self-steering axle replaced with a rigid axle for the high-speed manoeuvres.

In addition, certain axle spacings were adjusted, to assess their effect on dynamic performance.

Each of the candidate configurations was also evaluated as configured for Ontario-Michigan operations, with “invisible” liftable axles deployed as indicated in Figure 26, Figure 34, Figure 42, Figure 52 and Figure 54, at the best allowable gross weight possible under Ontario or Michigan rules that does not exceed any allowable axle group weight under the rules of both jurisdictions. No parametric variations were feasible for any of these configurations, because there was no space remaining to move any axle or add another axle.

6.4 Candidate Configuration 12S113

Figure 19 shows the dimensions for this configuration for operation within Ontario. The two single axles ahead of the tridem are both self-steering, and form a dual axle because each carries the same axle load. The symbol **S** indicates a liftable self-steering axle. The steer angle required of a self-steering axle increases as the axle is placed further away from the turn centre of a semitrailer, and as the turn radius decreases. Table 28 identifies a number of variations in the dimensions A, B and C shown in Figure 19 that allow the effect of axle spacing and location on self-steer angle to be determined. This limit may be challenged if the first self-steering axle on this configuration is placed too far ahead of the second axle. It may not be possible to space the two self-steering axles 2.77 m (109 in) apart to achieve the maximum gross weight in Michigan if the most forward self-steer axle will bottom out during a turn at an intersection.

Table 29 shows the allowable gross and axle weights under Ontario and Michigan rules. This configuration preserves the current gross weight but sacrifices 1,900 kg (4,188 lb) of axle capacity if a 3.66 m (144 in) spread tridem is used. It sacrifices more axle capacity, but preserves gross weight, if a 3.05 m (120 in) spread tridem is used. It sacrifices allowable gross weight if a tridem spread narrower than 3.0 m (118 in) is used, so this is not likely to be an option for use in Ontario. The table also shows the actual gross and axle weights used in the simulations, for a payload of 42,184 kg (93,000 lb) uniformly distributed along the entire length of the semitrailer.

Table 30 presents the performance measures derived from the simulation runs, for payloads with a low and a high centre of gravity, and self-steering axles with a low centring force characteristic. There are no static rollover thresholds for the low centre of gravity cases, because the vehicle was unstable in yaw, it tended to spin out. The table shows that all axle arrangements fail the high-speed offtracking and friction demand performance standards, only one fails the transient offtracking performance standard, and all but one fail the maximum self-steer angle performance standard. In all cases, the governing self-steer angle is for axle 4, the foremost self-steering axle. The high-speed offtracking is consistently about 0.05 m (2 in) higher than that for the self-steer quad, shown in Table 26, which also consistently exceeds the performance standard by about 0.05 m (2 in). The friction demand with a 3.66 m (144 in) spread tridem exceeds that that for the self-steer quad, while the friction demand with a 3.05 m (120 in) spread tridem is comparable to that that for the self-steer quad, as shown in Table 26. The high-speed performance measures, high-speed offtracking, load transfer ratio and transient offtracking are all lower for a payload with a low centre of gravity than for a payload with a high centre of gravity. However, maximum self-steer angle is about 1.5 deg higher for the low centre of gravity, which is difficult to explain, since all other low-speed performance measures are hardly affected by centre of gravity height.

Table 31 presents friction demand and maximum self-steer angle performance measures derived from the simulation runs for the parametric variations given in Table 28 with self-steering axles with a low centring force characteristic and for turns of 12.00 and 14.00 m (39.4 and 46 ft) at the left front wheel. A 12.00 m (39.4 ft) turn radius is about the tightest turn possible with the tractor used in this simulation. A tighter turn would be possible with a shorter wheelbase tractor, though such a tractor would probably not normally pull this semitrailer in highway service. Self-steer axle offset is defined as the distance the axle is from the nominal turn centre of the semitrailer, which is considered the centre of the tridem. Resistance of the self-steering axles influences turning, and moves the actual turn centre a little forward of the nominal turn centre. Figure 20 shows the effect of self-steer offset on maximum self-steer angle for the two self-steering axles and turn radii. The trend lines shown are simple linear least-square fits to the data points. Axle 5, the rearmost self-steering axle, should be satisfactory with 20 deg of steer, but axle 4, the foremost self-steering axle, clearly requires a steer capability of at least 25 deg, and possibly more. Figure 21 shows the effect of self-steer offset on friction demand for the two turn radii. The steer capability requirement and friction demand are each reduced if a 3.05 m (120 in) spread tridem is used, and if the self-steer axle offset is reduced.

Table 32 presents the performance measures derived from the simulation runs for cases 1a and 2a from Table 28 for low, medium and high self-steering axle centring force characteristics. Table 33 presents friction demand and maximum self-steer angle performance measures derived from the simulation runs for cases 1a and 2a from Table 28 for low, medium and high self-steer axle centring force characteristics and turns of 12 and 14 m (39.4 and 46 ft) at the left front wheel. Figure 22 shows the effect of self-steer centring force characteristic on the maximum self-steer angle of Axle 4 for the two self-steering axles and turn radii, and Figure 23 shows the effect on friction demand for the 14 m (46 ft) turn radius. The steer capability requirement diminishes for each tridem spread as self-steer centring force increases, but the friction demand increases significantly.

Table 34 presents the high-speed performance measures derived from the simulation runs for cases 1a and 2a from Table 28 for all combinations of locked and steering self-steering axles with a low centring force characteristic. When a self-steering axle is locked, it still has capability to steer a small amount against the stiffness of the tie rods and bushings. Table 34 therefore also includes a case where the two self-steering axles are replaced by rigid axles with the same suspension and tire as the self-steering axle, which would be somewhat representative of the ultimate performance. Figure 24 shows that locking one or both self-steering axles makes a slight improvement in high-speed offtracking, but even with rigid axles, the vehicle still does not quite meet the performance standard. Figure 25 shows that locking one or both self-steering axles has little effect on transient offtracking. The tendency to rollover, as measured by the static rollover threshold and load transfer ratio, increases slightly as axles are locked.

Table 35 presents the ultimate high-speed performance measures derived from a lane change with a lateral acceleration of 0.30 g for cases 1a and 2a for all combinations of locked and steering self-steering axles with a low centring force. The transient offtracking is large, and does not change significantly as one or both self-steering axles are locked, or with rigid axles. However, the load transfer ratio progressively increases as axles are locked, and the vehicle rolls over when both are locked or rigid.

Figure 26 shows the dimensions of a vehicle configured to operate between Ontario and Michigan. The locations of possible "invisible" liftable axles to allow a compromise for use in Michigan are shown by ghost images. This configuration has one more axle than the 12S114 configuration it would replace. The 3.66 m (144 in) spread tridem cannot be used, because the inter-vehicle-unit distance drops below 2.77 m (109 in) which reduces the allowable gross weight in Michigan. A 3.05 m (120 in) spread tridem provides just enough space for a 2.77 m (109 in) inter-vehicle-unit distance. It is not likely that the two self-steering axles can be spread 2.77 m apart, which would save one axle.

Table 36 shows the allowable gross and axle weights under Ontario and Michigan rules. This configuration has one more axle than the 12S114 configuration it would replace, which increases its allowable gross weight in Michigan by 1,360 kg (3,000 lb) for a net payload gain of about 454 kg (1,000 lb). This configuration can be loaded to its gross weight with a payload of 39,462 kg (87,000 lb) set back 0.30 m (12 in) from the front of the semitrailer but otherwise uniformly distributed load along the entire length of the semitrailer without exceeding any allowable axle weight, under both Ontario rules with the "invisible" liftable axles raised and load equalization enabled, and under Michigan rules with them down and load equalization disabled.

Table 37 presents the performance measures derived from the simulation runs for self-steering axles with a low centring force characteristic. Low-speed performance measures are not reported with the "invisible" liftable axles down, even though the simulation computed results, because they are unrealistic and the vehicle certainly could not make the turn. The high-speed performance is better with the invisible liftable axles raised, though they are required to be down to generate the gross weight for Michigan.

This configuration may be marginally satisfactory if it has a 3.05 m (120 in) tridem spread and the self-steering axles are as close to each other as possible, and as close to the tridem as possible. A 20 deg steer angle should be satisfactory for the rearmost self-steering axle, but the foremost self-steer axle will certainly require more than 20 deg steer capability to avoid bottoming frequently in normal turns. High-speed dynamic performance is not greatly affected either by self-steer axle centring force characteristic or whether the self-steering axles are locked or free to steer. The centring force should be as low as possible to minimize friction demand.

Figure 19: Candidate Configuration 12S113 Configured for Ontario

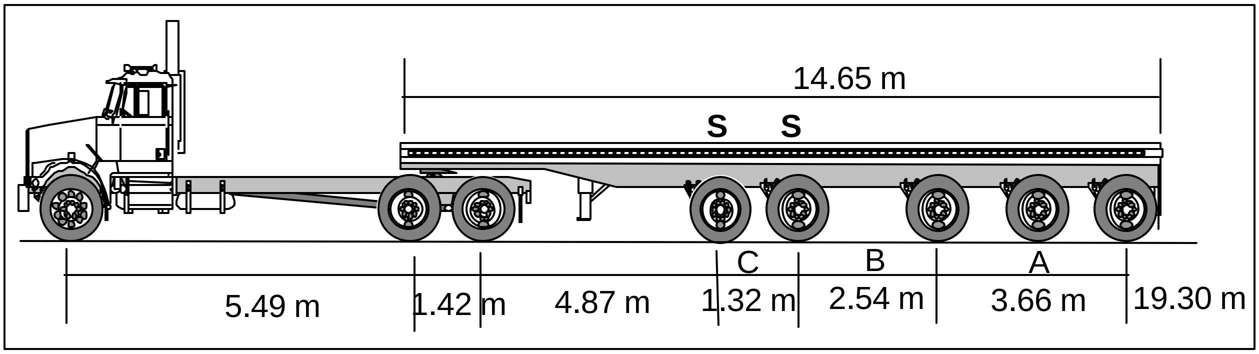


Table 28: Axle Spacing Parametric Variations for Candidate Configuration 12S113

Case	A	B	C
1a	3.66 m	2.54 m	1.32 m
1b	3.66 m	2.77 m	1.32 m
1c	3.66 m	3.00 m	1.32 m
1d	3.66 m	2.54 m	2.03 m
1e	3.66 m	2.77 m	2.77 m
2a	3.05 m	2.54 m	1.32 m
2b	3.05 m	2.77 m	1.32 m
2c	3.05 m	3.00 m	1.32 m
2d	3.05 m	2.54 m	2.03 m
2e	3.05 m	2.77 m	2.77 m

Table 29: Weights for Candidate Configuration 12S113

Rules	Gross	Front	Drive	Self-steer tandem	Tridem
Ontario	61,800 kg (136,244 lb)	5,443 kg (12,000 lb)	18,000 kg (39,684 lb)	17,000 kg (37,478 lb)	25,500 kg (52,910 lb)
Michigan	49,442 kg (109,000 lb)	5,443 kg (12,000 lb)	14,515 kg (32,000 lb)	11,793 kg (26,000 lb)	17,690 kg (39,000 lb)
Actual Case 1a	61,735 kg (136,100 lb)	5,351 kg (11,796 lb)	17,015 kg (37,511 lb)	15,910 kg (35,077 lb)	23,458 kg (51,716 lb)
Actual Case 1b	61,735 kg (136,100 lb)	5,331 kg (11,754 lb)	16,696 kg (36,808 lb)	16,046 kg (35,375 lb)	23,661 kg (52,163 lb)
Actual Case 1c	61,735 kg (136,100 lb)	5,312 kg (11,710 lb)	16,371 kg (36,092 lb)	16,184 kg (35,679 lb)	23,868 kg (52,619 lb)
Actual Case 1d	61,735 kg (136,100 lb)	5,320 kg (11,729 lb)	16,516 kg (36,412 lb)	16,122 kg (35,543 lb)	23,775 kg (52,415 lb)
Actual Case 1e	61,735 kg (136,100 lb)	5,267 kg (11,613 lb)	15,645 kg (34,491 lb)	16,492 kg (36,358 lb)	24,330 kg (53,638 lb)
Actual Case 2a	61,735 kg (136,100 lb)	5,028 kg (11,084 lb)	18,138 kg (39,987 lb)	15,590 kg (34,372 lb)	22,978 kg (50,657 lb)
Actual Case 2b	61,735 kg (136,100 lb)	5,017 kg (11,061 lb)	17,826 kg 39,298 lb)	15,720 kg 34,656 lb)	23,172 kg (51,084 lb)
Actual Case 2c	61,735 kg (136,100 lb)	5,006 kg (11,037 lb)	17,507 kg (38,597 lb)	15,852 kg 34,946 lb)	23,369 kg (51,520 lb)
Actual Case 2d	61,735 kg (136,100 lb)	5,011 kg (11,048 lb)	17,650 kg (38,910 lb)	15,792 kg (34,817 lb)	23,281 kg (51,325 lb)
Actual Case 2e	61,735 kg (136,100 lb)	4,982 kg (10,984 lb)	16,797 kg (37,030 lb)	16,146 kg (35,594 lb)	23,810 kg (52,491 lb)

Table 30: Performance Measures for Candidate Configuration 12S113

CG	Case	Performance Measure								
		SRT (g)	**HSOT (m)**	**LTR**	**TOT (m)**	**LSOT (m)**	**RO (m)**	**FD**	**LFU**	**MSSA (deg)**
		>0.400	**<0.460**	**<0.600**	**<0.800**	**<5.600**	**<0.200**	**<0.100**	**<0.800**	**<20.0**
Low	1a		**0.512**	0.365	0.660	4.996	0.039	**0.267**	0.550	**22.82**
Low	1b		**0.509**	0.369	0.681	4.980	0.042	**0.288**	0.538	**23.60**
Low	1c		**0.518**	0.374	0.698	4.979	0.037	**0.291**	0.526	**24.67**
Low	1d		**0.519**	0.370	0.691	4.988	0.038	**0.288**	0.529	**25.97**
Low	1e		**0.515**	0.382	0.740	4.957	0.038	**0.349**	0.514	**29.88**
Low	2a		**0.493**	0.357	0.637	5.070	0.039	**0.217**	0.597	**21.23**
Low	2b		**0.518**	0.361	0.653	5.065	0.036	**0.230**	0.568	**22.48**
Low	2c		**0.499**	0.366	0.668	5.056	0.040	**0.247**	0.575	**23.10**
Low	2d		**0.512**	0.364	0.664	5.062	0.039	**0.244**	0.572	**24.32**
Low	2e		**0.530**	0.373	0.710	5.038	0.036	**0.280**	0.549	**28.03**
High	1a	0.429	**0.563**	0.547	0.751	4.997	0.041	**0.263**	0.551	**21.49**
High	1b	0.437	**0.551**	0.553	0.767	4.989	0.043	**0.281**	0.528	**22.06**
High	1c	0.442	**0.577**	0.559	0.785	4.973	0.042	**0.313**	0.528	**22.73**
High	1d	0.432	**0.554**	0.554	0.779	4.987	0.041	**0.291**	0.534	**23.86**
High	1e	0.441	**0.578**	0.567	**0.828**	4.951	0.039	**0.355**	0.506	**27.31**
High	2a	0.433	**0.545**	0.536	0.721	5.068	0.037	**0.225**	0.580	19.63
High	2b	0.431	**0.545**	0.542	0.736	5.071	0.043	**0.219**	0.587	**20.61**
High	2c	0.440	**0.544**	0.551	0.751	5.060	0.043	**0.243**	0.555	**21.61**
High	2d	0.435	**0.561**	0.544	0.747	5.057	0.039	**0.237**	0.574	**22.34**
High	2e	0.441	**0.562**	0.557	0.794	5.040	0.040	**0.274**	0.540	**25.87**

Table 31: Effect of Self-steer Axle Offset on Low-speed Performance Measures

Case	Axle 5 Offset	Axle 4 Offset	Performance Measure 12 m Radius			Performance Measure 14 m Radius		
			FD	MSSA5 (deg)	MSSA4 (deg)	FD	MSSA5 (deg)	MSSA4 (deg)
			<0.100	<20.0	<20.0	<0.100	<20.0	<20.0
1a	4.37	5.69	**0.311**	17.55	**22.96**	**0.263**	16.64	**21.49**
1b	4.60	5.92	**0.321**	18.17	**23.76**	**0.281**	16.79	**22.06**
1c	4.83	6.15	**0.338**	19.57	**24.83**	**0.313**	17.50	**22.73**
1d	4.37	6.40	**0.333**	17.76	**25.73**	**0.291**	16.62	**23.86**
1e	4.60	7.37	**0.389**	18.81	**29.66**	**0.355**	16.93	**27.31**
2a	4.07	5.39	**0.248**	15.79	**21.16**	**0.225**	14.52	19.63
2b	4.30	5.62	**0.265**	17.01	**22.41**	**0.219**	15.75	**20.61**
2c	4.53	5.85	**0.270**	18.08	**23.22**	**0.243**	16.48	**21.61**
2d	4.07	6.10	**0.269**	16.51	**24.31**	**0.237**	14.85	**22.34**
2e	4.30	7.07	**0.312**	16.79	**28.14**	**0.274**	15.54	**25.87**

Notes: MSSA5 =maximum self-steer angle for axle 5, the rearmost self-steering axle
MSSA4 =maximum self-steer angle for axle 4, the foremost self-steering axle

Figure 20: Effect of Self-steer Axle Offset on Maximum Self-steer Angle

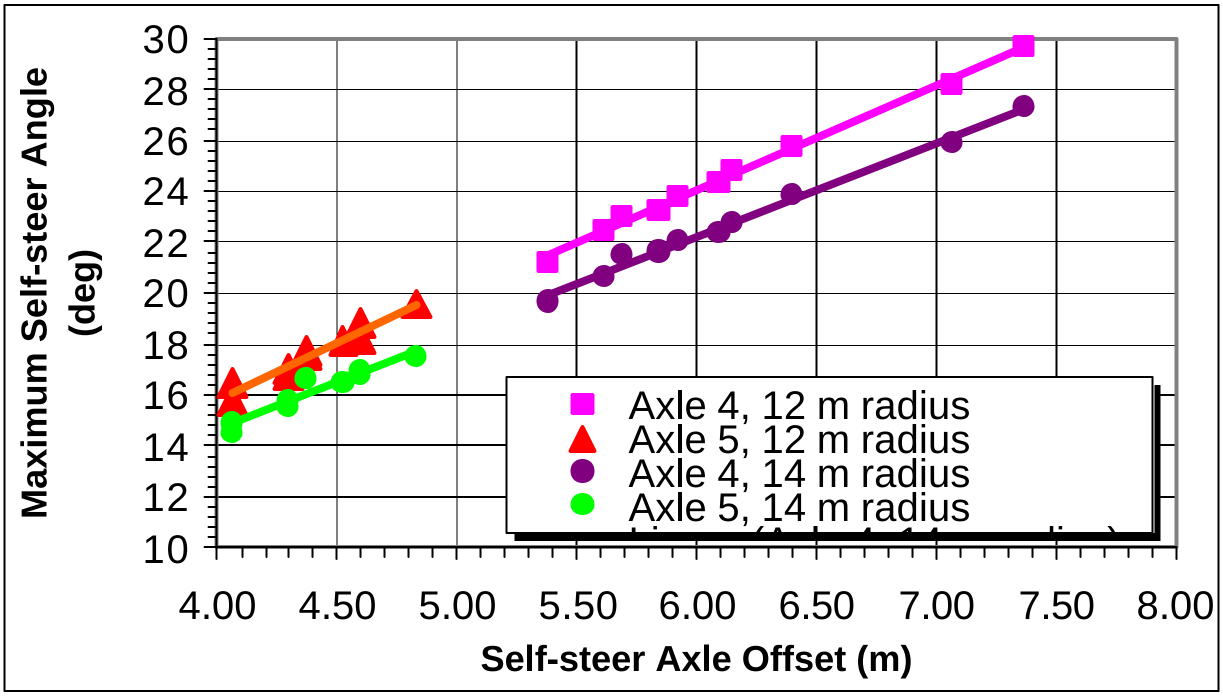


Figure 21: Effect of Self-steer Axle Offset on Friction Demand

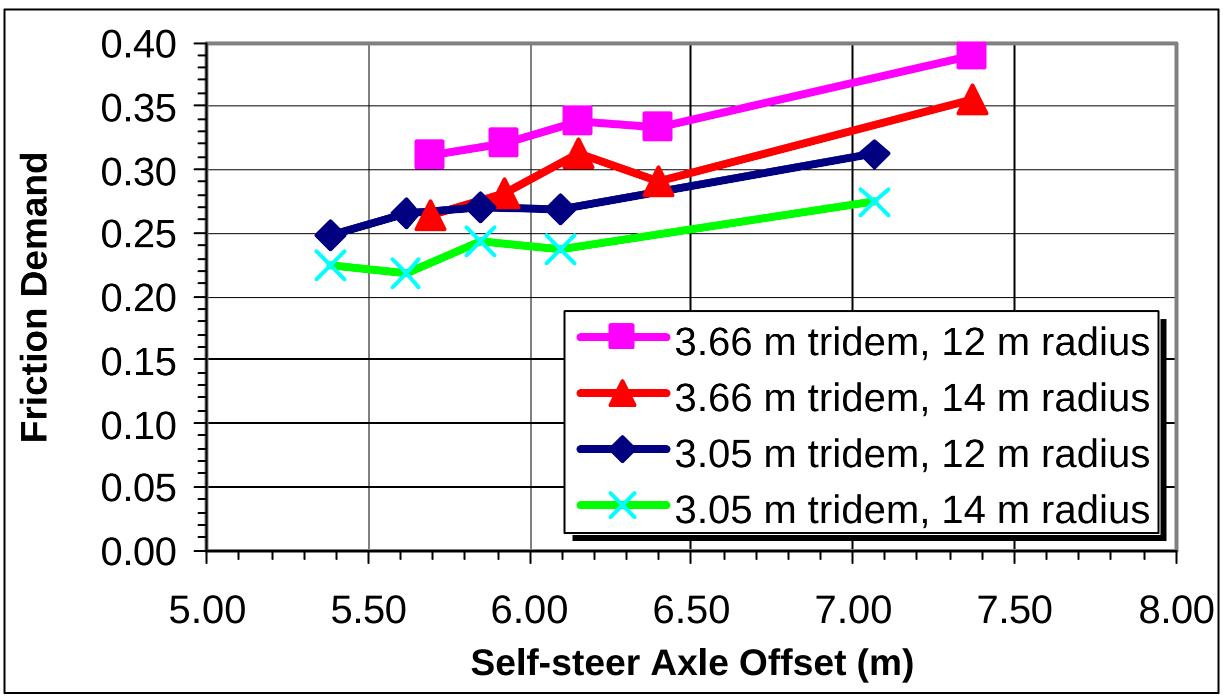


Table 32: Effect of Self-steer Axle Centring Force on Performance Measures

Case	SSA CF	Performance Measure								
		SRT (g)	HSOT (m)	LTR	TOT (m)	LSOT (m)	RO (m)	FD	LFU	MSSA (deg)
		>0.400	<0.460	<0.600	<0.800	<5.600	<0.200	<0.100	<0.800	<20.0
1a	Low	0.429	**0.563**	0.547	0.751	4.997	0.041	**0.263**	0.551	**21.49**
1a	Med	0.430	**0.522**	0.561	0.756	4.817	0.057	**0.352**	0.511	19.37
1a	High	0.424	**0.508**	0.568	0.760	4.630	0.071	**0.429**	0.521	17.66
2a	Low	0.433	**0.545**	0.536	0.721	5.068	0.037	**0.225**	0.580	19.63
2a	Med	0.424	**0.508**	0.549	0.723	4.905	0.056	**0.289**	0.540	18.06
2a	High	0.421	**0.498**	0.555	0.725	4.756	0.071	**0.357**	0.543	17.01

Table 33: Effect of Self-steer Centring Force on Low-speed Performance Measures

Case	SSA CF	Performance Measure 12 m Radius			Performance Measure 14 m Radius		
		FD	MSSA5 (deg)	MSSA4 (deg)	FD	MSSA5 (deg)	MSSA4 (deg)
		<0.100	<20.0	<20.0	<0.100	<20.0	<20.0
1a	Low	**0.311**	17.55	**22.96**	**0.263**	16.64	**21.49**
1a	Med	**0.391**	15.74	**21.53**	**0.352**	14.46	19.37
1a	High	**0.491**	13.87	18.82	**0.429**	13.11	17.66
2a	Low	**0.248**	15.79	**21.16**	**0.225**	14.52	19.63
2a	Med	**0.332**	14.53	19.29	**0.289**	12.97	18.06
2a	High	**0.399**	12.86	17.55	**0.357**	11.97	17.01

Figure 22: Effect of Self-steer Axle Centring Force on Maximum Self-steer Angle

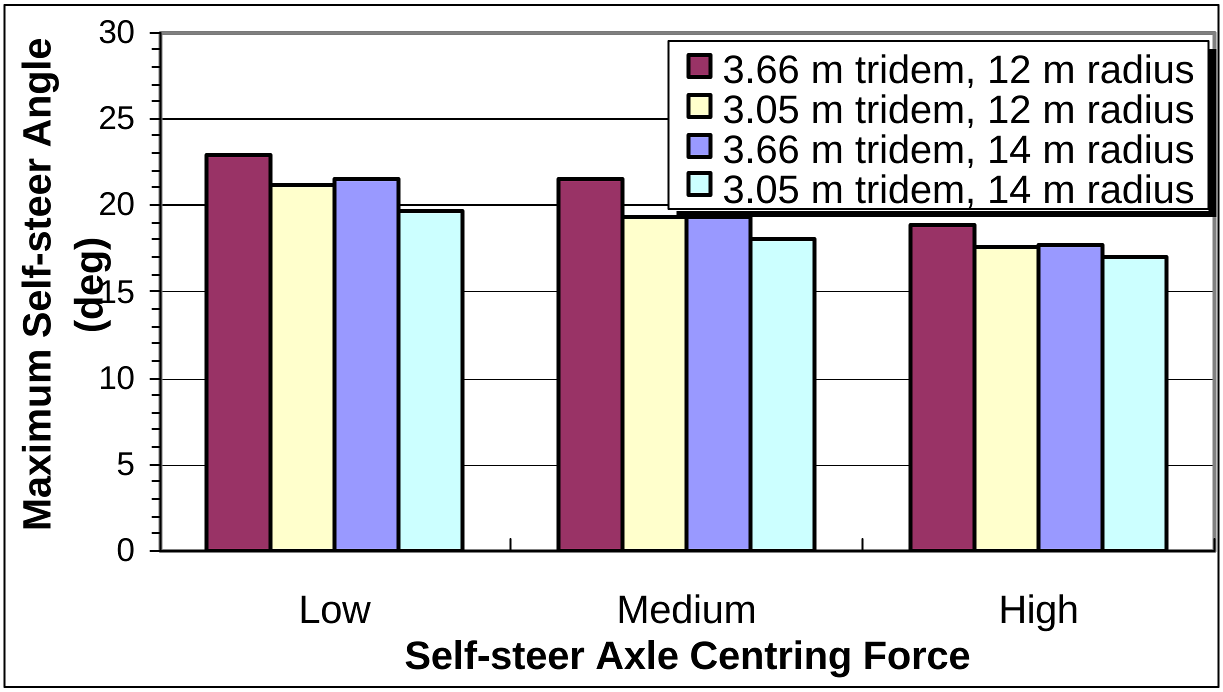


Figure 23: Effect of Self-steer Axle Centring Force on Friction Demand

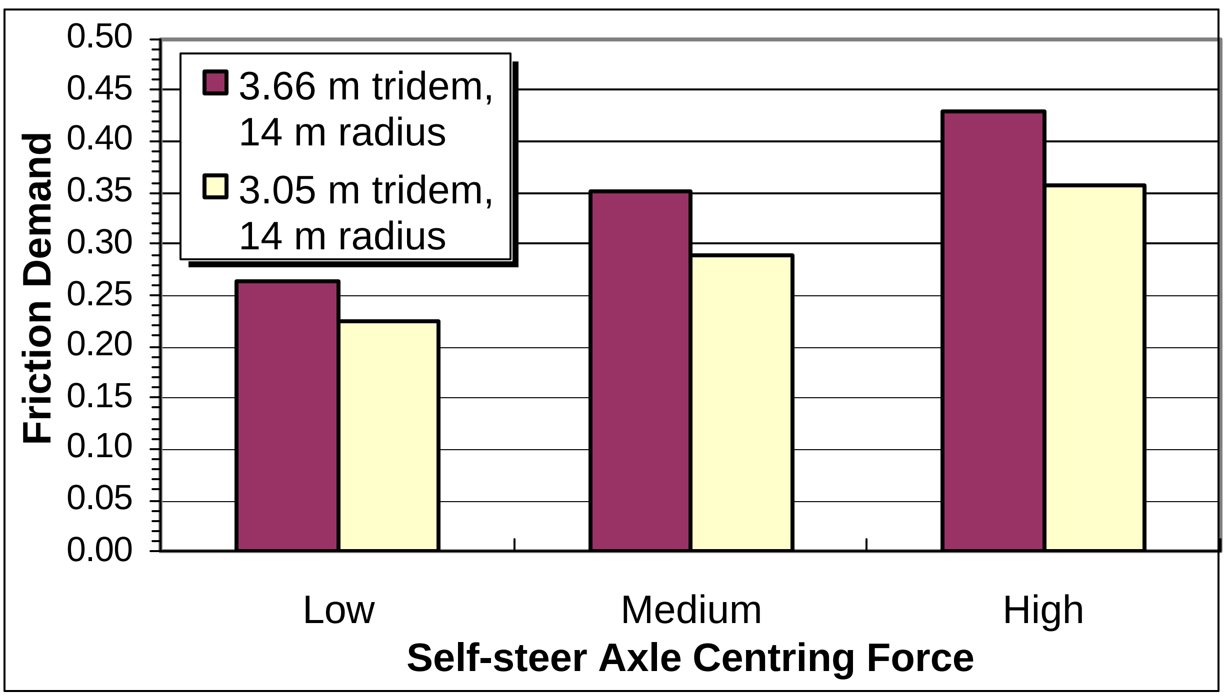


Table 34: Effect of Self-steer Axle Status on High-speed Performance Measures

Case	Axle 4 Status	Axle 5 Status	Performance Measure			
			SRT (g)	HSOT (m)	LTR	TOT (m)
			>0.400	<0.460	<0.600	<0.800
1a	Steer	Steer	0.429	**0.563**	0.547	0.751
1a	Lock	Steer	0.425	**0.525**	0.560	0.765
1a	Steer	Lock	0.425	**0.502**	0.570	0.757
1a	Lock	Lock	0.422	**0.479**	0.584	0.769
1a	Rigid	Rigid	0.422	**0.478**	0.587	0.766
2a	Steer	Steer	0.433	**0.545**	0.536	0.721
2a	Lock	Steer	0.431	**0.506**	0.549	0.728
2a	Steer	Lock	0.420	**0.526**	0.557	0.723
2a	Lock	Lock	0.419	**0.471**	0.568	0.731
2a	Rigid	Rigid	0.419	**0.470**	0.571	0.727

Table 35: Effect of Self-steer Axle Status on Ultimate Performance Measures

Case	Axle 4 Status	Axle 5 Status	Performance Measure	
			LTR	TOT (m)
1a	Steer	Steer	0.867	2.077
1a	Lock	Steer	0.955	2.153
1a	Steer	Lock	0.948	2.021
1a	Lock	Lock	Rollover	2.132
1a	Rigid	Rigid	Rollover	2.114
2a	Steer	Steer	0.837	2.077
2a	Lock	Steer	0.936	2.043
2a	Steer	Lock	0.932	1.943
2a	Lock	Lock	Rollover	1.932
2a	Rigid	Rigid	Rollover	1.925

Figure 24: Effect of Self-steer Axle Status on High-speed Offtracking

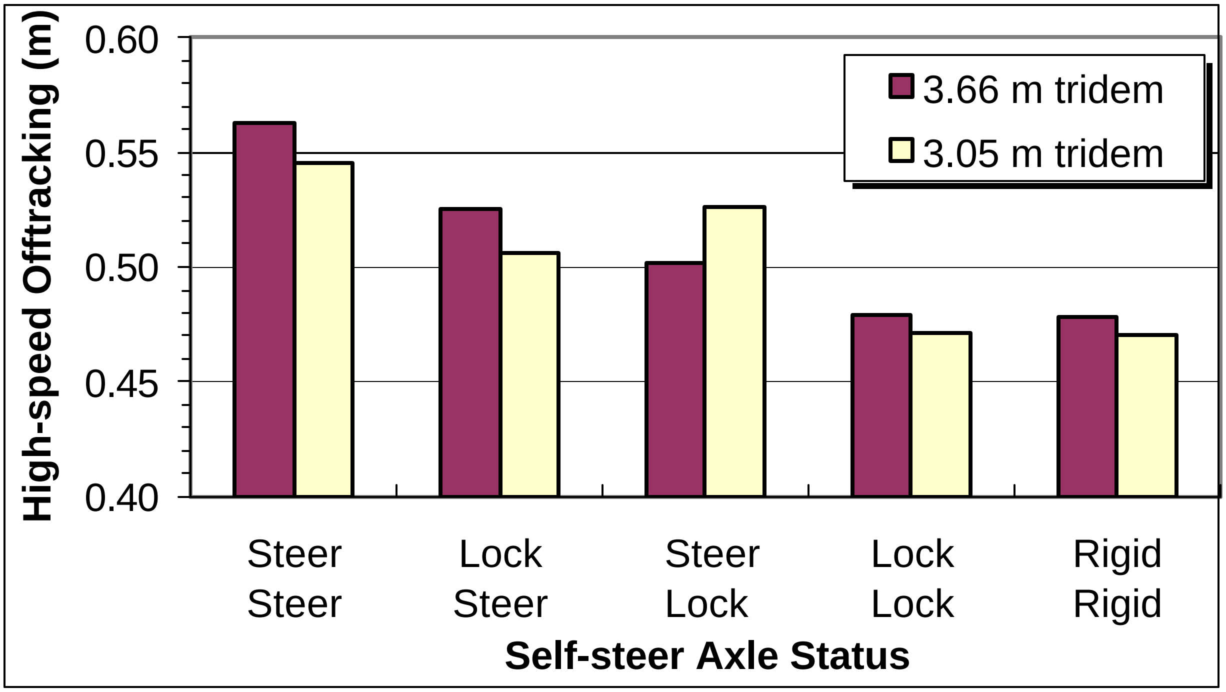


Figure 25: Effect of Self-steer Axle Status on Transient Offtracking

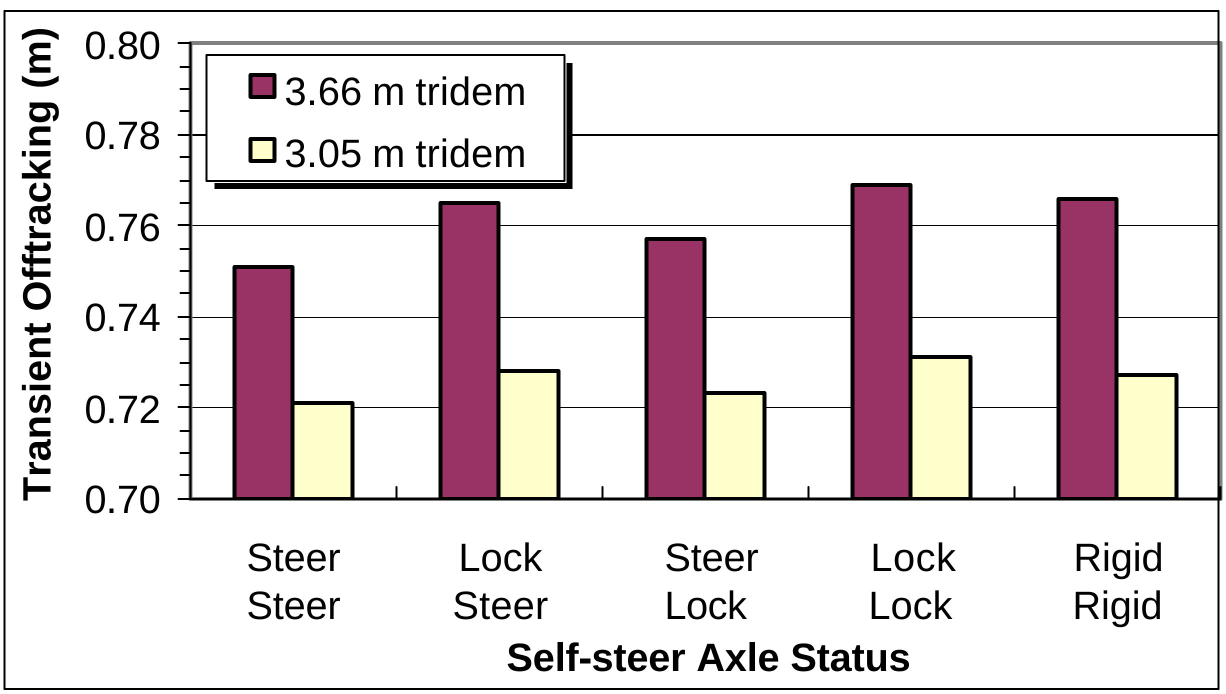


Figure 26: Candidate Configuration 12S113 Configured for Ontario-Michigan

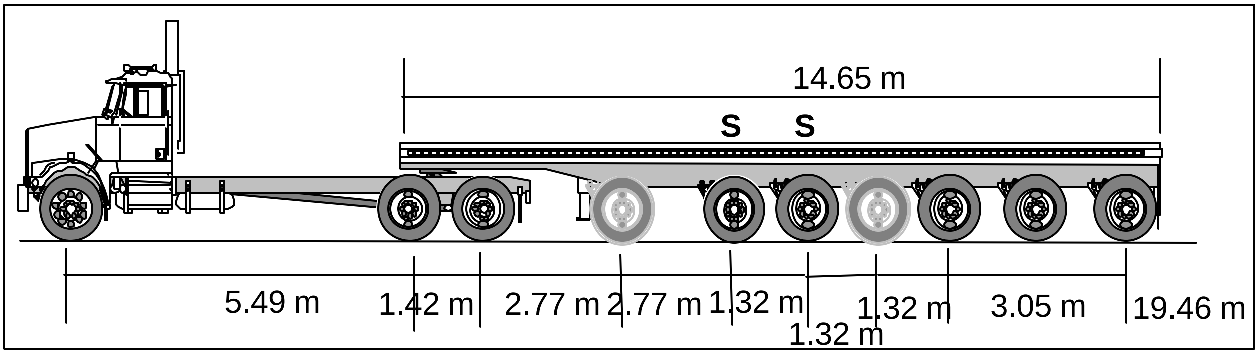


Table 36: Weights for Candidate Configuration 12S113

Rules	Gross	Front	Drive	Single	Self-steer tandem	Tridem/ 4-axle group
Ontario	61,800 kg (136,244 lb)	5,443 kg (12,000 lb)	18,000 kg (39,684 lb)		16,000 kg (35,273 lb)	24,000 kg (52,910 lb)
Michigan	63,503 kg (140,000 lb)	5,443 kg (12,000 lb)	14,515 kg (32,000 lb)	8,164 kg (18,000 lb)	11,793 kg (26,000 lb)	35,380 kg (52,000 lb)
Actual Lifts Up	60,827 kg (134,100 lb)	5,083 kg (11,206 lb)	19,772 kg (43,589 lb)		11,794 kg (26,000 lb)	24,179 kg (53,304 lb)
Actual Lifts Down	60,827 kg (134,100 lb)	4,852 kg (10,697 lb)	12,952 kg (28,554 lb)	8,165 kg (18,000 lb)	11,794 kg (26,000 lb)	23,065 kg (50,849 lb)

Table 37: Performance Measures for Candidate Configuration 12S113

CG	Lift	Performance Measure								
		SRT (g)	**HSOT (m)**	**LTR**	**TOT (m)**	**LSOT (m)**	**RO (m)**	**FD**	**LFU**	**MSSA (deg)**
		>0.400	**<0.460**	**<0.600**	**<0.800**	**<5.600**	**<0.200**	**<0.100**	**<0.800**	**<20.0**
Low	Down		**0.522**	0.388	**0.883**					
Low	Up		0.451	0.337	0.573	5.193	0.035	**0.206**	0.609	**21.34**
High	Down	0.488	**0.542**	0.548	**0.930**					
High	Up	0.459	**0.479**	0.491	0.639	5.186	0.032	**0.200**	0.602	**21.13**

6.5 Candidate Configuration 12S131

Figure 27 shows the dimensions for this configuration for operation within Ontario. The two single axles ahead and behind the tridem are both self-steering. Existing examples of configuration 12S131 typically use a 2.44 m (96 in) spread tridem, which has an allowable load of 21,300 kg (46,958 lb), and the semitrailer has an axle capacity of 41,300 kg (91,050 lb). If the single axles are constrained to the same weight as the axles of the tridem, each carries only 7,100 kg (15,652 lb), when the axle capacity of the semitrailer is reduced to 35,500 kg (78,263 lb) and it has hardly more payload than a self-steer quad. Increasing the tridem spread to 3.05 m (120 in) provides adequate axle capacity, but it also moves the tridem forward on the semitrailer, because the position of the last axle of the tridem is fixed relative to the last axle on the semitrailer. This increases the effective rear overhang over 50%, where 35% is the maximum allowed for semitrailers under Regulation 32/94. If this causes problems in meeting performance standards, the only option would be to slide the tridem rearward. The tridem and the rearmost axle would then become a four axle group, which would result in a significant reduction in both axle capacity and allowable gross weight. Table 38 identifies a number of variations on rear overhang, and their effect on the dimensions A, B and C shown in Figure 27.

Table 39 shows the allowable gross and axle weights under Ontario and Michigan rules. The weights given for Michigan assume that the two single axle spacings are 2.77 m (109 in). This configuration preserves the current gross weight but sacrifices 1,300 kg (2,866 lb) of axle capacity when a 3.05 m (120 in) spread tridem is used. The table also shows the actual gross and axle weights used in the simulation, for a payload of 42,184 kg (93,000 lb) uniformly distributed along the entire length of the semitrailer for all cases.

Table 40 presents the performance measures derived from the simulation runs, for payloads with a low and a high centre of gravity, and self-steering axles with a low centring force characteristic. The table shows that all axle arrangements fail the high-speed offtracking and friction demand performance standards, all but one fails the transient offtracking performance standard, and the most forward fails the rear outswing performance standard. In all cases, the governing self-steer angle is for axle 8, the rearmost self-steering axle, but this meets the performance standard. The high-speed offtracking is consistently about 0.10 m (4 in) higher than that for the self-steer quad, shown in Table 26, which also consistently exceeds the performance standard by about 0.05 m (2 in). The friction demand exceeds that that for the self-steer quad, as shown in Table 26. The high-speed performance measures, high-speed offtracking, load transfer ratio and transient offtracking are all lower for a payload with a low centre of gravity than for a payload with a high centre of gravity. Configuration 1b may be slightly preferable to configuration 1a, as it reduces all performance measures that exceed the performance standards.

Table 41 presents friction demand and maximum self-steer angle performance measures derived from the simulation runs for the parametric variations given in Table 38, self-steering axles with a low centring force characteristic, and turns of 12 and 14 m (39.4 and 46 ft) at the left front wheel. A 12 m (39.4 ft) turn radius is about the tightest turn possible with the steering of tractor used in this simulation. A tighter turn would be possible with a shorter wheelbase tractor, though such a tractor would probably not normally pull this semitrailer in highway service. Effective rear overhang is the distance from the centre of the tridem to the rear of the semitrailer as a percentage of the semitrailer wheelbase, from the kingpin to the centre of the tridem. Resistance of the self-steering axles influences turning, and moves the actual turn centre a little forward of the nominal turn centre. Figure 28 shows the effect of effective rear overhang on maximum self-steer angle for the two self-steering axles and turn radii. Axle 4, the foremost self-steering axle, should be satisfactory with 20 deg of steer with an effective rear overhang in the range 40-45%, and axle 8, the rearmost self-steering axle, is satisfactory with this steer regardless of effective rear overhang. Figure 29 shows the effect of effective rear overhang on friction demand for the two turn radii. The steer capability requirement is reduced for a more forward location of the tridem, but at the expense of a slight increase in friction demand.

Table 42 presents the performance measures derived from the simulation runs for cases 1a and 1b from Table 38 for low, medium and high self-steer axle centring force characteristics. Table 43 presents friction demand and maximum self-steer angle performance measures derived from the simulation runs for cases 1a and 1b from Table 38 for low, medium and high self-steer axle centring force characteristics and turns of 12 and 14 m (39.4 and 46 ft) at the left front wheel.

Figure 30 shows the effect of self-steer centring force characteristic on the maximum self-steer angle of Axle 4 for the two turn radii, and Figure 31 shows the effect on friction demand for the 14 m (46 ft) turn radius. The steer capability requirement diminishes as self-steer centring force increases, but the friction demand increases significantly, and is probably untenable even at the medium level. Again configuration 1b appears slightly preferable to configuration 1a.

Table 44 presents the high-speed performance measures derived from the simulation runs for cases 1a and 1b from Table 38, with self-steering axles with a low centring force characteristic, and all combinations of locked and steering self-steering axles. When a self-steering axle is locked, it still has capability to steer a small amount against the stiffness of the tie rods and bushings. Table 44 therefore also includes a case where the two self-steering axles are replaced by rigid axles with the same suspension and tire as the self-steering axle, which would be somewhat representative of the ultimate performance. Figure 32 shows that locking the rearmost, or both, self-steering axles makes some improvement in high-speed offtracking, but even with rigid axles, the vehicle still does not quite meet the performance standard. Figure 33 shows that locking the rearmost, or both, self-steering axles is necessary for the vehicle just to meet the transient offtracking performance standard. Locking both axles does increase the load transfer ratio slightly, but the vehicle still meets the performance standard. Again, configuration 1b appears slightly preferable.

Table 45 presents the ultimate high-speed performance measures derived from a lane change with a lateral acceleration of 0.30 g for cases 1a and 1b for all combinations of locked and steering self-steering axles. The transient offtracking is large, and diminishes as one or both self-steering axles are locked, or with rigid axles. However, the load transfer ratio progressively increases as axles are locked, and the vehicle rolls over when the foremost self-steering axle is locked, both are locked, or both are rigid. The response is clearly best when the rearmost self-steering is locked and the other is allowed to steer.

Figure 34 shows the dimensions of a vehicle configured to operate between Ontario and Michigan. The trailer is the same as that configured for Ontario, except the two self-steering axle spacings are adjusted to 2.64 m (104 in) to allow space for the “invisible” liftable axles that allow a compromise for use in Michigan, as shown by ghost images.

Table 46 shows the allowable gross and axle weights under Ontario and Michigan rules. This configuration has one more axle than the 12S141 configuration it would replace, which theoretically increases its allowable gross weight in Michigan by 1,360 kg (3,000 lb) for a net payload gain of about 454 kg (1,000 lb). However, the axle arrangement does not allow for any re-distribution of axle loads, so the configuration is restricted to a drive tandem weight of 14,515 kg (32,000 lb) in Ontario. This restricts the practical gross weight to about 60,000 kg (132,276 lb), which is about the same as the existing 12S141 configuration, but the additional axle results in about 907 kg (2,000 lb) less payload. This configuration can be loaded with a payload of 39,009 kg (86,000 lb) set back 0.30 m (12 in) from the front of the semitrailer but otherwise uniformly distributed load along the length of the semitrailer without exceeding any allowable axle weight, under both Ontario rules with the “invisible” liftable axles raised and load equalization enabled, and under Michigan rules with them down and load equalization disabled.

Table 47 presents the performance measures derived from the simulation runs, for self-steering axles with a low centring force characteristic. The simulation was able to compute results for the low-speed performance measures, but they are unrealistic and the vehicle certainly could not make the turn.

This configuration fails two high-speed and two low-speed performance standards with the tridem in the most forward location considered. Performance becomes more satisfactory as the tridem is moved rearward, though this could result in a reduction in axle weights, a factor not considered in this analysis, which would render the vehicle uneconomic. Its performance is hardly an improvement over the existing configuration. A 20 deg steer angle should be satisfactory for both self-steering axles. High-speed dynamic performance is significantly affected by the self-steer axle centring force characteristic and whether the axles are locked or free to steer. This configuration would require self-steering axles with a low centring force characteristic. The rearmost self-steering axle must be locked at high speed, and the other may be free to steer or locked.

Figure 27: Candidate Configuration 12S131 Configured for Ontario

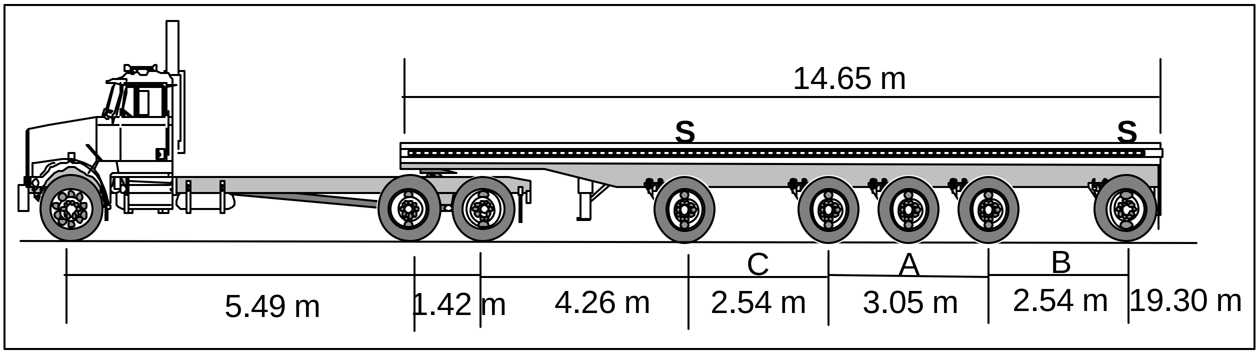


Table 38: Parametric Variations for Candidate Configuration 12S131

Case	Effective Rear Overhang	A	B	C
1a	50.8%	3.05 m	2.54 m	2.54 m
1b	45.3%	3.05 m	2.18 m	2.90 m
1c	40.2%	3.05 m	1.83 m	3.25 m
1d	35.1%	3.05 m	1.45 m	3.63 m

Table 39: Weights for Candidate Configuration 12S131

Rules	Gross	Front	Drive	Single	Tridem	Single
Ontario	61,800 kg (136,244 lb)	5,443 kg (12,000 lb)	18,000 kg (39,684 lb)	8,000 kg (17,636 lb)	24,000 kg (52,910 lb)	8,000 kg (17,636 lb)
Michigan	53,978 kg (119,000 lb)	5,443 kg (12,000 lb)	14,515 kg (32,000 lb)	8,164 kg (18,000 lb)	17,690 kg (39,000 lb)	8,164 kg (18,000 lb)
Actual Case 1a	61,735 kg (136,100 lb)	5,303 kg (11,690 lb)	16,225 kg (35,769 lb)	8,123 kg (17,908 lb)	23,961 kg (52,824 lb)	8,123 kg (17,908 lb)
Actual Case 1b	61,735 kg (136,100 lb)	5,349 kg (11,792 lb)	16,980 kg (37,434 lb)	7,963 kg (17,555 lb)	23,480 kg (51,765 lb)	7,963 kg (17,555 lb)
Actual Case 1c	61,735 kg (136,100 lb)	5,393 kg (11,889 lb)	17,702 kg (39,026 lb)	7,810 kg (17,217 lb)	23,021 kg (50,751 lb)	7,810 kg (17,217 lb)
Actual Case 1d	61,735 kg (136,100 lb)	5,438 kg (11,988 lb)	18,442 kg (40,656 lb)	7,653 kg (16,871 lb)	22,550 kg (49,713 lb)	7,653 kg (16,871 lb)

Table 40: Performance Measures for Candidate Configuration 12S131

CG	Case	Performance Measure								
		SRT (g)	**HSOT (m)**	**LTR**	**TOT (m)**	**LSOT (m)**	**RO (m)**	**FD**	**LFU**	**MSSA (deg)**
		>0.400	**<0.460**	**<0.600**	**<0.800**	**<5.600**	**<0.200**	**<0.100**	**<0.800**	**<20.0**
Low	1a	0.621	**0.546**	0.398	**0.997**	3.753	**0.227**	**0.231**	0.535	16.42
Low	1b	0.615	**0.560**	0.388	**0.804**	3.984	0.174	**0.220**	0.551	17.40
Low	1c	0.635	**0.498**	0.364	**0.810**	4.207	0.129	**0.205**	0.561	18.91
Low	1d	0.630	**0.577**	0.372	0.687	4.451	0.093	**0.197**	0.576	19.89
High	1a	0.423	**0.624**	0.561	**1.019**	3.753	**0.229**	**0.241**	0.514	16.71
High	1b	0.427	**0.593**	0.546	**0.990**	3.979	0.173	**0.215**	0.539	17.66
High	1c	0.416	**0.561**	0.543	**0.904**	4.203	0.133	**0.205**	0.561	18.71
High	1d	0.414	**0.579**	0.523	**0.816**	4.442	0.100	**0.199**	0.581	19.75

Table 41: Effect of Self-steer Axle Offset on Low-speed Performance Measures

Case	Effective Rear Overhang	Performance Measure 12 m Radius			Performance Measure 14 m Radius		
		FD	**MSSA4 (deg)**	**MSSA8 (deg)**	**FD**	**MSSA4 (deg)**	**MSSA8 (deg)**
		<0.100	**<20.0**	**<20.0**	**<0.100**	**<20.0**	**<20.0**
1a	50.8%	**0.283**	18.01	17.14	**0.241**	16.71	15.35
1b	45.3%	**0.242**	19.24	15.73	**0.215**	17.66	14.27
1c	40.2%	**0.233**	**20.48**	13.00	**0.205**	18.71	12.74
1d	35.1%	**0.225**	**22.00**	11.87	0.199	19.75	10.90

Notes: MSSA4 =maximum self-steer angle for axle 4, the foremost self-steering axle
MSSA8 =maximum self-steer angle for axle 8, the rearmost self-steering axle

Figure 28: Effect of Self-steer Axle Offset on Maximum Self-steer Angle

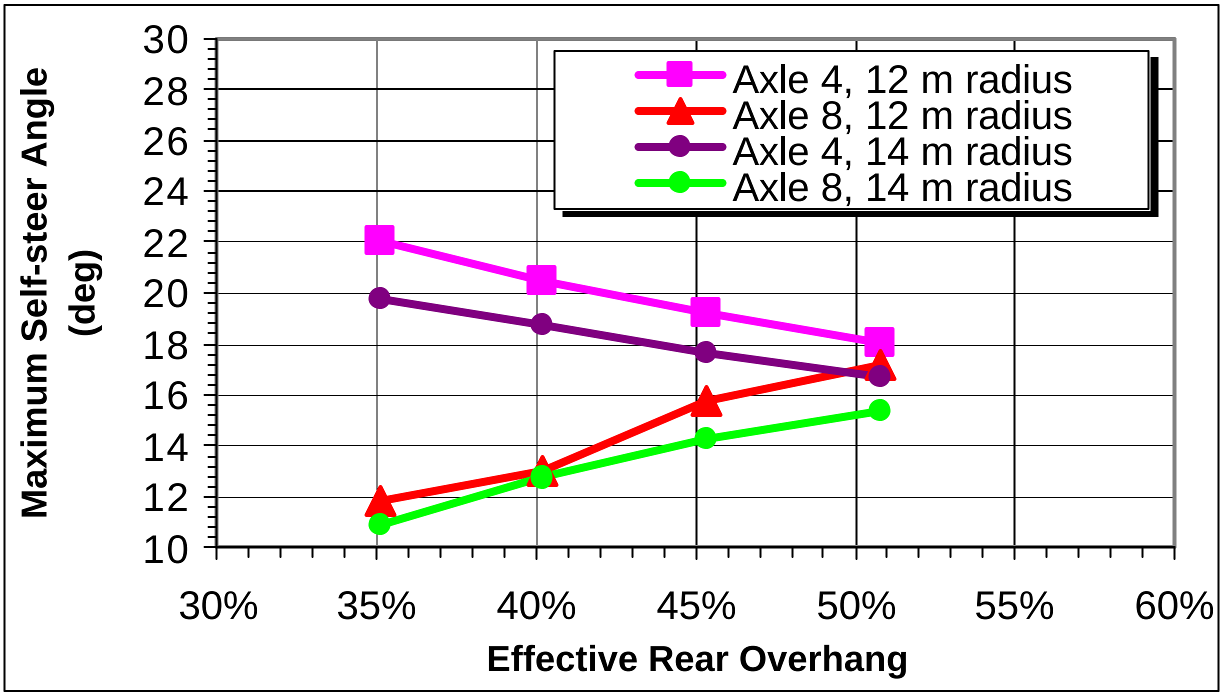


Figure 29: Effect of Self-steer Axle Offset on Friction Demand

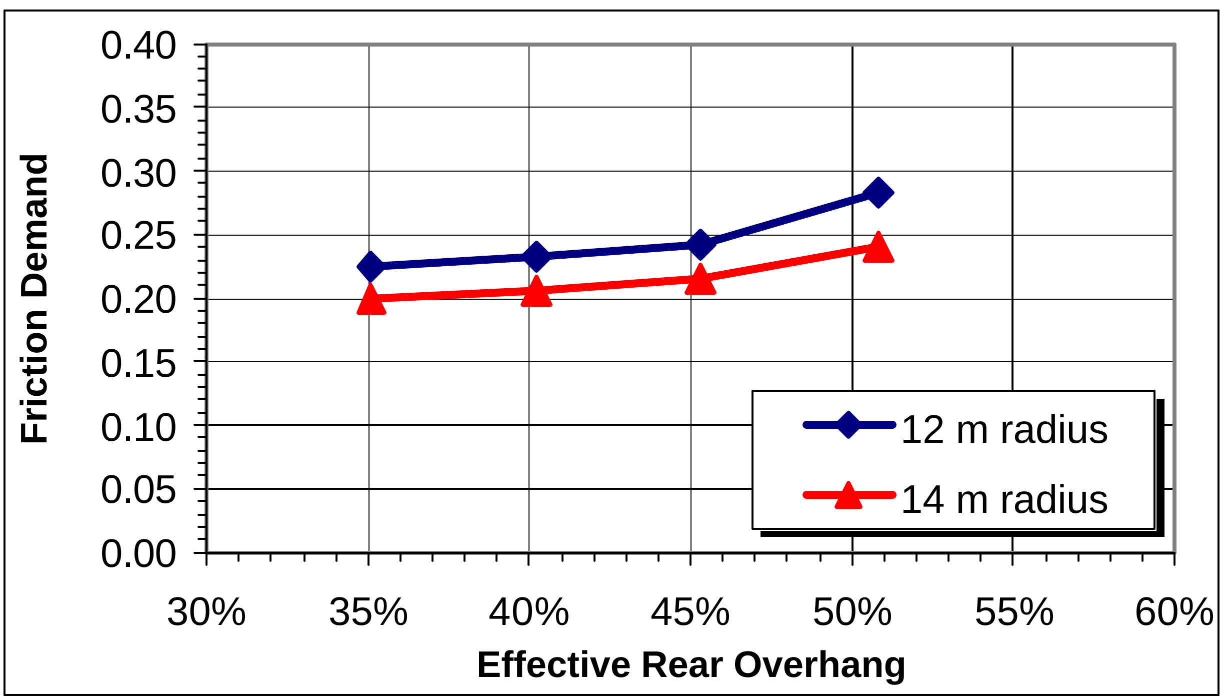


Table 42: Effect of Self-steer Axle Centring Force on Performance Measures

Case	SSA CF	SRT (g)	HSOT (m)	LTR	TOT (m)	LSOT (m)	RO (m)	FD	LFU	MSSA (deg)
		>0.400	<0.460	<0.600	<0.800	<5.600	<0.200	<0.100	<0.800	<20.0
1a	Low	0.423	**0.624**	0.561	**1.019**	3.753	**0.229**	**0.241**	0.514	16.71
1a	Med	0.425	**0.553**	0.586	**0.924**	3.749	**0.203**	**0.312**	0.496	15.98
1a	High	0.424	**0.535**	**0.602**	**0.866**	3.749	0.185	**0.415**	0.492	14.80
1b	Low	0.427	**0.593**	0.546	**0.990**	3.979	0.173	**0.215**	0.539	17.66
1b	Med	0.427	**0.546**	0.573	**0.851**	3.976	0.154	**0.296**	0.508	16.76
1b	High	0.420	**0.519**	0.582	**0.810**	3.973	0.137	**0.391**	0.525	15.62

Table 43: Effect of Self-steer Centring Force on Low-speed Performance Measures

Case	SSA CF	Performance Measure 12 m Radius			Performance Measure 14 m Radius		
		FD	MSSA4 (deg)	MSSA8 (deg)	FD	MSSA4 (deg)	MSSA8 (deg)
		<0.100	<20.0	<20.0	<0.100	<20.0	<20.0
1a	Low	**0.283**	17.14	18.01	**0.241**	15.35	16.71
1a	Med	**0.358**	15.43	17.29	**0.312**	13.66	15.98
1a	High	**0.471**	12.67	16.32	**0.415**	12.05	14.80
1b	Low	**0.242**	19.24	15.73	**0.215**	17.66	14.27
1b	Med	**0.320**	18.58	13.66	**0.296**	16.76	12.52
1b	High	**0.429**	17.11	12.10	**0.391**	15.62	10.41

Figure 30: Effect of Self-steer Axle Centring Force on Maximum Self-steer Angle

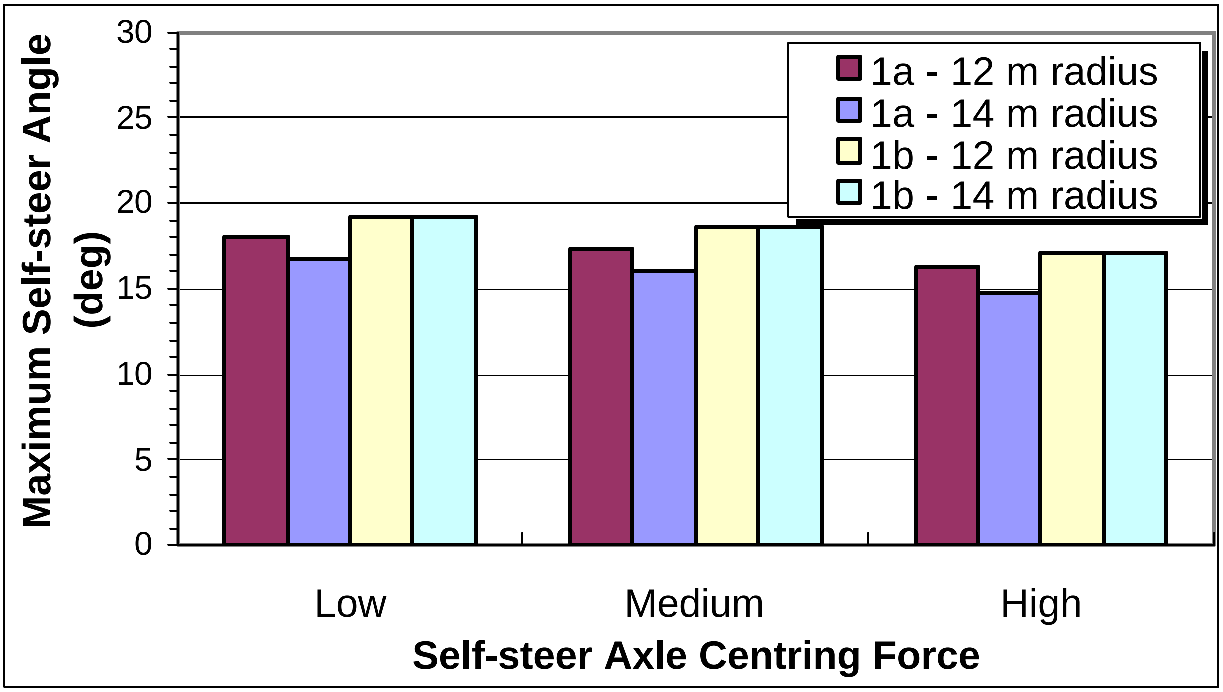


Figure 31: Effect of Self-steer Axle Centring Force on Friction Demand

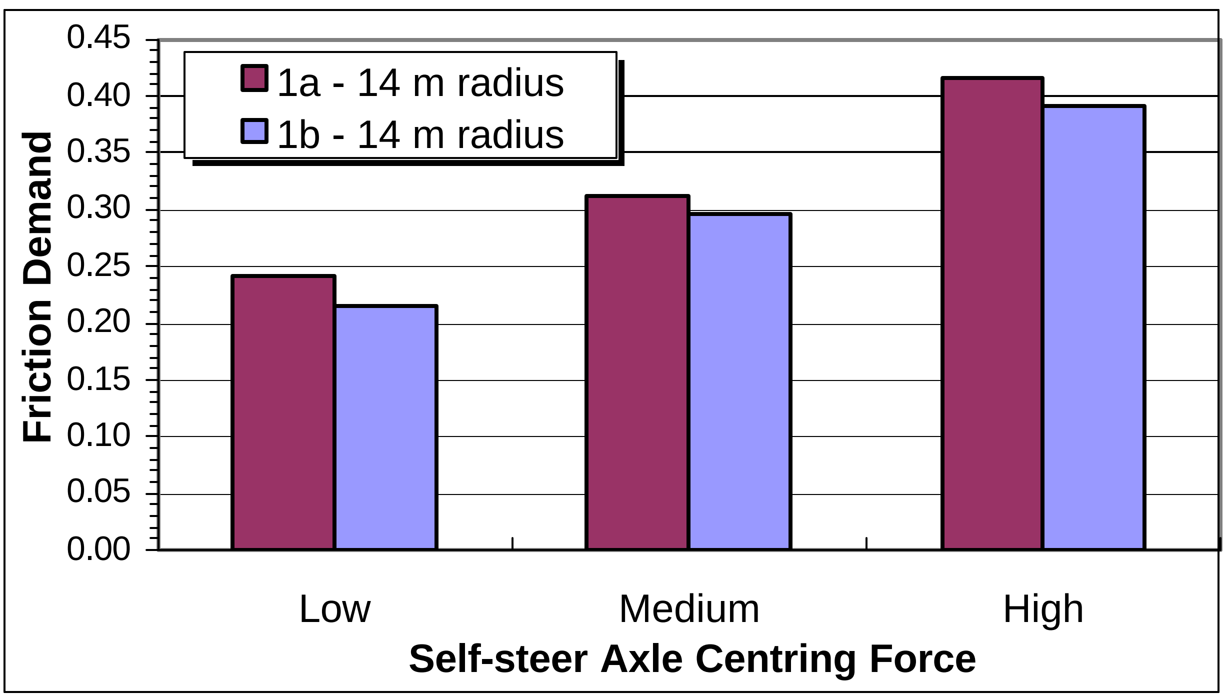


Table 44: Effect of Self-steer Axle Status on High-speed Performance Measures

Case	Axle 4 Status	Axle 8 Status	Performance Measure			
			SRT (g)	HSOT (m)	LTR	TOT (m)
			>0.400	<0.460	<0.600	<0.800
1a	Steer	Steer	0.423	**0.624**	0.561	**1.019**
1a	Lock	Steer	0.417	**0.558**	0.595	**1.091**
1a	Steer	Lock	0.430	**0.531**	0.581	0.787
1a	Lock	Lock	0.433	**0.492**	**0.600**	**0.806**
1a	Rigid	Rigid	0.433	**0.491**	**0.601**	**0.800**
1b	Steer	Steer	0.427	**0.593**	0.546	**0.990**
1b	Lock	Steer	0.399	**0.553**	**0.620**	**0.974**
1b	Steer	Lock	0.427	**0.533**	0.569	0.746
1b	Lock	Lock	0.428	**0.484**	0.581	0.761
1b	Rigid	Rigid	0.428	**0.483**	0.582	0.756

Table 45: Effect of Self-steer Axle Status on Ultimate Performance Measures

Case	Axle 4 Status	Axle 8 Status	Performance Measure	
			LTR	TOT (m)
1a	Steer	Steer	0.943	3.384
1a	Lock	Steer	Rollover	3.306
1a	Steer	Lock	0.951	2.102
1a	Lock	Lock	Rollover	2.237
1a	Rigid	Rigid	Rollover	2.227
1b	Steer	Steer	0.908	2.950
1b	Lock	Steer	Rollover	3.144
1b	Steer	Lock	0.951	1.927
1b	Lock	Lock	Rollover	2.008
1b	Rigid	Rigid	1.000	2.005

Figure 32: Effect of Self-steer Axle Status on High-speed Offtracking

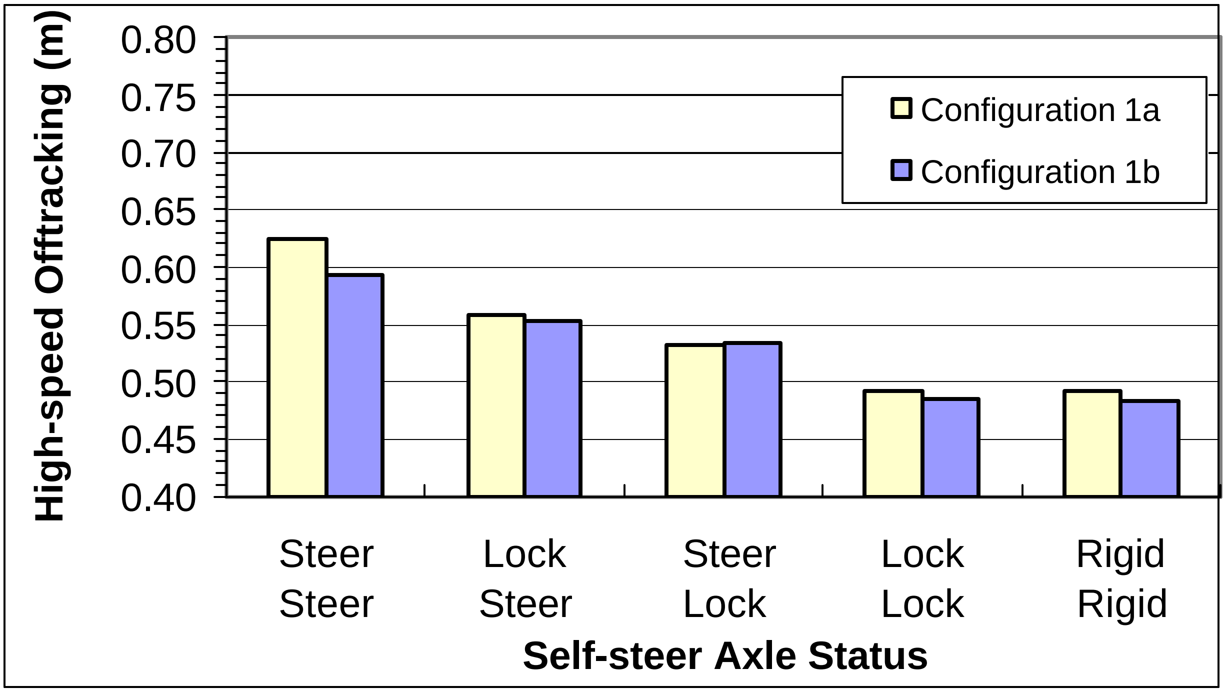


Figure 33: Effect of Self-steer Axle Status on Transient Offtracking

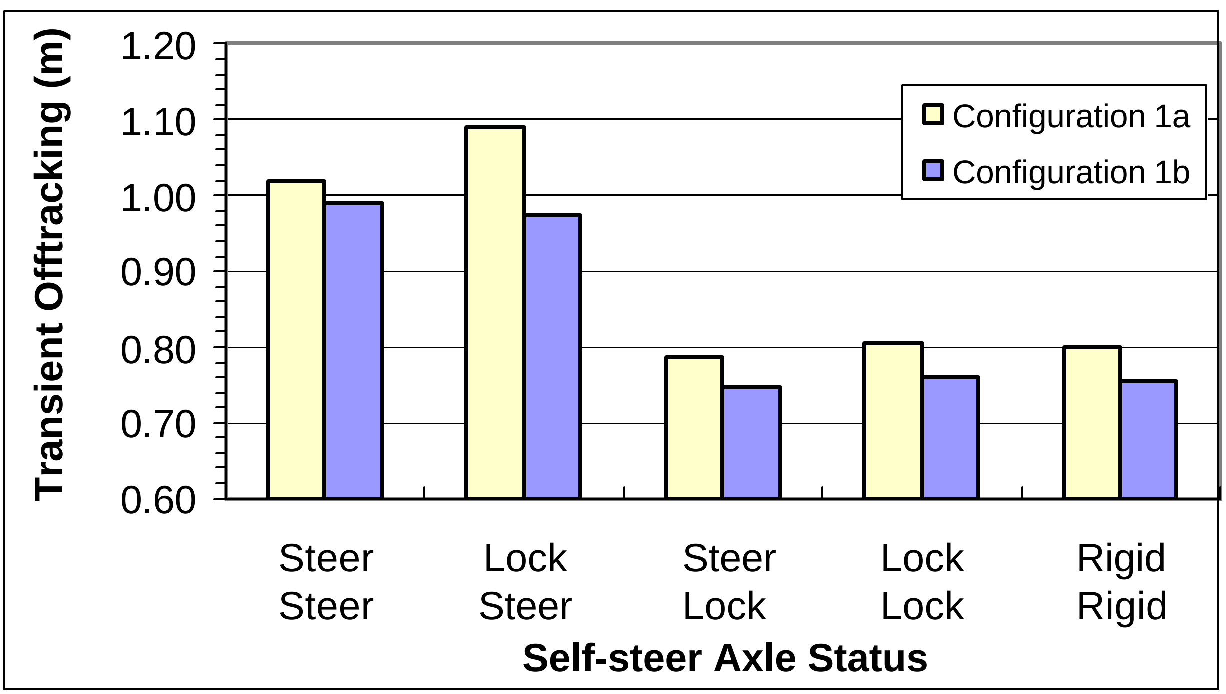


Figure 34: Candidate Configuration 12S131 Configured for Ontario-Michigan

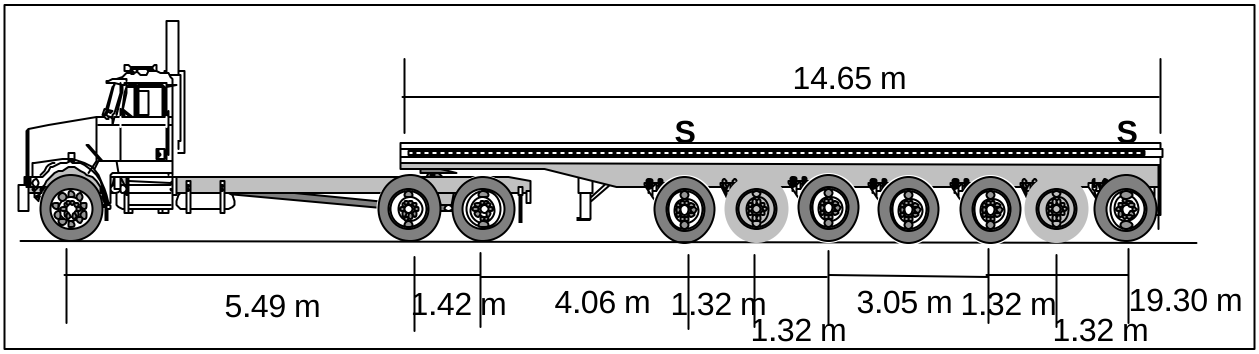


Table 46: Weights for Candidate Configuration 12S131

Rules	Gross	Front	Drive	Single/ 2-axle group	Tridem	Single/ 2-axle group
Ontario	61,800 kg (136,244 lb)	5,443 kg (12,000 lb)	18,000 kg (39,684 lb)	8,000 kg (17,636 lb)	24,000 kg (52,910 lb)	8,000 kg (17,636 lb)
Michigan	61,235 kg (135,000 lb)	5,443 kg (12,000 lb)	14,515 kg (32,000 lb)	11,793 kg (26,000 lb)	17,690 kg (39,000 lb)	11,793 kg (26,000 lb)
Actual Lifts Up	60,374 kg (133,100 lb)	5,196 kg (11,454 lb)	14,465 kg (31,890 lb)	8,224 kg (18,131 lb)	24,264 kg 53,493 lb)	8,224 kg (18,131 lb)
Actual Lifts Down	60,374 kg (133,100 lb)	5,196 kg (11,454 lb)	14,465 kg (31,890 lb)	11,794 kg (26,000 lb)	17,126 kg (37,756 lb)	11,794 kg (26,000 lb)

Table 47: Performance Measures for Candidate Configuration 12S131

CG	Lift	Performance Measure								
		SRT (g)	**HSOT (m)**	**LTR**	**TOT (m)**	**LSOT (m)**	**RO (m)**	**FD**	**LFU**	**MSSA (deg)**
		>0.400	**<0.460**	**<0.600**	**<0.800**	**<5.600**	**<0.200**	**<0.100**	**<0.800**	**<20.0**
Low	Down	0.650	**0.527**	0.387	0.774	3.681	0.192	**0.506**	0.478	19.16
Low	Up	0.659	**0.544**	0.396	**0.995**	3.659	**0.235**	**0.271**	0.489	16.96
High	Down	0.464	**0.502**	0.548	**0.840**	3.725	0.169	**0.493**	0.485	19.76
High	Up	0.452	**0.620**	0.571	**1.054**	3.662	**0.240**	**0.274**	0.494	16.97

6.6 Candidate Configuration 12S114

Figure 35 shows the dimensions for this configuration for operation within Ontario. The two axles ahead of the tridem are both self-steering, and form a tandem axle. The 4-axle group on an existing vehicle typically uses a spring suspension with an axle spacing of 1.12 to 1.22 m (44 to 48 in). The requirement for weight equalization among the six axles on the semitrailer means that all axles must use an air suspension, which requires a minimum axle spacing of 1.27 to 1.32 m (50 to 52 in) for the 4-axle group. The steer angle required of a self-steering axle increases as the axle is placed further away from the turn centre of a semitrailer, and as the turn radius decreases. Table 48 identifies a number of variations in the dimensions A, B and C shown in Figure 35 that should allow the effect of axle spacing and location on self-steer angle to be determined. This limit may be challenged if the first self-steering axle on this configuration is placed too far ahead of the second axle. It may not be possible to space the two self-steering axles 2.77 m (109 in) apart to achieve the maximum gross weight in Michigan if the most forward self-steer axle will bottom out during a turn at an intersection.

Table 49 shows the allowable gross and axle weights under Ontario and Michigan rules, using a weight of 26,000 kg (57,319 lb) on a four axle group with a 3.9 to 4.0 m (153 to 157 in) spread. Equalizing the semitrailer axle weights in Ontario gives an individual axle weight of 6,500 kg (14,329 lb) on each self-steering axle, and a total semitrailer axle capacity of 39,000 kg (85,979 lb). This is a reduction of 4,500 kg (9,920 lb) from the axle capacity of the comparable current vehicle, discussed in Section 4.5, but it does not reduce the allowable gross weight. The table also shows actual gross and axle weights used in the simulations, with a payload of 41,277 kg (91,000 lb) uniformly distributed load along the entire length of the semitrailer.

Table 50 presents the performance measures derived from the simulation runs, for payloads with a low and a high centre of gravity, and self-steering axles with a low centring force characteristic. The table shows that most axle arrangements fail the high-speed offtracking standard, and all fail the friction demand and maximum self-steer angle performance standards. In all cases, the governing self-steer angle is for axle 4, the foremost self-steering axle. The high-speed offtracking is consistently about 0.03 m (1 in) higher than the standard, and comparable to that for the self-steer quad, shown in Table 26. The friction demand exceeds that that for the self-steer quad, as shown in Table 26. The high-speed performance measures, high-speed offtracking, load transfer ratio and transient offtracking are all lower for a payload with a low centre of gravity than for a payload with a high centre of gravity.

Table 51 presents friction demand and maximum self-steer angle performance measures derived from the simulation runs for the parametric variations given in Table 48, for self-steering axles with a low centring force characteristic, and turns of 12 and 14 m (39.4 and 46 ft) at the left front wheel. A 12 m (39.4 ft) turn radius is about the tightest turn possible with the steering of tractor used in this simulation. A tighter turn would be possible with a shorter wheelbase tractor, though such a tractor would probably not normally pull this semitrailer in highway service. Self-steer axle offset is defined as the distance the axle is from the nominal turn centre of the semitrailer, which is considered the centre of the four-axle group. Resistance of the self-steering axles influences turning, and moves the actual turn centre a little forward of the nominal turn centre. Figure 36 shows the effect of self-steer offset on maximum self-steer angle for the two self-steering axles and turn radii. The trend lines shown are simple linear least-square fits to the data points. Axle 5, the rearmost self-steering axle, should be satisfactory with 20 deg of steer, but axle 4, the foremost self-steering axle, will require a steer capability between 25 and 30 deg, depending on the axle spacing. Figure 37 shows the effect of self-steer offset on friction demand for the two turn radii. The steer capability requirement and friction demand are each reduced if the self-steer axle offsets are reduced.

Table 52 presents the performance measures derived from the simulation runs for case 1a from Table 48 for low, medium and high self-steer axle centring force characteristics. Table 53 presents friction demand and maximum self-steer angle performance measures derived from the simulation runs for case 1a from Table 48 for low, medium and high self-steer axle centring force characteristics and turns of 12 and 14 m (39.4 and 46 ft) at the left front wheel. Figure 38 shows the effect of self-steer centring force characteristic on the maximum self-steer angle of Axle 4 for the two turn radii, and Figure 39 shows the effect on friction demand for the 14 m (46 ft) turn radius. The steer capability requirement diminishes as self-steer centring force increases, but the friction demand increases significantly, and is probably untenable even at the medium level.

Table 54 presents the high-speed performance measures derived from the simulation runs for case 1a from Table 48, for self-steering axles with a low centring force characteristic, and for all combinations of locked and steering self-steering axles. When a self-steering axle is locked, it still has capability to steer a small amount against the stiffness of the tie rods and bushings. Table 54 therefore also includes a case where the two self-steering axles are replaced by rigid axles with the same suspension and tire as the self-steering axle, which would be somewhat representative of the ultimate performance. Figure 40 shows that locking one or both self-steering axles makes a slight improvement in high-speed offtracking that is sufficient to meet the performance standard. Figure 41 shows that locking one or both self-steering axles has little effect on transient offtracking.

Figure 26 shows the dimensions of a vehicle configured to operate between Ontario and Michigan. The location of a possible “invisible” liftable axle to allow a compromise for use in Michigan is shown by ghost images

Figure 42 shows the dimensions of a vehicle configured to operate between Ontario and Michigan. The location of a possible “invisible” liftable axle to allow a compromise for use in Michigan is shown by a ghost image. It is not likely that the two self-steering axles can be spread 2.77 m apart, which would eliminate the need for the “invisible” liftable axle, unless the foremost axle had at least 25 to 30 deg of steer, as discussed above.

Table 55 shows the allowable gross and axle weights under Ontario and Michigan rules. This configuration has one more axle than the 12S114 configuration it would replace, which increases its allowable gross weight in Michigan by 1,360 kg (3,000 lb) for a net payload gain of about 454 kg (1,000 lb). This configuration can be loaded to its gross weight with a payload of 39,462 kg (87,000 lb) set back 0.30 m (12 in) from the front of the semitrailer but otherwise uniformly distributed load along the entire length of the semitrailer without exceeding any allowable axle weight, under both Ontario rules with the “invisible” liftable axles raised and load equalization enabled, and under Michigan rules with them down and load equalization disabled.

Table 56 presents the performance measures derived from the simulation runs, and self-steering axles with a low centring force characteristic. Low-speed performance measures are not reported with the “invisible” liftable axles down, even though the simulation computed results, because they are unrealistic and the vehicle certainly could not make the turn.

This configuration may be marginally satisfactory if the self-steering axles are as close to each other as possible, and as close to the four-axle group as possible. However, these restrictions make it uneconomic as a compromise vehicle to operate into Michigan, and it is certainly less economic than configuration 12S113 for operation in Ontario. A 20 deg steer angle should be satisfactory for the rearmost self-steering axle, but the foremost self-steer axle will require at least 25 deg steer capability to avoid bottoming frequently in normal turns. High-speed dynamic performance is not greatly affected either by self-steer axle centring force characteristic or whether the axle is locked or free to steer. Dynamic performance would be improved if the axles in the four-axle group could be spaced closer than 1.32 m (52 in), though this would probably also result in a reduction in the allowable weight on the semitrailer axles.

Figure 35: Candidate Configuration 12S114 Configured for Ontario

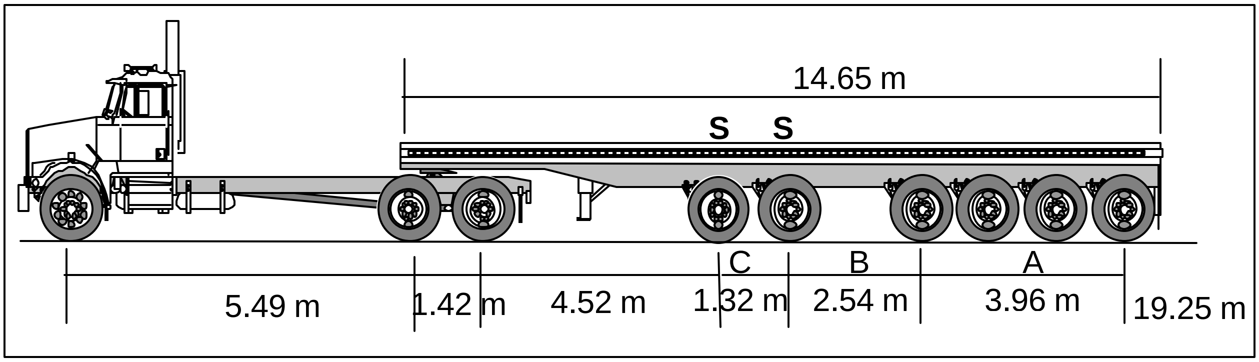


Table 48: Parametric Variations for Candidate Configuration 12S114

Case	A	B	C
1a	3.96 m	2.54 m	1.32 m
1b	3.96 m	2.77 m	1.32 m
1c	3.96 m	3.00 m	1.32 m
1d	3.96 m	3.00 m	2.03 m
1e	3.96 m	2.77 m	2.77 m

Table 49: Weights for Candidate Configuration 12S114

Rules	Gross	Front	Drive	Tandem	4-axle group
Ontario	61,800 kg (136,244 lb)	5,443 kg (12,000 lb)	18,000 kg (39,684 lb)	13,000 kg (28,659 lb)	26,000 kg (57,319 lb)
Michigan	55,338 kg (122,000 lb)	5,443 kg (12,000 lb)	14,515 kg (32,000 lb)	11,793 kg (26,000 lb)	23,587 kg (52,000 lb)
Actual Case 1a	61,598 kg (135,800 lb)	5,363 kg (11,823 lb)	17,211 kg 37,943 lb)	13,190 kg (29,078 lb)	25,835 kg (56,956 lb)
Actual Case 1b	61,598 kg (135,800 lb)	5,347 kg (11,789 lb)	16,958 kg (37,385 lb)	13,280 kg (29,276 lb)	26,014 kg (57,351 lb)
Actual Case 1c	61,598 kg (135,800 lb)	5,332 kg (11,754 lb)	16,700 kg (36,817 lb)	13,370 kg (29,476 lb)	26,196 kg (57,752 lb)
Actual Case 1d	61,598 kg (135,800 lb)	5,307 kg (11,699 lb)	16,292 kg (35,917 lb)	13,514 kg (29,795 lb)	26,485 kg (58,389 lb)
Actual Case 1e	61,598 kg (135,800 lb)	5,297 kg (11,677 lb)	16,128 kg 35,557 lb)	13,572 kg (29,922 lb)	26,601 kg (58,644 lb)

Table 50: Performance Measures for Candidate Configuration 12S114

CG	Case	Performance Measure								
		SRT (g)	HSOT (m)	LTR	TOT (m)	LSOT (m)	RO (m)	FD	LFU	MSSA (deg)
		>0.400	<0.460	<0.600	<0.800	<5.600	<0.200	<0.100	<0.800	<20.0
Low	1a	0.585	0.448	0.365	0.628	5.019	0.044	**0.254**	0.539	**21.90**
Low	1b	0.638	**0.461**	0.368	0.641	4.986	0.041	**0.294**	0.535	**23.15**
Low	1c	0.534	0.454	0.371	0.655	5.018	0.044	**0.292**	0.539	**23.40**
Low	1d	0.547	**0.476**	0.374	0.677	4.989	0.044	**0.320**	0.525	**29.62**
Low	1e	0.564	**0.481**	0.374	0.689	4.956	0.037	**0.371**	0.529	**29.59**
High	1a	0.435	**0.471**	0.536	0.680	5.024	0.039	**0.243**	0.536	**22.52**
High	1b	0.432	**0.484**	0.540	0.695	4.932	0.042	**0.298**	0.537	**22.74**
High	1c	0.438	**0.485**	0.544	0.710	4.930	0.044	**0.302**	0.532	**23.47**
High	1d	0.442	**0.494**	0.550	0.734	4.941	0.042	**0.309**	0.525	**26.45**
High	1e	0.449	**0.490**	0.551	0.744	4.905	0.039	**0.340**	0.513	**29.60**

Table 51: Effect of Self-steer Axle Offset on Low-speed Performance Measures

Case	Axle 5 Offset	Axle 4 Offset	Performance Measure 12 m Radius			Performance Measure 14 m Radius		
			FD	MSSA5 (deg)	MSSA4 (deg)	FD	MSSA5 (deg)	MSSA4 (deg)
			<0.100	<20.0	<20.0	<0.100	<20.0	<20.0
1a	4.37	5.69	**0.307**	18.91	**24.23**	**0.243**	17.59	**22.52**
1b	4.60	5.92	**0.324**	**20.23**	**24.56**	**0.298**	17.67	**22.74**
1c	4.83	6.15	**0.350**	**20.32**	**25.38**	**0.302**	18.59	**23.47**
1d	4.37	6.40	**0.392**	19.92	**27.52**	**0.309**	**20.08**	**26.45**
1e	4.60	7.37	**0.412**	18.07	**29.56**	**0.340**	18.18	**29.60**

Notes: MSSA5 =maximum self-steer angle for axle 5, the rearmost self-steering axle
MSSA4 =maximum self-steer angle for axle 4, the foremost self-steering axle

Figure 36: Effect of Self-steer Axle Offset on Maximum Self-steer Angle

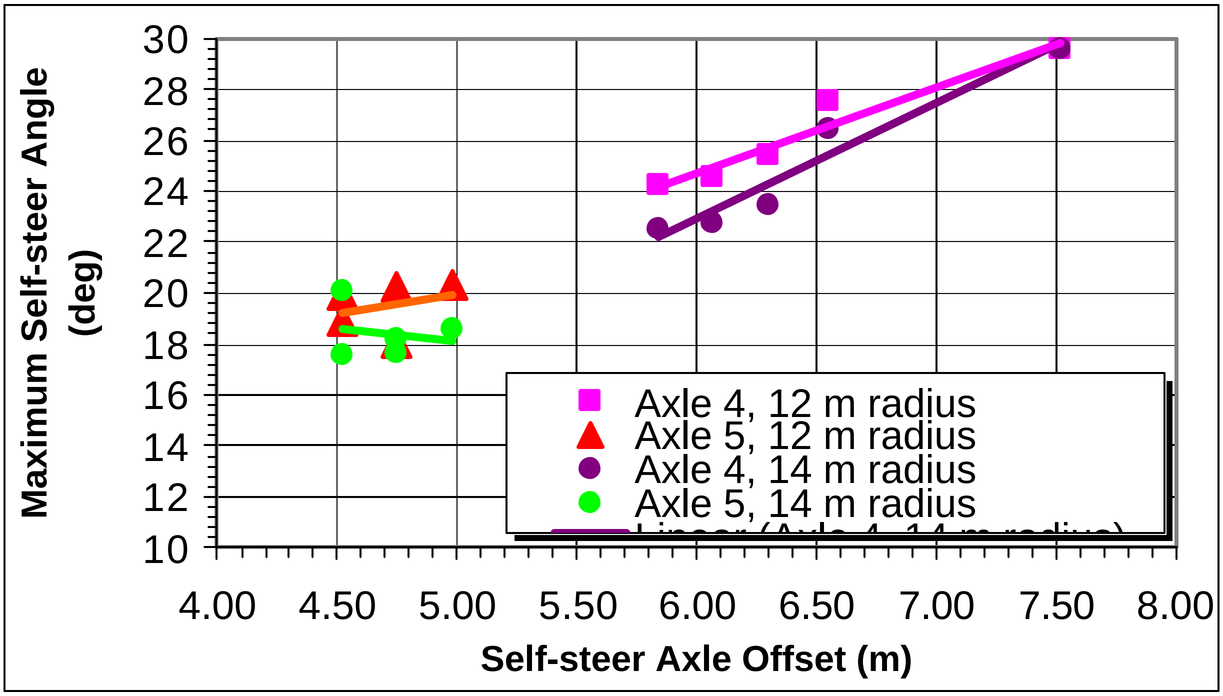


Figure 37: Effect of Self-steer Axle Offset on Friction Demand

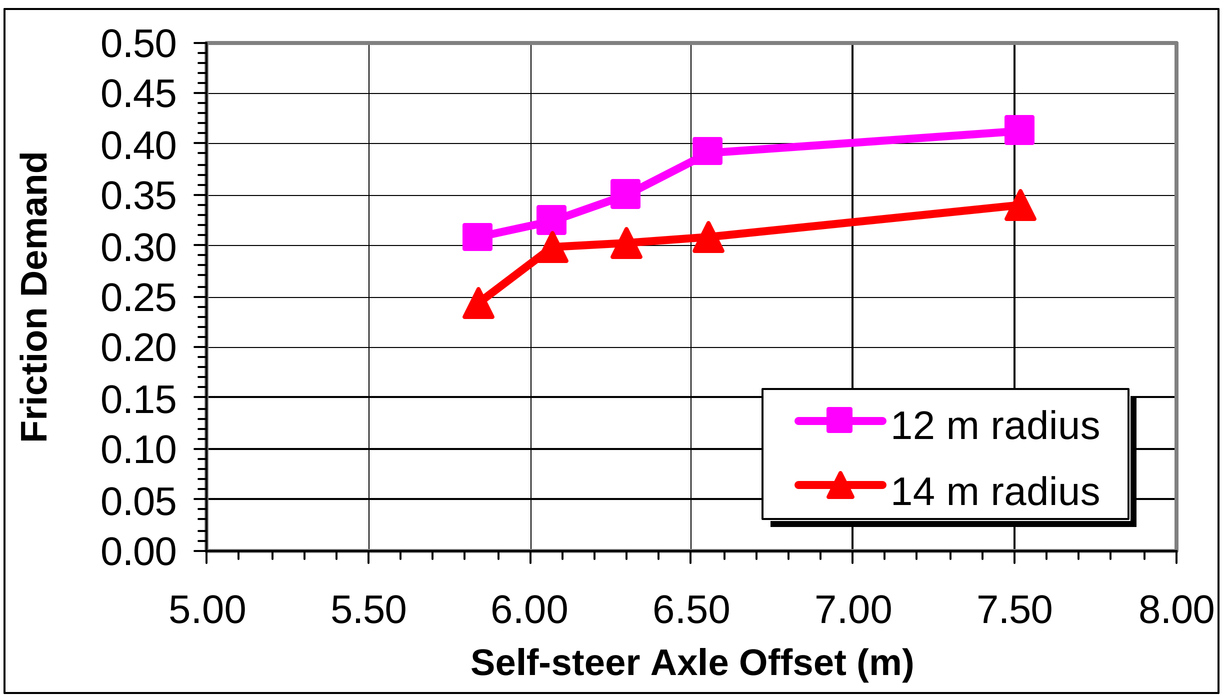


Table 52: Effect of Self-steer Axle Centring Force on Performance Measures

Case	SSA CF	SRT (g)	HSOT (m)	LTR	TOT (m)	LSOT (m)	RO (m)	FD	LFU	MSSA (deg)
		>0.400	**<0.460**	**<0.600**	**<0.800**	**<5.600**	**<0.200**	**<0.100**	**<0.800**	**<20.0**
1a	Low	0.435	**0.471**	0.536	0.680	5.024	0.039	**0.243**	0.536	**22.52**
1a	Med	0.426	0.458	0.539	0.680	4.813	0.062	**0.366**	0.511	**21.05**
1a	High	0.429	0.454	0.540	0.680	4.615	0.075	**0.473**	0.522	17.04

Table 53: Effect of Self-steer Centring Force on Low-speed Performance Measures

Case	SSA CF	Performance Measure 12 m Radius			Performance Measure 14 m Radius		
		FD	MSSA5 (deg)	MSSA4 (deg)	FD	MSSA5 (deg)	MSSA4 (deg)
		<0.100	**<20.0**	**<20.0**	**<0.100**	**<20.0**	**<20.0**
1a	Low	**0.307**	18.91	**24.23**	**0.243**	17.59	**22.52**
1a	Med	**0.408**	16.98	**22.65**	**0.366**	15.66	**21.05**
1a	High	**0.543**	13.81	18.77	**0.473**	16.15	17.04

Figure 38: Effect of Self-steer Axle Centring Force on Maximum Self-steer Angle

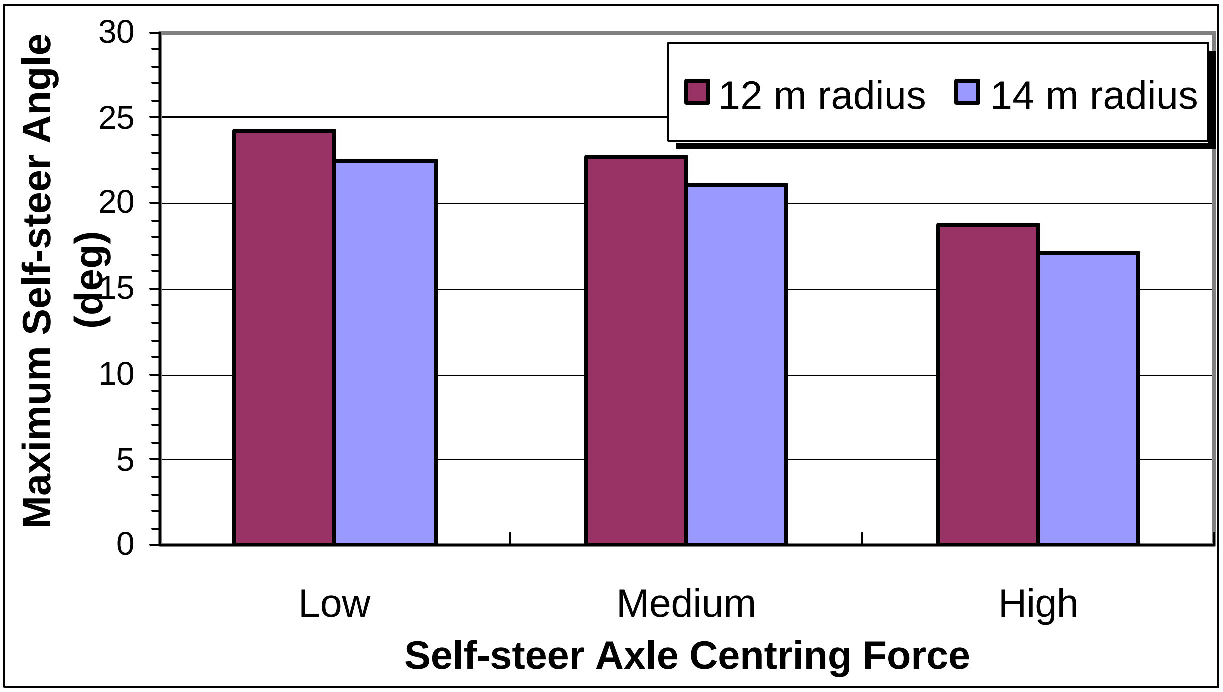


Figure 39: Effect of Self-steer Axle Centring Force on Friction Demand

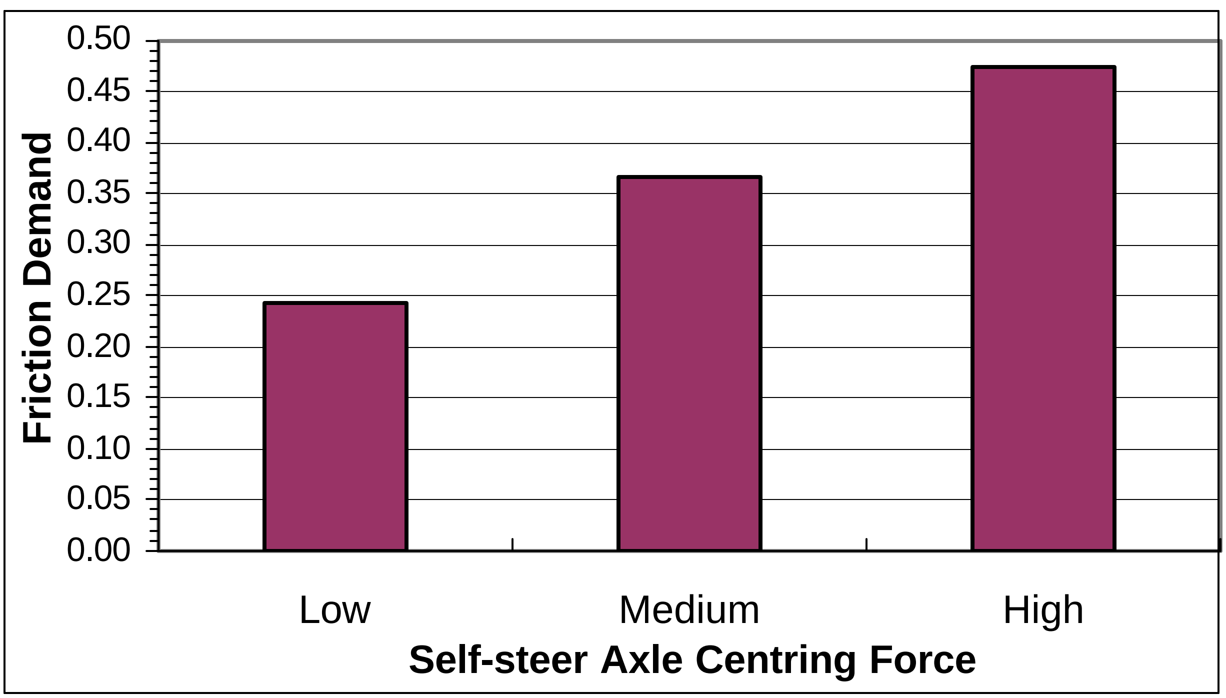


Table 54: Effect of Self-steer Axle Status on High-speed Performance Measures

Case	Axle 4 Status	Axle 5 Status	Performance Measure			
			SRT (g)	HSOT (m)	LTR	TOT (m)
			>0.400	<0.460	<0.600	<0.800
1a	Steer	Steer	0.435	**0.471**	0.536	0.680
1a	Lock	Steer	0.428	**0.473**	0.537	0.681
1a	Steer	Lock	0.428	0.450	0.541	0.680
1a	Lock	Lock	0.427	0.448	0.542	0.680
1a	Rigid	Rigid	0.427	0.447	0.544	0.678

Figure 40: Effect of Self-steer Axle Status on High-speed Offtracking

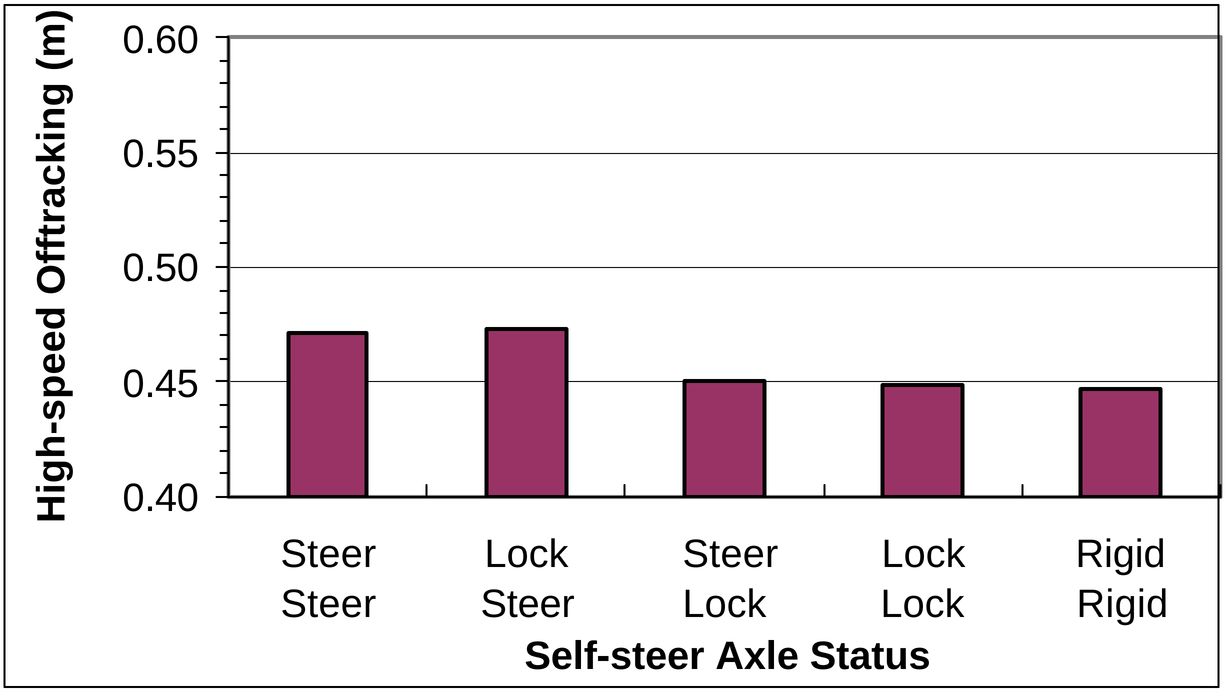


Figure 41: Effect of Self-steer Axle Status on Transient Offtracking

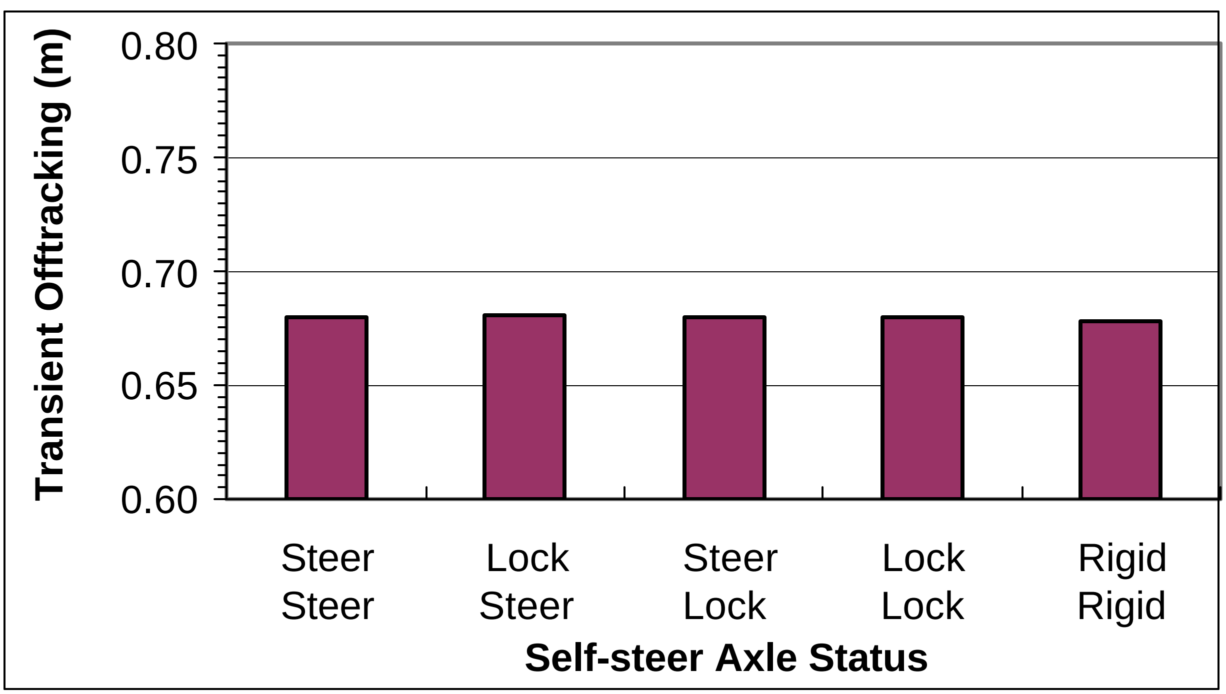


Figure 42: Candidate Configuration 12S114 Configured for Ontario-Michigan

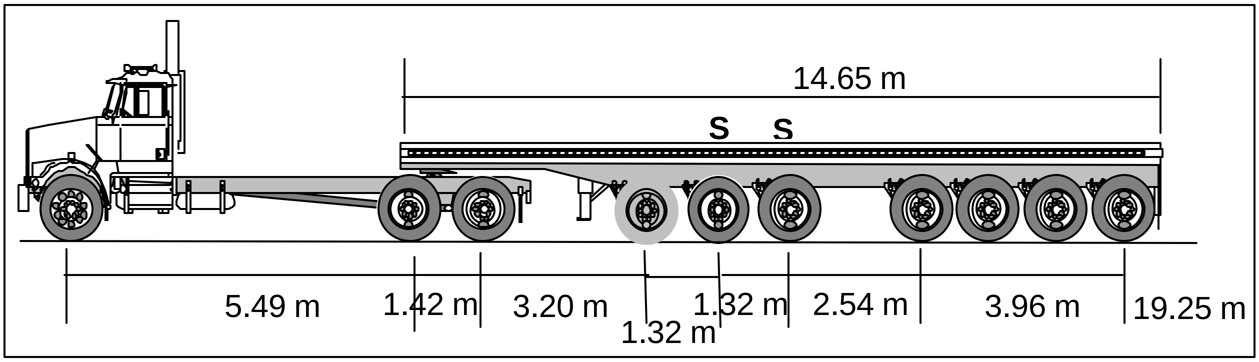


Table 55: Weights for Candidate Configuration 12S114

Rules	Gross	Front	Drive	Tandem/ 3-axle group	4-axle group
Ontario	61,800 kg (136,244 lb)	5,443 kg (12,000 lb)	18,000 kg (39,684 lb)	13,000 kg (28,659 lb)	26,000 kg (57,319 lb)
Michigan	61,235 kg (135,000 lb)	5,443 kg (12,000 lb)	14,515 kg (32,000 lb)	17,690 kg (39,000 lb)	23,587 kg (52,000 lb)
Actual Lifts Up	61,145 kg (134,800 lb)	5,369 kg (11,835 lb)	17,307 kg (38,154 lb)	13,004 kg (28,670 lb)	25,465 kg (56,140 lb)
Actual Lifts Down	61,145 kg (134,800 lb)	5,189 kg (11,439 lb)	14,354 kg (31,645 lb)	17,691 kg (39,000 lb)	23,912 kg (52,716 lb)

Table 56: Performance Measures for Candidate Configuration 12S114

CG	Lift	Performance Measure								
		SRT (g)	HSOT (m)	LTR	TOT (m)	LSOT (m)	RO (m)	FD	LFU	MSSA (deg)
		>0.400	<0.460	<0.600	<0.800	<5.600	<0.200	<0.100	<0.800	<20.0
Low	Down	0.527	**0.488**	0.383	0.765	4.385	0.071	**0.728**	0.477	**21.21**
Low	Up	0.618	0.451	0.355	0.620	4.987	0.038	**0.265**	0.537	**23.10**
High	Down	0.479	**0.500**	0.547	**0.811**	4.374	0.073	**0.736**	0.468	**21.53**
High	Up	0.454	**0.470**	0.514	0.665	4.950	0.044	**0.266**	0.536	**22.11**

6.7 Candidate Configuration 12S141

Figure 43 shows the dimensions of this configuration for operation within Ontario. The two single axles ahead and behind the four-axle group are both self-steering. The minimum axle spacing of 1.32 m (52 in) for consecutive axles with an air suspension increases the spread of the four-axle group compared to the existing configuration, so this configuration cannot achieve an inter-vehicle-unit distance of 3.60 m (142 in). It also has an effective rear overhang of about 58%, where 35% is the maximum allowed for semitrailers under Regulation 32/94. If this causes problems in meeting performance standards, the only option would be to slide the four axle group rearward. The rearmost axle would then form a four axle group with the last three axles of the centre group, which would significantly reduce both axle capacity and allowable gross weight. Table 57 identifies a number of variations on rear overhang, and their effect on dimensions A, B and C shown in Figure 43.

Table 58 shows the allowable weights for this configuration for operation in Ontario or in Michigan. The spread of the four-axle group reduces the inter-vehicle-unit distance below 3.60 m (142 in), so the allowable gross weight of this configuration in Ontario is slightly less than for the comparable existing configuration. The table also shows the actual gross and axle weights used in the simulation, for a payload of 40,823 kg (90,000 lb) uniformly distributed along the entire length of the semitrailer, except for the last 1.22 m (48 in).

Table 59 presents the performance measures derived from the simulation runs, for payloads with a low and a high centre of gravity, and self-steering axles with a low centring force characteristic. The table shows that all axle arrangements fail the high-speed offtracking and friction demand performance standards, one fails the load transfer ratio performance standard, three fail the transient offtracking performance standard, six fail the maximum self-steer angle performance standard, and four fail the rear outswing performance standard. In all cases, the governing self-steer angle is for axle 9, the rearmost self-steering axle. The high-speed offtracking exceeds the performance standard by up to 0.10 m (4 in), whereas the self-steer quad exceeds the performance standard by about 0.05 m, as shown in Table 26. The friction demand approaches that for the self-steer quad, as shown in Table 26, as the four-axle group moves rearward. The high-speed performance measures, high-speed offtracking, load transfer ratio and transient offtracking are all lower for a payload with a low centre of gravity than for a payload with a high centre of gravity.

Table 60 presents friction demand and maximum self-steer angle performance measures derived from the simulation runs for the parametric variations given in Table 57, for self-steering axles with a low centring force characteristic, and turns of 12 and 14 m (39.4 and 46 ft) at the left front wheel. A 12 m (39.4 ft) turn radius is about the tightest turn possible with the steering of tractor used in this simulation. A tighter turn would be possible with a shorter wheelbase tractor, though such a tractor would probably not normally pull this semitrailer in highway service. Effective rear overhang is the distance from the centre of the tridem to the rear of the semitrailer as a percentage of the semitrailer wheelbase, from the kingpin to the centre of the tridem. Resistance of the self-steering axles influences turning, and moves the actual turn centre a little forward of the nominal turn centre. Figure 44 shows the effect of effective rear overhang on maximum self-steer angle for the two self-steering axles and turn radii. Axle 4, the foremost self-steering axle, is marginal with 20 deg of steer with the four-axle group in its most forward position, and would require a larger steer capability for any more rearward location of the four-axle group. Axle 9, the rearmost self-steering axle, is satisfactory with 20 deg of steer, regardless of effective rear overhang. Figure 45 shows the effect of effective rear overhang on friction demand for the two turn radii. The steer capability requirement is reduced for a more forward location of the tridem, but at the expense of a slight increase in friction demand.

Table 61 presents the performance measures derived from the simulation runs for case 1a from Table 57 for low, medium and high self-steer axle centring force characteristics. A higher centring force slightly improves high-speed offtracking, transient offtracking and maximum self-steer angle, but slightly degrades load transfer ratio and significantly degrades friction demand.

Table 62 presents friction demand and maximum self-steer angle performance measures derived from the simulation runs for case 1a from Table 57 for low, medium and high self-steer axle centring force characteristics and turns of 12 and 14 m (39.4 and 46 ft) at the left front wheel. Figure 46 shows the effect of self-steer centring force characteristic on the maximum self-steer angle of Axle 4 for the two turn radii, and Figure 47 shows the effect on friction demand for the 14 m (46 ft) turn radius. The steer capability requirement diminishes as self-steer centring force increases, but the friction demand increases significantly, and is probably untenable even at the medium level.

Table 63 presents the high-speed performance measures derived from the simulation runs for case 1a from Table 57, for self-steering axles with a low centring force characteristic, and for all combinations of locked and steering self-steering axles. When a self-steering axle is locked, it still has capability to steer a small amount against the stiffness of the tie rods and bushings. Table 63 therefore also includes a case where the two self-steering axles are replaced by rigid axles with the same suspension and tire as the self-steering axle, which would be somewhat representative of the ultimate performance. Figure 48 shows that locking the rearmost, or both, self-steering axles makes some improvement in high-speed offtracking, but even with rigid axles, the vehicle still does not quite meet the performance standard. Figure 49 shows that locking the rearmost, or both, self-steering axles is necessary for the vehicle to meet the transient offtracking performance standard. Locking both axles also reduces the load transfer ratio slightly, so that the vehicle meets the performance standard.

Figure 50 shows the dimensions of a vehicle configured to operate between Ontario and Michigan.

Table 64 shows the allowable weights for operation between Ontario and Michigan. The increase in single axle spacings from Figure 43 to Figure 50 causes a further reduction in an inter-vehicle-unit distance, and so the allowable gross weight of this configuration in Ontario is now about 1,700 kg (3,747 lb) less than for the comparable existing configuration. The table also shows actual gross and axle weights used in the simulations, with a payload of 38,555 kg

(85,000 lb) uniformly distributed load along the entire length of the semitrailer, except for the last 0.76 m (30 in). The vehicle can be loaded with this payload without exceeding any allowable axle weight, with the axle loads equalized in Ontario, and with equalization disabled in Michigan.

Table 65 presents the performance measures derived from the simulation runs, for self-steering axles with a low centring force characteristic. This configuration fails the high-speed offtracking, transient offtracking and friction demand performance standards by a wide margin than that shown in Figure 43, and it also just fails the rear outswing performance standard, too.

This configuration fails three high-speed and two low-speed performance standards with the four-axle group in the most forward location considered. Performance becomes more satisfactory as the four-axle group is moved rearward, though this would undoubtedly result in a significant reduction in axle weights not considered in this analysis, which would render the vehicle uneconomic. Its performance is hardly an improvement over the existing configuration. A 20 deg steer angle is marginal for both self-steering axles. High-speed dynamic performance is significantly affected by the self-steer axle centring force characteristic and whether the axles are locked or free to steer. This configuration requires self-steering axles with a low centring force characteristic, and these must be locked at high speed. The performance would improve if the axle spacing required for the four-axle group could be reduced from 1.32 m (52 in). As it is, the four-axle group is further forward than for existing configurations, so this configuration is probably going to be unsuitable for uniformly distributed cargo like municipal waste, whose centre of gravity cannot be biased forward. The dynamic performance of this configuration with any single axle spacing wider than 2.54 m (100 in) is significantly poorer than the configuration shown in Figure 43, so there is no satisfactory compromise configuration for Michigan.

Figure 43: Candidate Configuration 12S141 Configured for Ontario

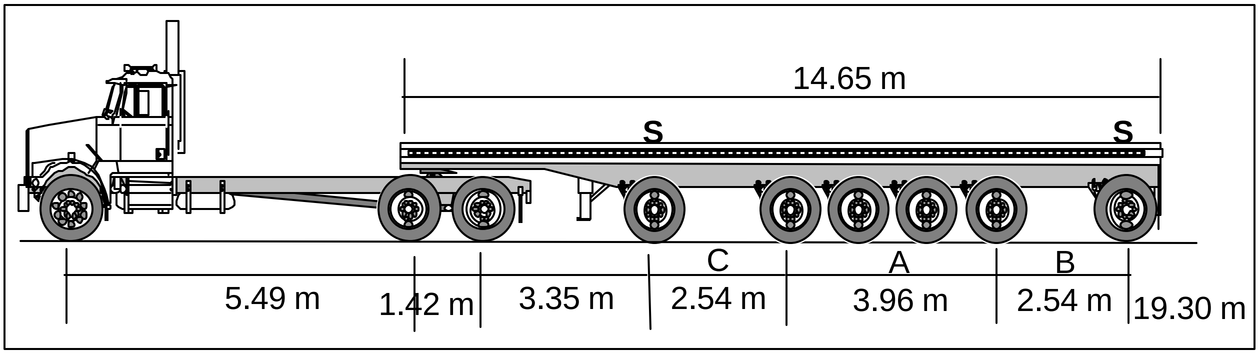


Table 57: Parametric Variations for Candidate Configuration 12S141

Case	Effective Rear Overhang	A	B	C
1a	58.5%	3.96 m	2.54 m	2.54 m
1b	50.8%	3.96 m	2.08 m	3.00 m
1c	45.3%	3.96 m	1.73 m	3.35 m
1d	39.5%	3.96 m	1.32 m	3.76 m

Table 58: Weights for Candidate Configuration 12S141

Rules	Gross	Front	Drive	Single	4-axle group	Single
Ontario	61,300 kg (135,142 lb)	5,443 kg (12,000 lb)	18,000 kg (39,684 lb)	6,500 kg (14,329 lb)	26,000 kg (57,319 lb)	6,500 kg (14,329 lb)
Michigan	59,874 kg (132,000 lb)	5,443 kg (12,000 lb)	14,515 kg (32,000 lb)	8,164 kg (18,000 lb)	23,587 kg (52,000 lb)	8,164 kg (18,000 lb)
Actual Case 1a	61,145 kg (134,800 lb)	5,338 kg (11,769 lb)	16,811 kg (37,061 lb)	6,590 kg (14,528 lb)	25,816 kg (56,914 lb)	6,590 kg (14,528 lb)
Actual Case 1b	61,145 kg (134,800 lb)	5,403 kg (11,911 lb)	17,870 kg (39,397 lb)	6,403 kg (14,115 lb)	25,066 kg (55,262 lb)	6,403 kg (14,115 lb)
Actual Case 1c	61,145 kg (134,800 lb)	5,450 kg (12,015 lb)	18,647 kg (41,110 lb)	6,265 kg (13,813 lb)	24,517 kg (54,050 lb)	6,265 kg (13,813 lb)
Actual Case 1d	61,145 kg (134,800 lb)	5,501 kg (12,128 lb)	19,489 kg (42,965 lb)	6,116 kg (13,484 lb)	23,922 kg (52,738 lb)	6,116 kg (13,484 lb)

Table 59: Performance Measures for Candidate Configuration 12S141

CG	Case	SRT (g)	HSOT (m)	LTR	TOT (m)	LSOT (m)	RO (m)	FD	LFU	MSSA (deg)
		>0.400	<0.460	<0.600	<0.800	<5.600	<0.200	<0.100	<0.800	<20.0
Low	1a	0.626	**0.558**	0.401	**0.850**	3.414	**0.309**	**0.288**	0.526	18.96
Low	1b	0.623	**0.576**	0.385	0.759	3.791	**0.221**	**0.256**	0.548	**20.82**
Low	1c	0.633	**0.492**	0.372	0.706	4.001	0.171	**0.228**	0.559	**21.61**
Low	1d	0.611	**0.550**	0.360	0.674	4.276	0.123	**0.203**	0.574	**23.75**
High	1a	0.415	**0.556**	**0.611**	**0.907**	3.444	**0.308**	**0.295**	0.529	19.84
High	1b	0.407	**0.543**	0.573	**0.848**	3.742	**0.215**	**0.257**	0.541	**21.03**
High	1c	0.409	**0.530**	0.556	0.772	4.020	0.162	**0.243**	0.556	**21.73**
High	1d	0.402	**0.488**	0.537	0.745	4.274	0.113	**0.223**	0.561	**22.59**

Table 60: Effect of Effective Rear Overhang on Low-speed Performance Measures

Case	Effective Rear Overhang	Performance Measure 12 m Radius			Performance Measure 14 m Radius		
		FD	MSSA4 (deg)	MSSA9 (deg)	FD	MSSA4 (deg)	MSSA9 (deg)
		<0.100	<20.0	<20.0	<0.100	<20.0	<20.0
1a	58.5%	**0.329**	**21.32**	**20.79**	**0.295**	19.84	17.18
1b	50.8%	**0.285**	**21.58**	16.42	**0.257**	**21.03**	17.26
1c	45.3%	**0.265**	**24.17**	15.68	**0.243**	**21.73**	14.44
1d	39.5%	**0.244**	**24.63**	14.31	**0.223**	**22.59**	13.10

Notes: MSSA4 =maximum self-steer angle for axle 4, the foremost self-steering axle
MSSA9 =maximum self-steer angle for axle 9, the rearmost self-steering axle

Table 61: Effect of Self-steer Axle Centring Force on Performance Measures

Case	SSA CF	Performance Measure								
		SRT (g)	HSOT (m)	LTR	TOT (m)	LSOT (m)	RO (m)	FD	LFU	MSSA (deg)
		>0.400	<0.460	<0.600	<0.800	<5.600	<0.200	<0.100	<0.800	<20.0
1a	Low	0.415	**0.556**	**0.611**	**0.907**	3.444	**0.308**	**0.295**	0.529	19.841
1a	Med	0.411	**0.523**	**0.604**	**0.839**	3.459	**0.255**	**0.354**	0.520	18.723
1a	High	0.420	**0.500**	**0.602**	**0.811**	3.395	**0.235**	**0.532**	0.502	16.242

Table 62: Effect of Self-steer Centring Force on Low-speed Performance Measures

Case	SSA CF	Performance Measure 12 m Radius			Performance Measure 14 m Radius		
		FD	MSSA4 (deg)	MSSA9 (deg)	FD	MSSA4 (deg)	MSSA9 (deg)
		<0.100	<20.0	<20.0	<0.100	<20.0	<20.0
1a	Low	**0.329**	**20.79**	**21.32**	**0.295**	17.18	19.84
1a	Med	**0.423**	17.94	18.75	**0.354**	16.66	18.72
1a	High	**0.591**	13.59	17.20	**0.532**	13.01	16.24

Figure 44: Effect of Effective Rear Overhang on Maximum Self-steer Angle

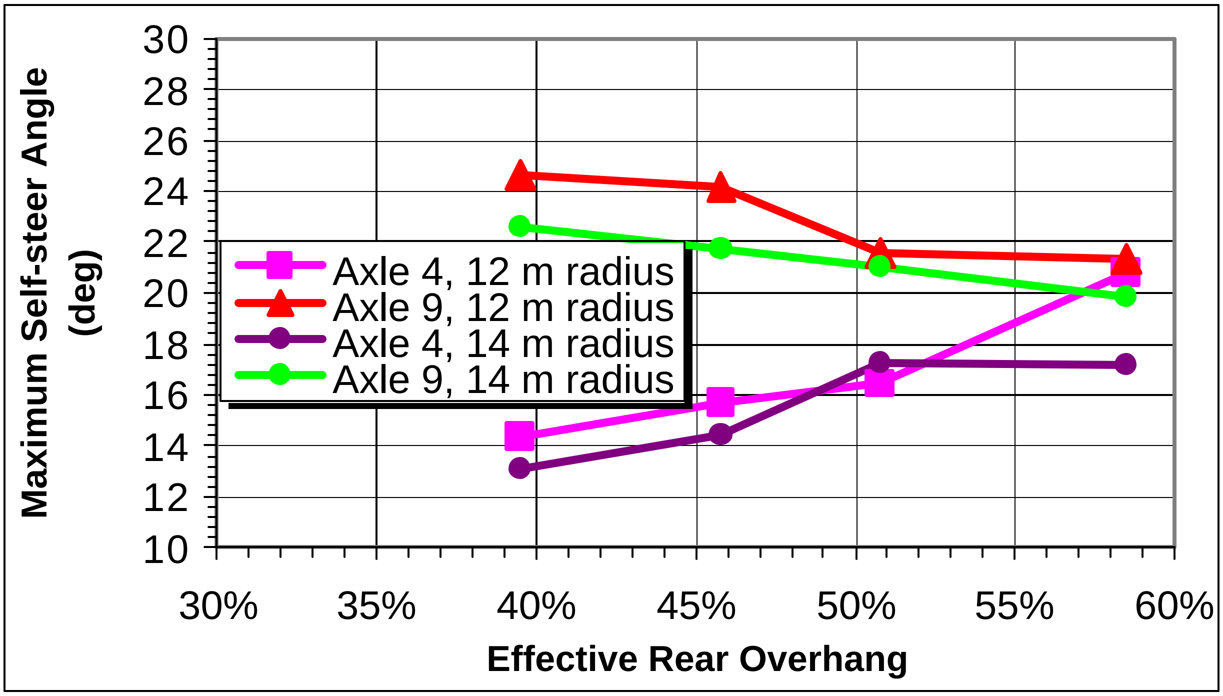


Figure 45: Effect of Effective Rear Overhang on Friction Demand

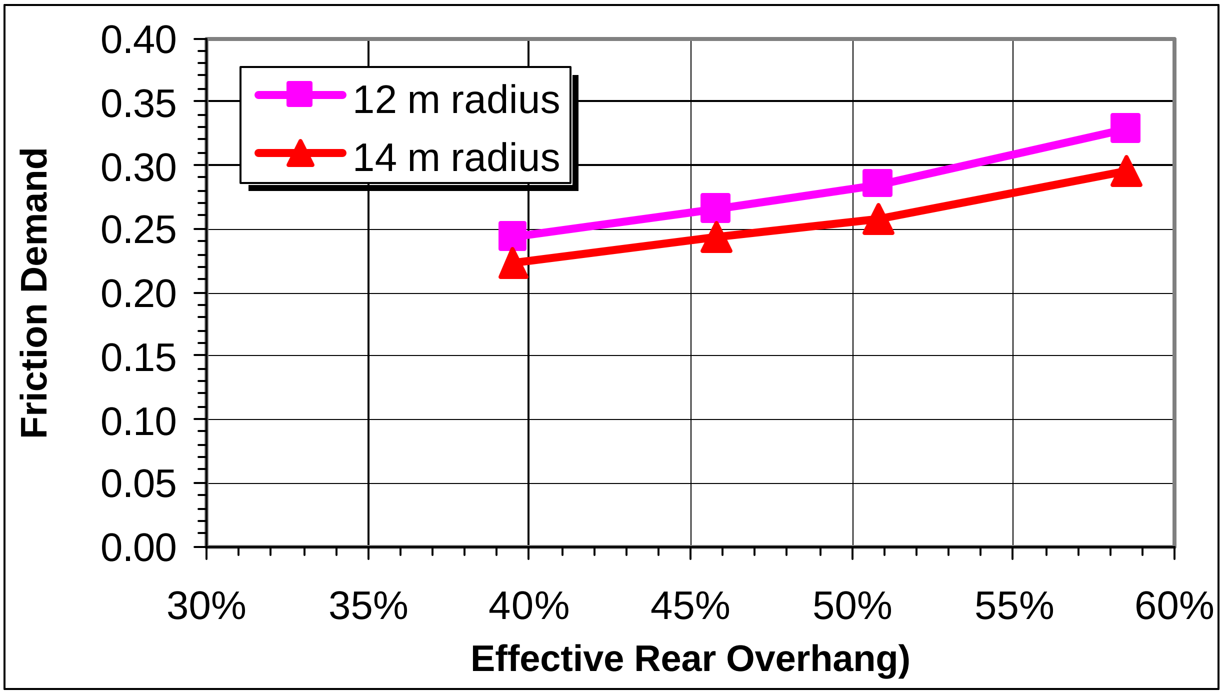


Figure 46: Effect of Self-steer Axle Centring Force on Maximum Self-steer Angle

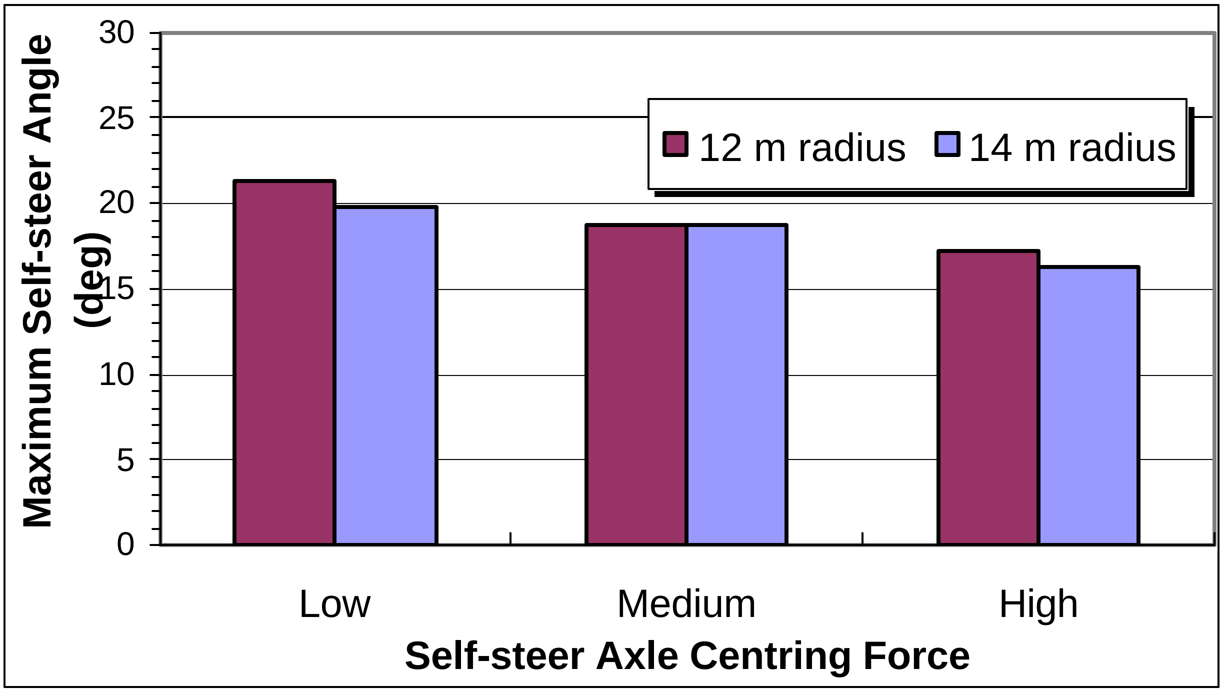


Figure 47: Effect of Self-steer Axle Centring Force on Friction Demand

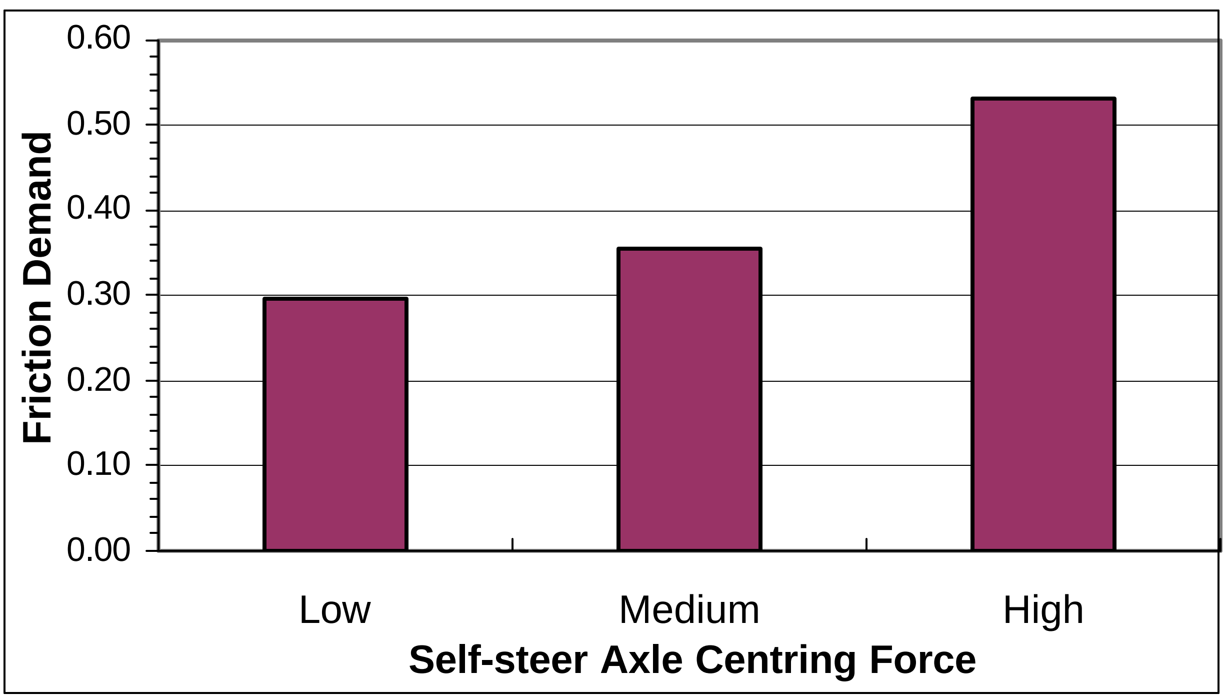


Table 63: Effect of Self-steer Axle Status on High-speed Performance Measures

Case	Axle 4 Status	Axle 9 Status	Performance Measure			
			SRT (g)	**HSOT (m)**	**LTR**	**TOT (m)**
			>0.400	**<0.460**	**<0.600**	**<0.800**
1a	Steer	Steer	0.415	**0.556**	**0.611**	**0.907**
1a	Lock	Steer	**0.386**	**0.543**	**0.616**	**0.932**
1a	Steer	Lock	0.422	**0.487**	0.588	0.764
1a	Lock	Lock	0.420	**0.486**	0.590	0.766
1a	Rigid	Rigid	0.420	**0.486**	0.591	0.764

Figure 48: Effect of Self-steer Axle Status on High-speed Offtracking

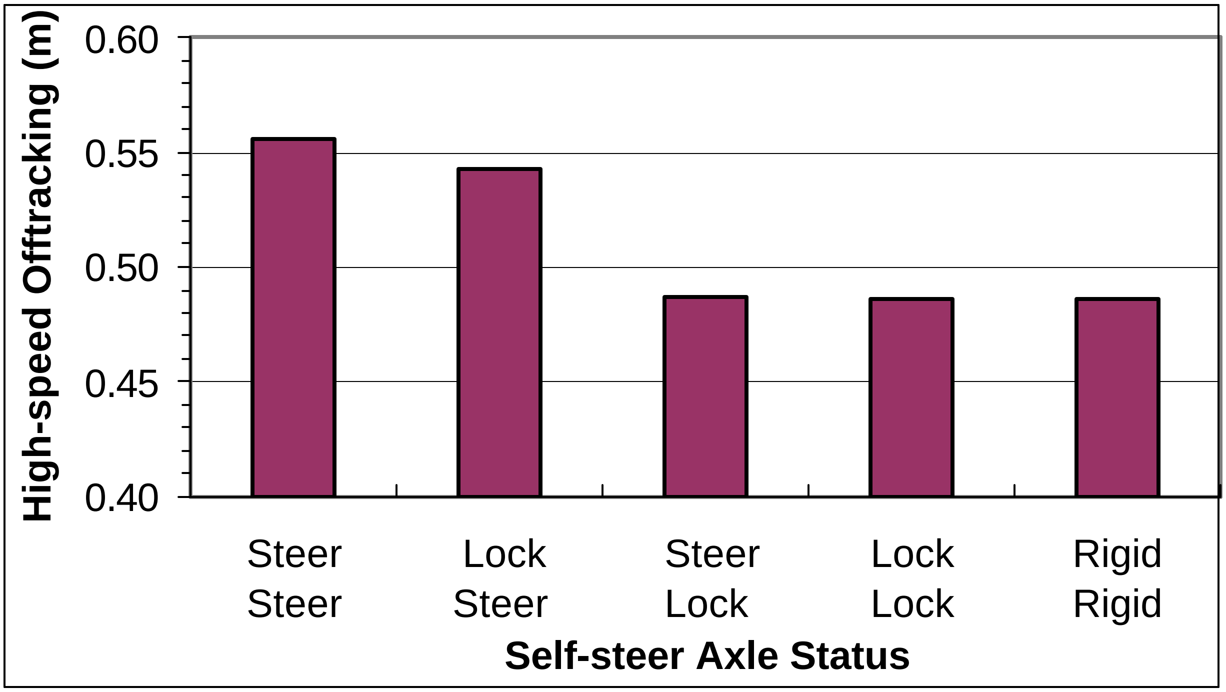


Figure 49: Effect of Self-steer Axle Status on Transient Offtracking

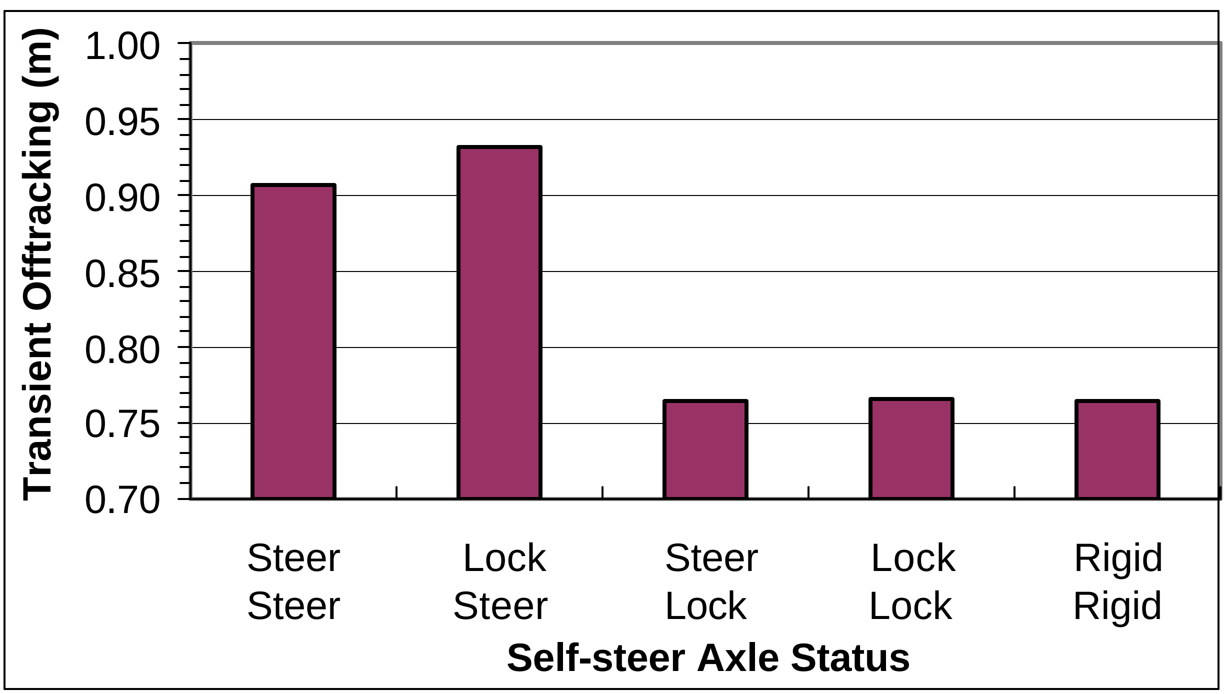


Figure 50: Candidate Configuration 12S141 Configured for Ontario-Michigan

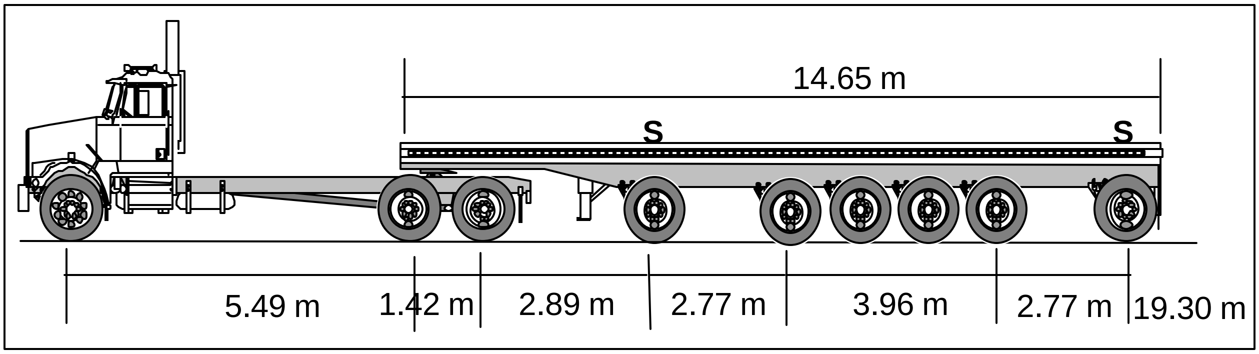


Table 64: Weights for Candidate Configuration 12S141

Rules	Gross	Front	Drive	Single	4-axle group	Single
Ontario	59,200 kg (130,512 lb)	5,443 kg (12,000 lb)	18,000 kg (39,684 lb)	6,500 kg (14,329 lb)	26,000 kg (57,319 lb)	6,500 kg (14,329 lb)
Michigan	59,874 kg (132,000 lb)	5,443 kg (12,000 lb)	14,515 kg (32,000 lb)	8,164 kg (18,000 lb)	23,587 kg (52,000 lb)	8,164 kg (18,000 lb)
Actual Lifts Up	58,877 kg (129,800 lb)	5,192 kg (11,447 lb)	14,409 kg (31,766 lb)	6,637 kg (14,631 lb)	26,002 kg (57,325 lb)	6,637 kg (14,631 lb)
Actual Lifts Down	58,877 kg (29,800 lb)	5,192 kg (11,447 lb)	14,409 kg (31,766 lb)	8,164 kg (18,000 lb)	22,946 kg (50,587 lb)	8,164 kg (18,000 lb)

Table 65: Performance Measures for Candidate Configuration 12S141

CG	Lift	Performance Measure								
		SRT (g)	**HSOT (m)**	**LTR**	**TOT (m)**	**LSOT (m)**	**RO (m)**	**FD**	**LFU**	**MSSA (deg)**
		>0.400	**<0.460**	**<0.600**	**<0.800**	**<5.600**	**<0.200**	**<0.100**	**<0.800**	**<20.0**
Low	Down	0.643	**0.606**	0.397	**1.059**	3.298	**0.334**	**0.359**	0.485	**21.67**
High	Down	0.452	**0.617**	0.558	**1.156**	3.292	**0.326**	**0.336**	0.489	**21.47**

6.8 Candidate Configuration 13S13

Figure 51 shows the dimensions for this configuration as configured for Ontario, using a self-steer quad semitrailer as defined in Regulation 597. That regulation requires a 5.50 m (217 in) inter-vehicle-unit distance when the self-steer quad semitrailer is used with a three-axle tractor. It may be necessary to waive or reduce that requirement for this configuration. The tractor wheelbase is in the range 6.60 to 6.80 m (260 to 268 in), to be consistent with permit policies of B.C. and Alberta. The tridem drive axle on the tractor attracts additional weight, compared to the tandem drive tractor of the baseline self-steer quad, so the semitrailer kingpin must be moved rearward to generate the necessary kingpin load. The self-steer quad semitrailer configured to be pulled by a tridem drive tractor is different from one configured to be pulled by a tandem drive tractor. It requires a longer gooseneck, and the landing gear must be placed farther back for clearance from the rear drive axle. These semitrailers may not be readily interchangeable for uniformly distributed loads, but should be interchangeable for heavy dense cargo like metal coils.

Table 66 shows the allowable weights for operation in Ontario or in Michigan. The Michigan weights shown assume that the self-steer axle is 2.77 m (109 in) ahead of the tridem. A load of 22,500 kg (49,603 lb) was used on a tridem with a spread of 2.84 m (112 in) for this analysis. The front axle load was at least 27% of the drive axle load at all times, to be consistent with permit policies of B.C. and Alberta. The long tractor wheelbase allows the vehicle to reach a base length over 19.25 m (758 in), for an allowable gross weight of 62,700 kg (138,228 lb). The table also shows the actual gross and axle weights used in the simulation, for a payload of 41,730 kg (92,000 lb) uniformly distributed along the entire length of the semitrailer, except for the last 0.15 m (6 in).

Table 67 presents the performance measures derived from the simulation runs, for self-steering axles with a low centring force characteristic. Performance is generally similar to that of the self-steer quad semitrailer with a tandem tractor, presented in Chapter 5. Friction demand is less than for the tandem tractor, because of the extra axle and the weight it attracts. Lateral friction utilization just meets the performance standard.

Table 68 shows the effect of self-steering axle centring force characteristics on the performance measures. These have little effect on the high-speed performance measures. An increase in self-steer centring force increases both friction demand and lateral friction utilization, but reduces maximum self-steer angle.

Figure 52 shows the dimensions for this configuration as configured for operation between Ontario and Michigan. This is the same base configuration as shown in Figure 51, except that the semitrailer kingpin setback has been reduced to achieve a 2.77 m (109 in) inter-vehicle-unit distance, the self-steering axle has been moved forward 0.1 m (4 in), and “invisible” liftable axles have been added for use in Michigan, as shown by ghost images.

Table 69 shows the allowable weights for operation between Ontario and Michigan. The table also shows actual gross and axle weights used in the simulations, with a payload of 38,555 kg

(85,000 lb) uniformly distributed load along the most forward 13.41 m (44 ft) of the semitrailer. It is necessary to bias the load forwards, because of the forward location of the semitrailer kingpin necessary to achieve a 2.77 m (109 in) inter-vehicle-unit distance. The vehicle can be loaded with this payload without exceeding any allowable axle weight, with the quad-axle group equalized and “invisible” liftable axles raised in Ontario, and with equalization disabled and the “invisible” liftable axles deployed in Michigan.

Table 70 presents the performance measures derived from the simulation runs, for self-steering axles with a low centring force characteristic.

This configuration comes close to meeting the performance standards. Lateral friction utilization is marginal, which is typical for a tractor of this configuration. Friction demand is less than that for a tridem semitrailer as shown in Table 27, because of the additional drive axle load allowed by the tridem. This configuration offers an increase in drive traction over a tandem tractor, though there would be little increase in payload. The long tractor wheelbase also offers the option of a drome box, which would certainly increase the reliability of the front axle load.

Figure 51: Candidate Configuration 13S13 Configured for Ontario

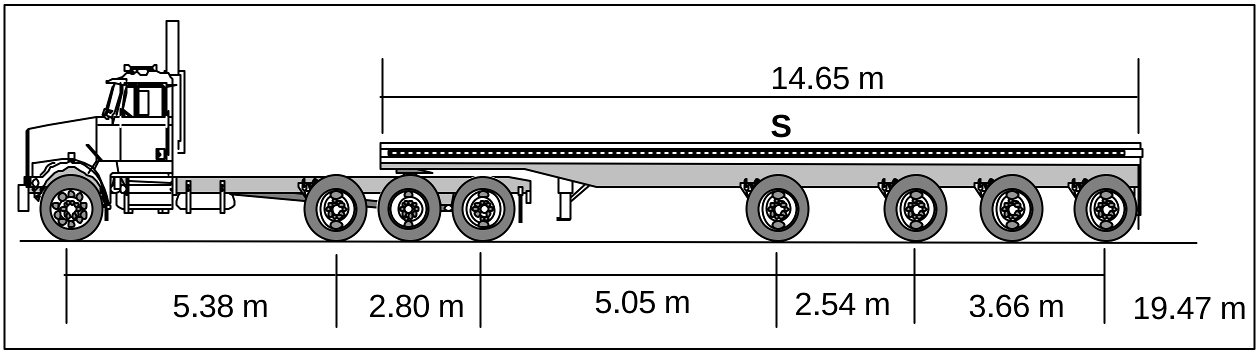


Table 66: Weights for Candidate Configuration 13S13

Rules	Gross	Front	Drive	Single	Tridem
Ontario	62,700 kg (138,228 lb)	6,350 kg (14,000 lb)	22,500 kg (49,603 lb)	8,500 kg (18,739 lb)	25,500 kg (56,217 lb)
Michigan	48,988 kg (108,000 lb)	6,350 kg (14,000 lb)	17,690 kg (39,000 lb)	8,164 kg (18,000 lb)	17,690 kg (39,000 lb)
Actual	62,642 kg (138,100 lb)	6,168 kg (13,597 lb)	22,473 kg (49,544lb)	8,602 kg (18,965 lb)	25,399 kg (55,994 lb)

Table 67: Performance Measures for Candidate Configuration 13S13

CG	Performance Measure								
	SRT (g)	**HSOT (m)**	**LTR**	**TOT (m)**	**LSOT (m)**	**RO (m)**	**FD**	**LFU**	**MSSA (deg)**
	>0.400	**<0.460**	**<0.600**	**<0.800**	**<5.600**	**<0.200**	**<0.100**	**<0.800**	**<20.0**
Low	0.602	0.448	0.339	0.549	5.157	0.035	**0.121**	0.800	16.98
High	0.408	**0.491**	0.521	0.640	5.154	0.037	**0.116**	0.798	17.11

Table 68: Effect of Self-steer Axle Centring Force on Performance Measures

CG	SSA CF	Performance Measure								
		SRT (g)	HSOT (m)	LTR	TOT (m)	LSOT (m)	RO (m)	FD	LFU	MSSA (deg)
		>0.400	<0.460	<0.600	<0.800	<5.600	<0.200	<0.100	<0.800	<20.0
High	Low	0.408	**0.491**	0.521	0.640	5.154	0.037	**0.116**	0.798	17.11
High	Med	0.409	**0.477**	0.528	0.640	5.077	0.042	**0.155**	0.790	15.05
High	High	0.407	**0.470**	0.532	0.640	5.002	0.047	**0.176**	0.778	14.22
High	Lock	0.406	0.451	0.542	0.644	4.625	0.056	**0.290**	**0.810**	

Figure 52: Candidate Configuration 13S13 Configured for Ontario-Michigan

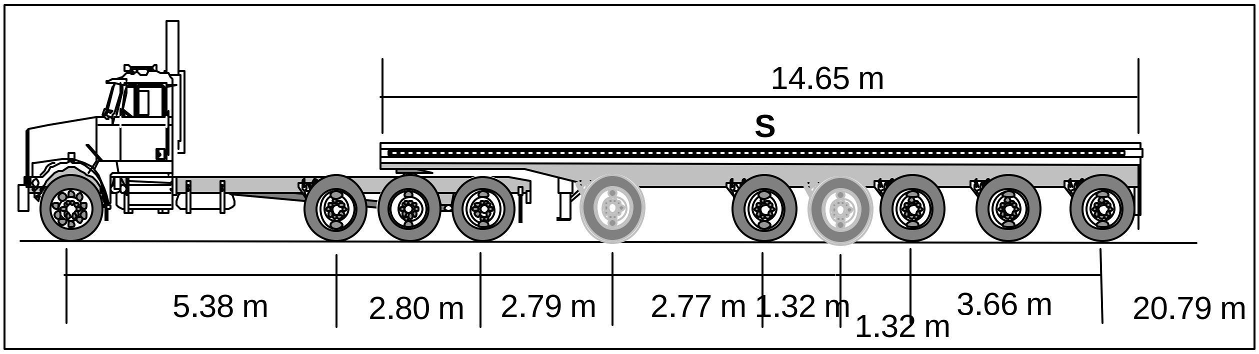


Table 69: Weights for Candidate Configuration 13S13

Rules	Gross	Front	Drive	Single	Tridem/ 5-axle group
Ontario Lifts Up	62,300 kg (137,347 lb)	6,350 kg (14,000 lb)	22,500 kg (39,684 lb)	8,500 kg (18,739 lb)	25,500 kg (56,217 lb)
Michigan Lifts Down	61,538 kg (135,668 lb)	6,350 kg (14,000 lb)	17,690 kg (39,000 lb)	8,164 kg (18,000 lb)	29,483 kg (65,000 lb)
Actual Lifts Up	61,281 kg (135,100 lb)	6,188 kg (13,643 lb)	22,848 kg (50,372 lb)	8,163 kg (17,966 lb)	24,081 kg (53,089 lb)
Actual Lifts Down	61,281 kg (135,100 lb)	5,889 kg (12,982 lb)	17,417 kg (38,397 lb)	8,165 kg (18,000 lb)	29,811 kg (64,397 lb)

Table 70: Performance Measures for Candidate Configuration 13S13

CG	Lift	Performance Measure								
		SRT (g)	HSOT (m)	LTR	TOT (m)	LSOT (m)	RO (m)	FD	LFU	MSSA (deg)
		>0.400	<0.460	<0.600	<0.800	<5.600	<0.200	<0.100	<0.800	<20.0
Low	Down	0.634	**0.465**	0.343	0.633	4.236	0.116	**0.631**	0.657	13.92
Low	Up	0.613	0.433	0.314	0.487	5.495	0.029	**0.115**	0.787	16.58
High	Down	0.435	**0.477**	0.513	0.684	4.187	0.106	**0.687**	0.664	13.46
High	Up	0.414	**0.475**	0.490	0.557	5.495	0.033	**0.117**	0.794	16.70

6.9 Candidate Configuration 112S13

Figure 53 shows the dimensions for this configuration as configured for Ontario. The tractor has a self-steer liftable pusher axle, and a self-steer quad semitrailer is used, as defined in Regulation 597. The self-steer pusher axle on the tractor reduces its effective wheelbase and attracts additional weight, compared to the tandem drive tractor of the baseline self-steer quad semitrailer. The tractor fifth wheel must be moved forward to maintain the front axle load, and the semitrailer kingpin must be moved rearward to increase the kingpin load. The semitrailer requires a longer gooseneck, and the landing gear must be placed farther back for clearance from the rear drive axle. The semitrailer may not be readily interchangeable for uniformly distributed loads, but should be interchangeable for heavy dense cargo like metal coils. A consequence of this is that the vehicle is likely to have a base length around 18.85 m (742 in), which is short of the 19.25 m (758 in) base length required for maximum gross weight. The pusher axle needs to be far enough ahead of the drive tandem that the three axle group they form generates a worthwhile weight, but not so far ahead that it unloads the front axle to any significant extent. This configuration was evaluated with a three-axle group spread of 2.84 m (112 in) for this analysis, which puts the pusher axle 1.42 m (56 in) ahead of the first axle of the drive tandem.

Table 71 shows the allowable weights for operation in Ontario or in Michigan. The allowable gross weight is limited to 60,843 kg (134,135 lb) by the short base length and the axle capacity. A gross weight of 61,000 kg (134,480 lb) would be achieved if a larger pusher axle spacing would be used. The three-axle group spread of 2.84 m (112 in) gives an axle group load of 21,400 kg (47,178 lb). Axle loads must not be equalized between the pusher axle and the drive tandem. An excessive pusher axle load would significantly reduce the front axle load, and would also reduce the drive tandem load, which would reduce the mobility of the vehicle. It is not immediately clear how the pusher axle load should be controlled at this time, and it is premature to consider it here, because the issue is to be addressed in Phase 4 of MTO's Weight and Dimension Reform package. For this work, it is simply assumed that the pusher axle is loaded to 3,400 kg (7,495 lb) whenever it is required to be down, and is fitted with a single 275 mm (11 in) wide tire. This leaves 18,000 kg (39,684 lb) on the drive tandem. The table also shows actual gross and axle weights used in the simulations, with a payload of 40,824 kg (90,000 lb) uniformly distributed load along the entire length of the semitrailer. The Michigan weights shown assume that the self-steer axle is 2.77 m (109 in) ahead of the tridem. The Michigan allowable gross weight is higher than practical, because the pusher axle would unload the front axle to such an extent a driver's ability to control the vehicle would be problematic.

Table 72 presents the performance measures derived from the simulation runs, for self-steering axles with a low centring force characteristic. This configuration fails the friction demand performance standard, and the lateral friction utilization is marginal. The maximum self-steer angle shown is from the semitrailer. The tractor self-steer angle should not exceed about 5 deg.

Table 73 shows the effect of self-steering axle centring force characteristics on the performance measures. These have little effect on the high-speed performance measures. An increase in self-steer centring force increases both friction demand and lateral friction utilization, but reduces maximum self-steer angle.

Figure 54 shows the dimensions for this configuration as configured for operation between Ontario and Michigan. This is the same base configuration as shown in Figure 53, except that the self-steering axle has been moved forward 0.1 m (4 in), and "invisible" liftable axles have been added for use in Michigan, as shown by ghost images.

Table 74 shows the allowable weights for operation between Ontario and Michigan. The single 275 mm (11 in) tire on the pusher axle allows the full single axle weight of 5,896 kg (13,000 lb) in Michigan, where the tire load is 12.5 kg/mm (700 lb/in). However, this reduces the front axle load excessively, and the same 3,400 kg (7,495 lb) pusher axle load is used as above. The table also shows actual gross and axle weights used in the simulations, with a payload of 36,741 kg (81,000 lb) uniformly distributed load along the entire length of the semitrailer. The vehicle can be loaded with this payload without exceeding any allowable axle weight, with the quad-axle group equalized and "invisible" liftable axles raised in Ontario, and with equalization disabled and the "invisible" liftable axles deployed in Michigan.

Table 75 presents the performance measures derived from the simulation runs, for self-steering axles with a low centring force characteristic.

This configuration is somewhat similar to configuration 13S13. However, it is more difficult to configure and load than that configuration. Control of the load on the pusher axle is critical, and must not be equalized with the load on the drive tandem. The full allowable load on the pusher axle cannot practically be used in Michigan, because it will reduce the front axle load excessively.

Figure 53: Candidate Configuration 112S13 Configured for Ontario

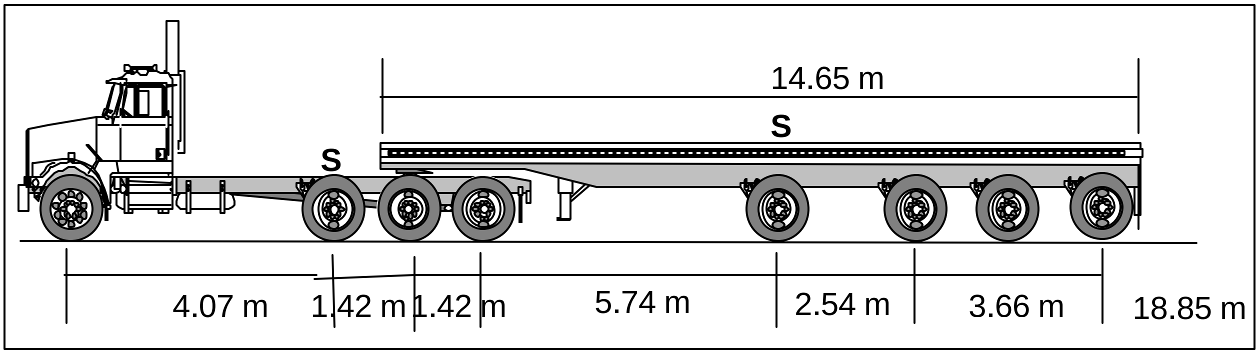


Table 71: Weights for Candidate Configuration 112S13

Rules	Gross	Front	Pusher	Drive	Single	Tridem
Ontario	60,843 kg (134,135 lb)	5,443 kg (12,000 lb)	3,400 kg (7,495 lb)	18,000 kg (39,684 lb)	8,500 kg (18,739 lb)	25,500 kg (56,217 lb)
Michigan	48,988 kg (108,000 lb)	5,443 kg (12,000 lb)	5,896 kg (13,000 lb)	11,793 kg (26,000 lb)	8,164 kg (18,000 lb)	17,690 kg (39,000 lb)
Actual	60,464 kg (133,300 lb)	5,237 kg (11,546 lb)	3,400 kg (7,496 lb)	17,825 kg (39,297 lb)	8,603 kg (18,965 lb)	25,400 kg (55,996 lb)

Table 72: Performance Measures for Candidate Configuration 112S13

CG	Performance Measure								
	SRT (g)	**HSOT (m)**	**LTR**	**TOT (m)**	**LSOT (m)**	**RO (m)**	**FD**	**LFU**	**MSSA (deg)**
	>0.400	**<0.460**	**<0.600**	**<0.800**	**<5.600**	**<0.200**	**<0.100**	**<0.800**	**<20.0**
Low	0.633	0.444	0.341	0.553	4.926	0.031	**0.157**	0.793	17.33
High	0.438	**0.482**	0.510	0.636	4.918	0.031	**0.150**	0.793	17.47

Table 73: Effect of Self-steer Axle Centring Force on Performance Measures

CG	SSA CF	Performance Measure								
		SRT (g)	HSOT (m)	LTR	TOT (m)	LSOT (m)	RO (m)	FD	LFU	MSSA (deg)
		>0.400	<0.460	<0.600	<0.800	<5.600	<0.200	<0.100	<0.800	<20.0
High	Low	0.438	**0.482**	0.510	0.636	4.918	0.031	**0.150**	0.793	17.47
High	Med	0.429	**0.497**	0.517	0.638	4.844	0.041	**0.191**	0.787	16.26
High	High	0.429	**0.497**	0.517	0.638	4.844	0.041	**0.191**	0.787	16.26
High	Lock	0.425	**0.445**	0.529	0.645	4.317	0.071	**0.327**	0.788	

Figure 54: Candidate Configuration 112S13 Configured for Ontario-Michigan

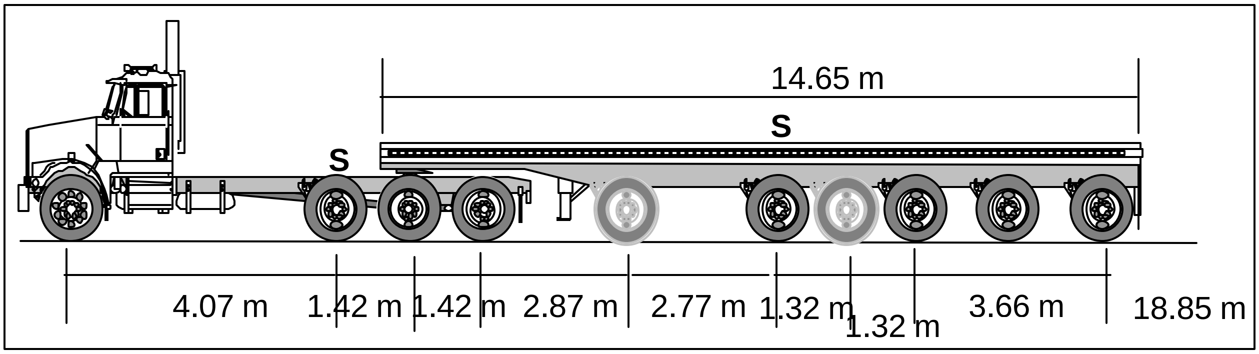


Table 74: Weights for Candidate Configuration 112S13

Rules	Gross	Front	Pusher	Drive	Single	Tridem/ 5-axle group
Ontario Lifts Up	59,943 kg (132,150 lb)	5,443 kg (12,000 lb)	4,500 kg (9,921 lb)	18,000 kg (39,684 lb)	8,000 kg (17,636 lb)	24,000 kg (52,910 lb)
Michigan Lifts Down	60,782 kg (134,000 lb)	5,443 kg (12,000 lb)	5,896 kg (13,000 lb)	11,793 kg (26,000 lb)	8,164 kg (18,000 lb)	29,483 kg (65,000 lb)
Actual Lifts Up	58,196 kg (128,300 lb)	5,170 kg (11,398 lb)	3,400 kg (7,496 lb)	17,077 kg (37,649 lb)	8,239 kg (18,164 lb)	24,309 kg (53,593 lb)
Actual Lifts Down	58,196 kg (128,300 lb)	4,684 kg (10,326 lb)	3,400 kg (7,496 lb)	11,631 kg (25,642 lb)	8,165 kg (18,000 lb)	30,317 kg (66,835 lb)

Table 75: Performance Measures for Candidate Configuration 112S113

		Performance Measure								
		SRT (g)	**HSOT (m)**	**LTR**	**TOT (m)**	**LSOT (m)**	**RO (m)**	**FD**	**LFU**	**MSSA (deg)**
CG	**Lift**	**>0.400**	**<0.460**	**<0.600**	**<0.800**	**<5.600**	**<0.200**	**<0.100**	**<0.800**	**<20.0**
Low	Down	0.477	0.453	0.382	**0.802**					
Low	Up	0.656	0.452	0.326	0.531	4.916	0.032	**0.163**	0.791	17.675
High	Down	0.510	**0.470**	0.533	**0.841**					
High	Up	0.474	0.457	0.475	0.615	4.918	0.033	**0.160**	0.787	17.384

6.10 Candidate Configuration 22S13

Québec has considerable experience with twin-steer straight trucks, and is currently considering configuration 22S3 as an alternative to the self-steer quad configuration 12S13 for applications where the ground clearance of the liftable self-steering axle creates problems. Figure 55 shows the dimensions for this configuration as configured for Ontario. The twin steer front axle attracts considerable weight, which could only be achieved by placing the fifth wheel about 1.52 m (60 in) ahead of the centre of the drive tandem. The semitrailer would require a long gooseneck, which must be contoured to avoid interference with the rear of the tractor frame. The landing gear would need to be placed farther back for clearance from the rear drive axle. The vehicle is likely to have a base length less than the 19.25 m (758 in) required for maximum gross weight. It will also have a higher tare weight than other candidate configurations. This configuration does not appear to be a realistic prospect as a pure tractor-semitrailer in this configuration. It may be more practical if the tractor carries load in a drome box or bed immediately behind the driver's cab, when a base length of 19.25 m (758 in) is achievable. The drome box shown is 2.03 m (80 in) long. The tractor still requires a significant forward setting of the fifth wheel, perhaps 0.61 m (24 in) ahead of the centre of the drive tandem. This configuration may be able to use a self-steer quad semitrailer configured to be pulled by a tandem drive tractor.

Table 76 shows the allowable weights for operation in Ontario or in Michigan. The Michigan weights shown assume that the self-steer axle is 2.77 m (109 in) ahead of the tridem. The vehicle will have a base length just over 19.25 m (758 in), and with a front axle load over 6,000 kg (13,227 lb), the allowable gross weight is 62,700 kg (138,228 lb). It can be loaded to its gross weight with a payload of 42,184 kg (93,000 lb), with 6,803 kg (15,000 lb) on the tractor and the balance on the semitrailer. The payload can be uniformly distributed along the entire length of the drome bed and semitrailer without exceeding any allowable axle weight.

Table 77 presents the performance measures derived from the simulation runs, for self-steering axles with a low centring force characteristic. Any measure that failed the applicable performance standard is highlighted in bold.

This configuration is already legal in Ontario and Michigan, but is not in use either within or between these two jurisdictions. Its limitations for domestic Ontario service make it unlikely it will be developed for Ontario-Michigan service, so a compromise configuration for Michigan has not been developed.

Figure 55: Candidate Configuration 22S13 Configured for Ontario

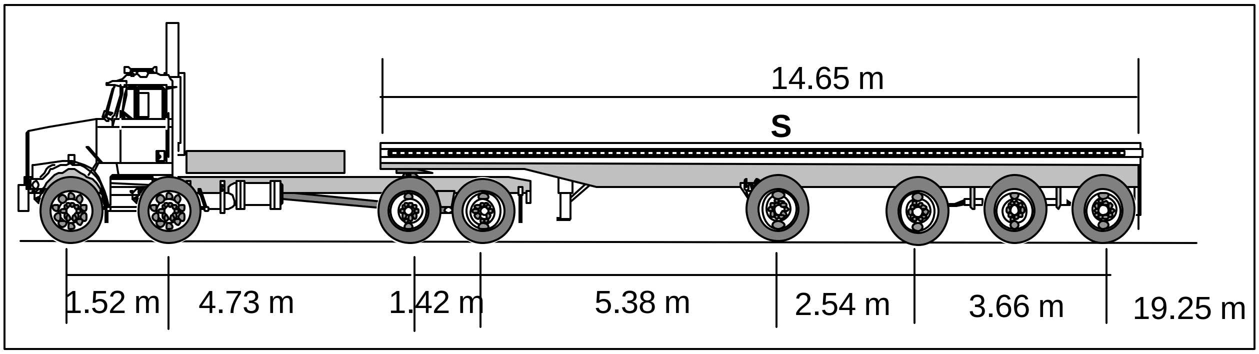


Table 76: Weights for Candidate Configuration 22S13

Rules	Gross	Front	Drive	Single	Tridem
Ontario	62,700 kg (139,110 lb)	14,000 kg (30,864 lb)	18,000 kg (39,684 lb)	8,500 kg (18,739 lb)	25,500 kg (56,217 lb)
Michigan	52,163 kg (115,000 lb)	11.793 kg (26,000 lb)	14,515 kg (32,000 lb)	8,164 kg (18,000 lb)	17,690 kg (39,000 lb)
Actual	62,642 kg (138,100 lb)	12,061 kg (26,590 lb)	18,066 kg (39,829 lb)	8,231 kg (18,145 lb)	24,283 kg (53,535 lb)

Table 77: Performance Measures for Candidate Configuration 22S13

CG	Performance Measure								
	SRT (g)	HSOT (m)	LTR	TOT (m)	LSOT (m)	RO (m)	FD	LFU	MSSA (deg)
	>0.400	<0.460	<0.600	<0.800	<5.600	<0.200	<0.100	<0.800	<20.0
Low	0.581	0.459	0.329	0.511	4.964	-0.044	**0.191**	0.453	16.010
High	0.406	**0.506**	0.500	0.589	4.967	-0.075	**0.186**	0.458	15.875

6.11 Summary of Performance of Candidate Configurations

Table 78 summarizes the performance measures for the candidate configurations with a high centre-of-gravity payload. This is the critical case for the high speed performance measures, but is not significant for the low-speed performance measures. The performance measures presented are those for the most practical axle arrangement for each of the configurations considered. These are configuration 2a for configuration 12S113, which uses a 3.05 m (120 in) spread tridem, configuration 1b for configuration 12S131, and configuration 1a for configurations 12S114 and 12S141. The high-speed performance measures given for configurations 12S131 and 12S141 have the rearmost self-steering axle locked. The bottom row shows the performance measures for configuration 1a of configuration 12S13, the self-steer quad, as a baseline, from Table 26.

Table 78: Summary of Performance of Candidate Vehicle Configurations

Conf	Performance Measure								
	SRT (g)	**HSOT (m)**	**LTR**	**TOT (m)**	**LSOT (m)**	**RO (m)**	**FD**	**LFU**	**MSSA (deg)**
	>0.400	**<0.460**	**<0.600**	**<0.800**	**<5.600**	**<0.200**	**<0.100**	**<0.800**	**<20.0**
12S113	0.433	**0.545**	0.536	0.721	5.068	0.037	**0.225**	0.580	19.63
12S131	0.427	**0.533**	0.569	0.746	3.979	0.173	**0.215**	0.539	17.66
12S114	0.435	**0.471**	0.536	0.680	5.024	0.039	**0.243**	0.536	**22.52**
12S141	0.420	**0.486**	0.590	0.766	3.444	**0.308**	**0.295**	0.529	19.84
13S13	0.408	**0.491**	0.521	0.640	5.154	0.037	**0.116**	0.798	17.11
112S13	0.438	**0.482**	0.510	0.636	4.918	0.031	**0.150**	0.793	17.47
22S13	0.406	**0.506**	0.500	0.589	4.967	-0.075	**0.186**	0.458	15.88
12S13	0.429	**0.496**	0.515	0.654	4.972	0.045	**0.199**	0.605	17.06

All configurations fail the high-speed offtracking performance standard by 0.03-0.08 m (1-3 in), which is comparable to that for a self-steer quad. All configurations also fail the friction demand performance standard. The five and six-axle semitrailers have higher friction demand than a self-steer quad, while configurations 13S13 and 112S13 have friction demand in the low end of the range for tridem semitrailers. The lateral friction utilization for the two latter configurations is marginal, but typical for tridem drive tractors. Configuration 12S141 fails the rear outswing performance standard. Configuration 12S114 clearly requires at least 25 deg of steer for the foremost self-steering axle, and more would be most desirable. It would also be prudent to provide at least 25 deg of steer for the foremost self-steering axle on configuration 12S113, and the rearmost self-steering axle on configuration 12S141. The ultimate performance of configurations 12S113 and 12S114 does not require either axle to be locked at high speed. Locking either or both axles reduces high-speed offtracking “normal” performance, but increases the tendency to rollover at "ultimate" performance. The ultimate performance of configurations 12S131 and 12S141 is best if the rearmost self-steering axle is locked at high speed. The other may remain free to steer, or may also be locked.

The friction demand performance measure represents the effort needed to turn a vehicle. The performance standard of 0.1 is based on the "side friction factor" used in highway design, which represents the design lateral acceleration based on the lateral friction of a slippery highway. This ensures that cars can travel on a ramp at or close to the posted speed when the road surface is slippery, such as under wet snow or ice, when roadway friction may be as low as 0.2. The value of 0.1 recognizes that drive traction consumes some of the available roadway friction, allows some margin for manoeuvring, and also recognizes that the friction characteristics of truck tires are less than those of car tires [7]. That work identified the potential of jackknife arising during a low-speed turn on a low friction surface, and the performance measure was established to guard against this. Tests were unable to demonstrate such a jackknife [6]. However, it is known that high-speed tractor jackknife does occur with when the tractor is towing a multi-axle semitrailer, and the high friction demand of the semitrailer would certainly contribute to occurrence of such a jackknife, though it may not always be the critical event in such a crash. A rigorous imposition of the friction demand performance measure is an effective way to control semitrailer axle spread, which, when combined with Ontario's weight and dimension regulations, effectively reduces the scope for rigid liftable axles. However, the friction demand performance standard is exceeded by many tridem and self-steer quad semitrailers, as shown in Table 26 and Table 27. These vehicles are able to make low-speed turns at intersections on slippery roads, and no occurrences of low-speed jackknife are known, though this does not mean they may not have occurred. Drivers probably tend to operate a vehicle to what they perceive as the safe limits of its capability. Friction demand is most critical on a slippery road. Roads definitely get slippery during the winter in Ontario, but they are not very slippery for a significant portion of the year. The friction demand performance measure is evaluated at 8.8 km/h (5.5 mi/h) in a 14 m (46 ft) radius turn. However, friction demand appears to decrease with a decrease in speed, and with an increase in turn radius, as shown in Table 80. If friction demand appears excessive on a slippery road at 8.8 km/h (5.5 mi/h) in a 14 m (46 ft) radius turn, it is a natural response for a driver to reduce speed, or increase the turn radius to the extent that it may be possible. This is not necessarily a traffic problem, as traffic volumes are often reduced when roads are very slippery, and drivers expect to make allowances for other vehicles. This does not mean that the friction demand performance measure is not important. It is an effective way to control multi-axle configurations. However, because the driver can (to some extent) adjust speed and turn radius to reduce a moderate (but not extreme) friction demand, it may be argued that friction demand may not be as critical to safety as (say) high-speed or transient offtracking, where the vehicle ends up outside its own lane and may run off the road or side-swipe another vehicle. It is apparent that vehicles with friction demand in the range 0.10 to 0.20 or 0.25 can operate reasonably effectively. It is also apparent that vehicles with a friction demand over 0.40 cannot operate without raising liftable axles to reduce their friction demand. It is not intended to propose a new performance standard. However, if the driver of a vehicle with moderate (0.10 to 0.25) friction demand can reduce the friction demand to make a turn successfully by reducing speed or increasing turn radius, then there does not appear to be any *a priori* safety hazard.

Configuration of these “infrastructure-friendly” candidate configurations was driven by the requirements that:

- The load carried by each axle on the semitrailer must be equal; and
- Self-steering axles are necessary to provide the same payload as on existing configurations and meet performance requirements.

It was not difficult to meet these requirements for the self-steer triaxle and self-steer quad introduced in Ontario Regulation 597, because there was enough room under the semitrailer to locate the axles to achieve maximum weight and to distribute that weight over the length of the semitrailer. For a five-axle semitrailer to have about the same payload as existing semitrailers, it needs about 8,000 kg (17,636 lb) on each of the axles, with load equalization. This translates into 24,000 kg (52,910 lb) on a tridem, which requires a spread of 3.05 m (120 in), presuming that this tridem would qualify for the same weight as if it were on a tridem or self-steer quad semitrailer. This is larger than the tridem spread currently used on existing 131 five-axle semitrailer configurations. Similarly, a six-axle semitrailer needs about 6,500 kg (14,330 lb) on each axle, which with load equalization translates into 26,000 kg (52,910 lb) on a four-axle group. This has been assumed to require a spread of 3.96 m (156 in), which is significantly larger than the 3.35 m (132 in) spread commonly used on both 114 and 141 semitrailer configurations. The axle spreads on the 131, 114 and 141 semitrailer configurations therefore will be larger than for existing semitrailers, which moves the self-steering axles away from the turn centre of the fixed axle group. The steer capability of a self-steering axle is more likely to be exceeded the further that axle is from the turn centre. This means that the two self-steering axles on 113 and 114 semitrailers should be placed as close together as possible, and as close to the fixed axle group as possible. This almost certainly eliminates the possibility of 2.77 m (109 in) axle spacings to achieve maximum weight in Michigan. Even if the fixed axle group spread could be reduced, bridge loading considerations will still likely prevent any reduction in the total spread of all axles on the semitrailer. The weight currently allowed on some axle arrangements on existing multi-axle semitrailer configurations that have been operating for many years is known to exceed a prudent level by a considerable margin. These vehicles are the principal reason that the risk of bridge failure in Ontario is much higher than good engineering practice should require [4].

Regulation 597 requires that self-steer triaxle and quad semitrailers have 20 deg of steer. This wording appears to have served as the minimum requirement for many carriers and manufacturers. It appears that some vehicles in particular operations may occasionally or regularly bottom the self-steer axle, which drags sideways and potentially results in tire wear and axle, suspension and frame damage. These vehicles either need more than 20 deg of steer, or operational changes need to be made so that they can operate within the capability of the self-steering axle. The foremost self-steering axle on configurations 12S113 and 12S114, and the rearmost such axle on configuration 12S141 probably need closer to 25 deg of steer. If these vehicles are operated like self-steer quads, they would certainly benefit by having greater steer capability than this, though suitable axles may not exist. Axles in other positions on these vehicles need “at least” 20 deg of steer, which means closer to 25 deg.

The existing 12S113 and 12S131 configurations provide the best payload under Ontario rules. The 12S113 and 12S131 candidate configurations could have about the same payload, but the semitrailer axle capacity may be limited so that the allowable gross weight is very close to the sum of allowable axle loads. This removes much of the flexibility in load distribution that has been available with the existing configurations.

The existing 12S114 and 12S141 configurations provide the best payload for operation between Ontario and Michigan. The axle spacing restrictions are likely to reduce the allowable gross weight of the candidate 12S114 and 12S141 configurations in Michigan by a substantial amount. The requirement for load equalization appears to eliminate any future for these configurations in Ontario, and between Ontario and Michigan.

The existing configurations 12S114 and 12S141 are natural extensions of the existing configurations 12S113 and 12S131 that provide similar payload between Ontario and Michigan, simply by adding one more axle and adjusting the axle spacings. Essentially, these vehicles need a fixed axle group with the minimum spread, and single axles with 2.77 m (109 in) spacing. Load equalization increases the spread of the fixed axle group, and considerations of self-steer angle reduce the single axle spacings. Consequently, for the candidate configurations to achieve similar allowable gross weights in Ontario and Michigan, it appears they will require two “invisible” liftable axles, rather than the one for the existing vehicles. This reduces the payload in some cases, though there are cases where the allowable gross weight in Michigan may increase.

Configuration 13S13 provides the best dynamic performance, and should be preferred to configuration 112S13, because load on the self-steer pusher axle will be difficult to control, and the axle capacity it provides in Michigan may be very difficult to use. Configuration 22S13 would likely appeal only to a very limited market, and to be practical in Ontario, would need a different tractor than currently being considered for configuration 22S3 in Québec.

This study has not allowed sufficient time to optimize the candidate configurations. It may well be possible to improve the performance of some of these configurations by a series of compromises on axle spacings, self-steer axle characteristics, maximum self-steer angle, allowable weights, and possibly a 15.24 m (50 ft) semitrailer length for semitrailers intended to operate into Michigan.

7. SELF-STEERING AXLE TECHNOLOGY, APPLICATION AND EXPERIENCE

7.1 Steering Systems

There are three principal types of steering system:

- Command steering;
- Forced, or linked articulation, steering; and
- Self-steering.

The front axle of a vehicle uses a command steering system. The driver turns the steering wheel, which creates a command to a system that causes the wheels on the axle to steer in a manner proportional to the steering wheel input. The command is most commonly transferred by a mechanical linkage to a hydraulic system that actually steers the wheels, but other transfer and actuation systems may be used. The command controls the steer angle between the wheels and the longitudinal axis of the vehicle, which creates a force that moves the vehicle towards the desired direction of travel.

A forced-steering system most commonly uses a mechanical linkage to steer an axle or bogie as a function of the articulation angle between a towing vehicle and the vehicle unit to which the axle or bogie is attached. Other linkages are possible. The articulation angle and linkage control the steer angle between the wheels and the longitudinal axis of the vehicle, and assist turning. The compensating reach of a western log truck is effectively a forced steering system. The steer angle of a forced-steering system is fixed during a steady turn, so the wheels provide lateral forces that can contribute to lateral/directional stability of the vehicle.

A self-steering axle steers only in response to lateral forces that develop between its tires and the roadway. The steering system is not connected to any other part of the vehicle, or controlled in any way. The self-steering axle requires a combination of trail, stiffness and damping to track faithfully without shimmy. Trail is the longitudinal distance between the rotational axis of the steering system and the centre of the tire contact patch. It is composed of mechanical trail, which is the physical distance between the rotational axis and the axle spindle, and pneumatic trail, which is the distance of the centre of the tire contact patch behind the spindle, which varies with forward speed of the vehicle. The self-steering axle is usually fitted with a device or system that provides a restoring force to return the steer to centre, and also helps offset the effect of unbalanced braking forces between wheels of the axle. The tire lateral forces must overcome friction before the axle will begin to steer, and then steers against the resistance of the centring device or system. Friction and stiffness in the steering system, and damping where shock absorbers are also used, also contribute to the stability of the self-steering system. The wheels are not controlled, and steer where they want to based on the instantaneous heading of the trailer and the internal resistances in the self-steering system. The lateral force on a self-steering axle may be quite small, and it may only contribute to lateral/directional stability of the vehicle to the extent that the centring device or system provides resistance.

When the wheels on the two ends of an axle are mounted individually, each on their own kingpin, then a tie-rod assembly is used to coordinate steering of the two wheels and provide the necessary steering geometry.

The legal definition of a self-steering axle used in Ontario Regulation 597, "… wheels can articulate in response to forces generated between the tires and the road or through mechanisms and linkages that operate independently of the driver", includes both a self-steering axle and a forced steering axle.

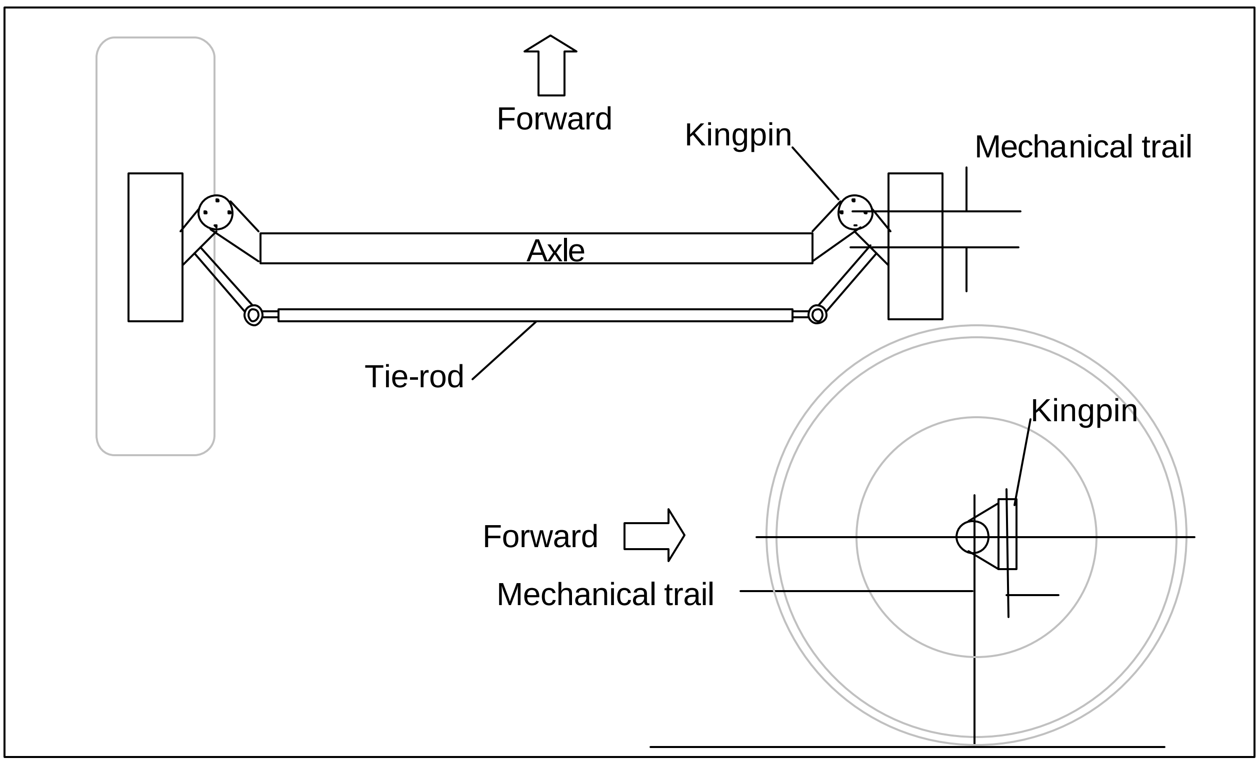
7.2 Self-steering Axle Technology

There are three principal types of self-steering axle:

- Leading kingpin;
- In-line kingpin; and
- Turntable.

The leading kingpin self-steering axle has a nominally vertical kingpin that is typically placed about 0.15-0.20 m (6-8 in) ahead of the axle spindle, as shown in Figure 56. This diagram is simply a schematic of the steering mechanism that omits details of the suspension, centring device and any lock for clarity. The mechanical trail is usually sufficient to ensure dynamic

Figure 56: Leading Kingpin Self-steering Axle



tracking stability, so that the axle is free of shimmy. The kingpin may deviate from a true vertical position due to changes in ride height of the self-steering axle, changes in semitrailer deck angle that arise with different tractor fifth wheel heights, deflection of the tractor suspension under load, deflection of the semitrailer suspension under load, and bending of the semitrailer frame. Common use of air suspension on tractors, and the requirement for load equalization leading to use of air suspensions on the semitrailer, eliminates most of the suspension height variation with load, so these axles typically can be mounted on a simple trailing arm air suspension. The leading kingpin self-steering axle is fitted to most semitrailers, and is also widely used as a pusher axle on straight trucks.

The in-line kingpin self-steering axle has an inclined kingpin that is in-line with the axle spindle, as shown in Figure 57. This diagram is also simply a schematic of the steering mechanism that omits details of the suspension, centring device and any lock for clarity. This axle is essentially similar to the front steering axle of a truck, though the axle is usually installed with a greater inclination angle to increase the trail to ensure dynamic tracking stability. Stability of this type of axle is critically dependent on the kingpin inclination angle, which may vary due to the same factors as discussed above. A simple trailing arm air suspension has not always been able to provide sufficient control of kingpin inclination angle to ensure dynamic tracking stability, so this type of self-steering axle is often installed with a parallel arm mechanism that fixes the kingpin inclination angle relative to the vehicle frame, as shown in the Figure 57. The vertical position of the tire contact patch of a leading kingpin axle running with the kingpin

Figure 57: In-line Kingpin Self-steering Axle

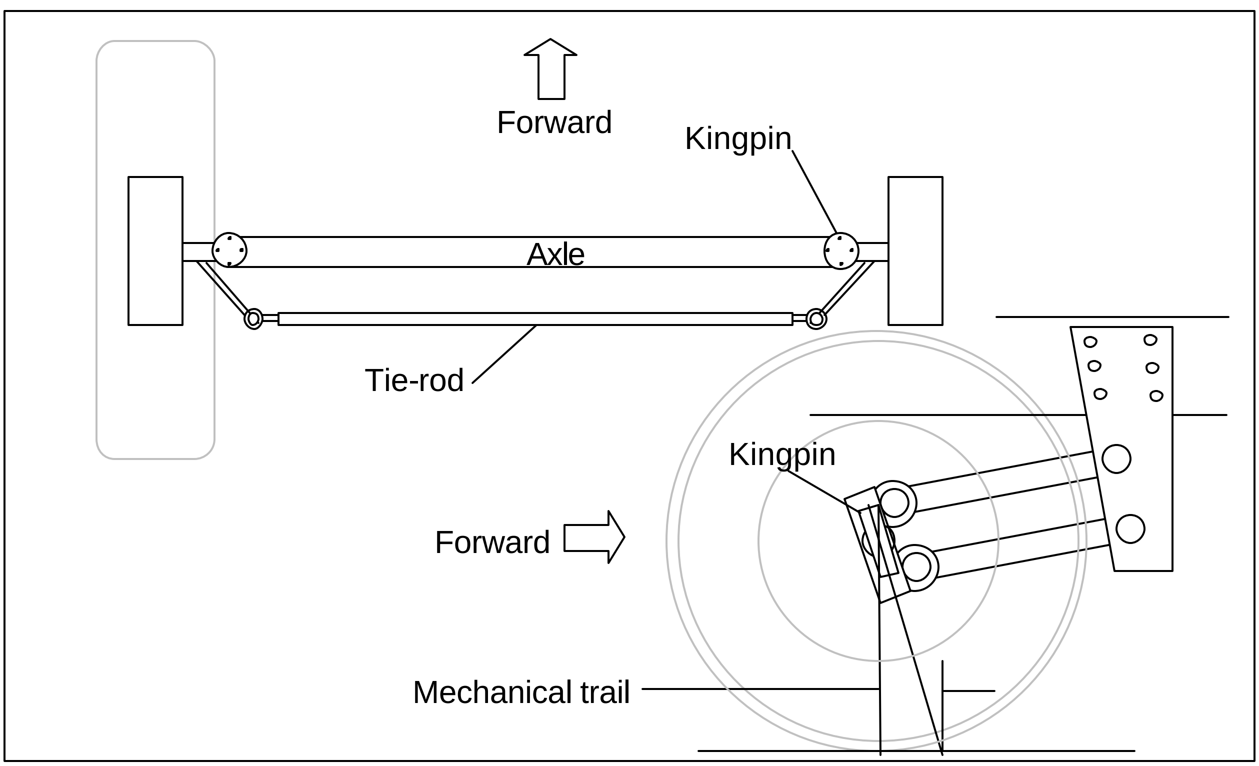
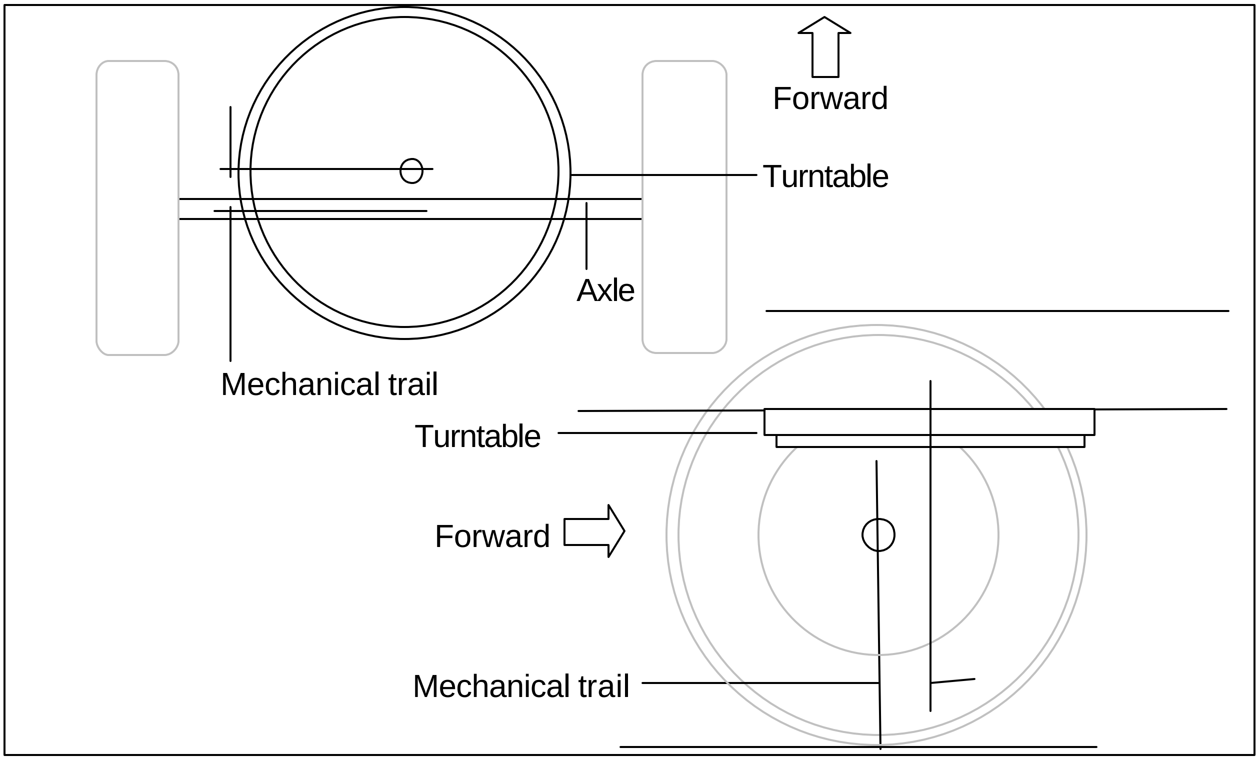


Figure 58: Turntable Self-steering Axle



vertical stays in the same horizontal plane as the axle steers. However, the vertical position of the tire contact patch of an in-line kingpin axle drops as the axle steers, which increases the vertical tire loads on each side, and tends to limit the maximum self-steer angle. The in-line kingpin self-steering axle has primarily, but not necessarily exclusively, been used as a pusher axle on straight trucks.

The turntable self-steering axle simply installs a rigid axle beneath an automotive turntable, as shown in Figure 58. The axle is usually about 0.30-0.38 m (12-15 in) behind the centre of the turntable to provide the mechanical trail necessary for dynamic tracking stability. It has been used on a small number of C-dollies. It is probably impractical to use it on a semitrailer with frame rails, because the thickness of the turntable will use valuable vertical space needed for suspension travel and axle lift. It may be possible to use it on a van semitrailer. The distance from a tire centre-line to the turn centre of a turn table is considerably greater than the distance to the kingpin of a leading kingpin or in-line kingpin self-steering axle, which exaggerates the steer effect of a left-right imbalance in brake forces.

Any of these self-steering axles may:

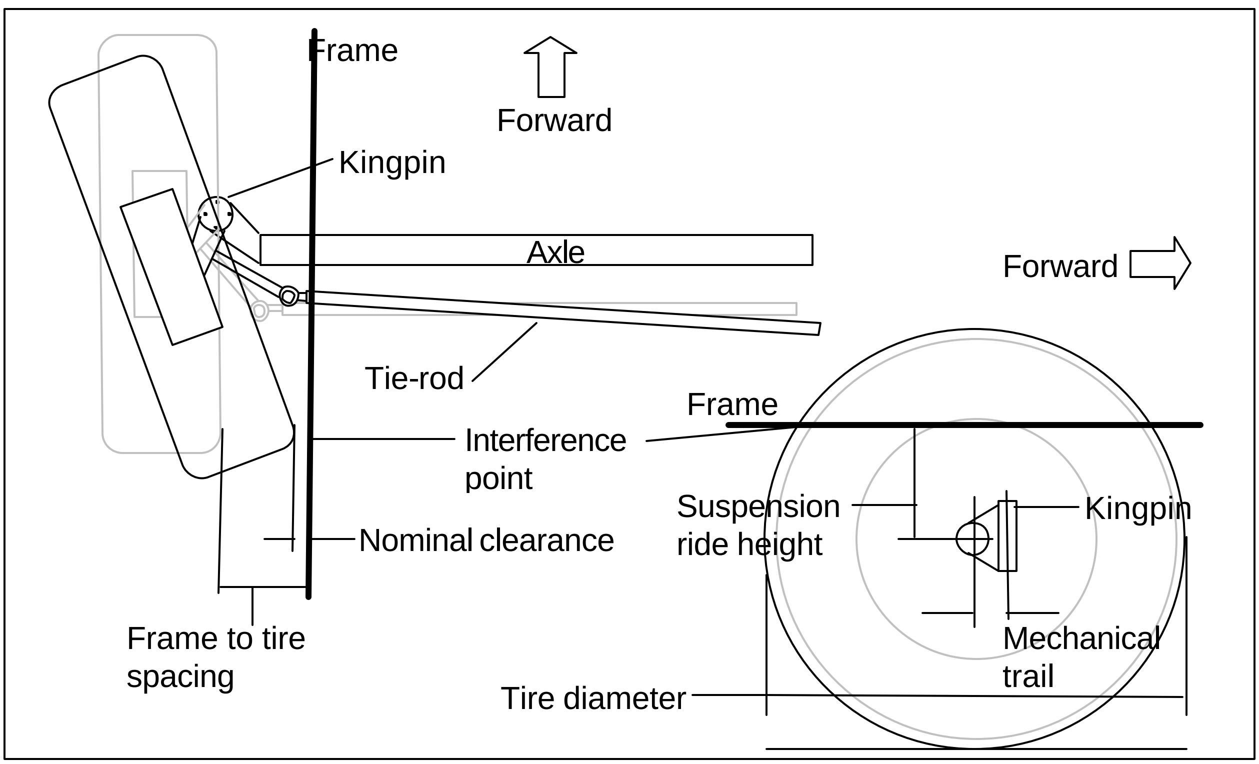
- Use single tires or dual tires;
- Be fitted with a device to cause the steering to centre;
- Be fitted with a device to augment dynamic tracking stability; and

- Be fitted with a locking device.

7.3 Factors Affecting Maximum Self-steer Angle

The maximum self-steer angle is usually limited by a stop for rotation of the self-steering system itself. This is typically adjusted to ensure there will be no contact between equipment mounted on the axle, and between the inner rear edge of the tire tread and the outside edge of the semitrailer frame, as shown in Figure 59. While this shows a leading kingpin axle, the rear edge of the tire is the critical interference point for all three types of self-steering axle, because is each case the vertical rotational axis is effectively ahead of the spindle. The maximum self-steer angle for frame-tire interference is determined principally by the ride height of the suspension, the unloaded tire diameter, and the horizontal transverse distance between the bottom of the frame and the edge of the tire tread, less a nominal clearance, as shown in Figure 59 for a conventional frame and air suspension. It is also affected by the geometry of the steering system, and a number of lesser factors, which may become more significant as the available space gets tighter.

Figure 59: Interference between Self-steering Axle and Frame



A suspension with a 0.35 m (14 in) ride height, 0.20 m (8 in) spacing from frame to tire, and a 1.07 m (42 in) tire diameter allows a self-steer angle of about 20 deg. For this situation, a 25 mm (1 in) increase in frame to tire spacing allows 2.5 deg more steer, a 25 mm (1 in) increase in ride height allows 0.9 deg more steer, and a 25 mm (1 in) increase in tire diameter decreases steer by 0.7 deg. These values change somewhat as the basic parameters change, but the relationships do not change. With a fixed frame location, the greatest self-steer angle is obtained with the smallest diameter tire with the largest ride height and the greatest frame to tire spacing, which itself implies the narrowest tire. There is no simple "one size fits all" answer. Each application must be custom-fitted based on the operational requirements for the vehicle.

The self-steer angle in a high-speed dynamic manoeuvre is quite small, and is unlikely to exceed 5 deg. Significant self-steer angles only occur during a low-speed turn. Right-hand turns made on-road tend to be tighter than left-hand turns. A tight turn made off-road need not be an issue, as the driver may raise any liftable self-steering axle that could bottom during the turn. The critical situation therefore should be contact of the inside rear of the right-hand tire when the vehicle is making a right-hand turn. The maximum self-steer angle will differ from that obtained from the nominal geometry shown in Figure 59 to the extent that the relative positions of the axle and the frame of the vehicle, the ride height, changes during the turn. Either the body of the vehicle may move relative to the axle, or the axle may move relative to the body. The axle may either move vertically, when upward movement is critical, or in roll, when upward movement of the wheel on the inside of the turn is critical.

The forces on the body are low during a low-speed turn, as the lateral acceleration is of the order of 0.05 g. There will be no significant vertical movement of the body, which tends to roll towards the outside of the turn. This increases the space between the rear of the inside tire and the frame, but by no more than about 2-5 mm (0.1-0.2 in) for a semitrailer with a high centre of gravity, and less for a semitrailer with a low centre of gravity. This is hardly significant, and tends to increase clearance.

Vertical movement of the self-steering axle occurs when the axle crosses a crest while the vehicle is turning tightly. One scenario would be when the vehicle turns right into a descending driveway. The tractor descends the driveway, and the semitrailer axles remain up on the roadway, presumed level. In this situation, the self-steering axle would effectively be pushed up towards the body of the semitrailer, which is equivalent to reducing its ride height. The maximum self-steer angle in a tight turn is reached at the point of tightest steer, which in a simple turn is when the driver starts to straighten out the steering wheel. It is likely that the self-steering axle will not be close to maximum steer before it enters the descending part of the driveway, so such a temporary reduction in maximum self-steer angle due to axle vertical movement may not result in interference.

Roll of the self-steering axle occurs when the wheel on the inside of the turn runs over an obstruction that raises the wheel. The most likely obstructions are a curb or a snow bank. It is unlikely that a vehicle would be so far into a turn when the self-steering axle strikes a curb or snow bank that it would have reached the maximum self-steer angle for the turn. Even if it did, the angle of attack would be shallow, and the curb or snow bank would tend to straighten out the self-steer, which reduces the likelihood that disturbance of the axle would precipitate contact between the tire and the frame of the vehicle.

Any number of bizarre or unpredictable things might occur that could reduce the space between the tire and the frame and limit the self-steer angle below the nominal maximum angle. It is difficult to envisage that many of these might occur while turning on a highway, and the driver is always free to stop and raise the self-steering axle off-highway.

7.4 Kingpin Inclination Angle

Kingpin inclination angle is critical to stability of a self-steering axle, and may also be a significant factor in tire wear. Every self-steering axle should be installed with the kingpin inclination angle specified by its manufacturer under the nominal operating conditions for the vehicle. However, the kingpin inclination may vary during the life of a vehicle due to various factors. The semitrailer deck angle may change, due to changes in fifth wheel height between tractors, deflection of a steel spring suspension on the tractor or wear of the semitrailer tires, or deflection of the semitrailer under load.

A 25 mm (1 in) change in height at the fifth wheel or the centre of the tridem of a typical 14.65 m (48 ft) self-steer quad semitrailer results in about 0.13 deg change in kingpin inclination angle, and about 0.17 deg for a 10.97 m (36 ft) long self-steer tri-axle. A 25 mm (1 in) change in deck height due to semitrailer deflection under load at the location of a self-steer quad semitrailer results in about 0.15 deg change in kingpin inclination angle. Deflection is small for a semitrailer whose body has substantial structural depth, like a van or tanker, or which supports the load at each end of the vehicle, like a dump or log trailer, so this is principally an issue for flatbed semitrailers, where deflection may be of the order of 100-150 mm (4-6 in). A 25 mm (1 in) change in diameter of the tires on the self-steering axle may result in as much as 3.0 deg change in kingpin inclination angle. If the tire diameter is changed, either because a different tire is used, or a recap has a significantly different diameter than the original tire, it will be necessary to adjust the kingpin inclination angle and suspension ride height. An increase in fifth wheel height, downward deflection of the centre of the semitrailer, and a decrease in tire diameter all move the top of the kingpin rearward, which tends to increase the mechanical trail, which tends to improve stability. The opposite movements have the opposite effect. Axle manufacturers typically allow a variation of +-1-2 deg for installation tolerances and in-service variations in kingpin inclination. However, the further the kingpin is from true vertical, the higher tire wear is likely to be.

7.5 Effect of Turn Radius and Turn Angle on Low-speed Performance Measures

If a self-steer axle hits its stop during a turn, and the tractor keeps on turning, the friction demand increases rapidly and the tire of the self-steer axle is dragged sideways. This wears the tire, and puts high forces into the vehicle. The maximum self-steer angle therefore is a critical performance measure. If the self-steer capability is exceeded, bad things always happen, though they may not result in a crash. If many of the other performance standards are exceeded, bad things may not happen, but the probability of a crash is increased to the extent that the vehicle may be intruding into the space of other vehicles.

It is always possible for a tractor to get to 90 deg articulation, when it simply pulls the semitrailer kingpin sideways and the semitrailer rotates about its turn centre, which stays pretty much in the same place. This would require the self-steering steer about 90 deg. This may theoretically be feasible for a turntable steer axle, but is impractical for an automotive steer axle. However, such an extreme manoeuvre would generally take place in a yard or other off-road situation, when the self-steering axles may be raised. Thus, the practical limit for maximum self-steer angle will be the tightest turn that can arise on a highway. The maximum self-steer angle is limited by design of the steering system, and interference with axle components and the structure of the semitrailer.

The maximum self-steer angle and other low-speed performance measures were computed using a 90 deg right-hand turn with a 14.00 m (46 ft) radius at the left front wheel of a 6.20 m (244 in) wheelbase tractor. A shorter wheelbase tractor that can turn more tightly increases both friction demand and maximum self-steer angle. A turn that is more than 90 deg increases maximum self-steer angle. The maximum self-steer angle, friction demand and low-speed offtracking performance measures were evaluated for the baseline self-steer quad semitrailer with a 2.54 m (100 in) single axle spacing and a low self-steer centring stiffness for turns of various radius, and length, as expressed by the included angle of the turn. The 6.20 m (244 in) wheelbase tractor used may not actually be able to make a turn much tighter than about 12 m (39.4 m), but the simulation does not know that, and the tighter turns simply illustrate the progression of trends which would apply if a shorter wheelbase tractor was used that could make those tighter turns. Table 79 and Figure 60 show the effect of turn radius and turn angle on maximum self-steer angle, Table 80 and Figure 61 show the effect of turn radius and turn angle on friction demand, and Table 81 and Figure 62 show the effect of turn radius and turn angle on low-speed offtracking. Maximum self-steer angle, friction demand and low-speed offtracking all increase as turn radius decreases, and all increase as turn angle increases. While a driver may be able to cope with an increase in friction demand, and low-speed offtracking is not critical, the maximum steer angle of the particular self-steering axle fitted to a semitrailer is fixed. Drivers may need to make special manoeuvres to avoid bottoming the steer at critical turns on routes, or may need to find alternate routes that avoid those turns. Drivers may also need to ensure that any turns made off-road do not bottom the self-steer, or if this would be inevitable, they must stop and raise the self-steering axle.

Table 79: Effect of Turn on Maximum Self-steer Angle for Self-steer Quad

Turn Radius (m)	Turn Angle (deg)					
	75	90	105	120	135	150
10	15.17	20.22	23.95	29.88		
12	14.36	18.60	22.49	25.60		
14	13.58	17.06	20.04	22.48	24.32	27.39
16	12.94	15.13	17.54	19.59	21.55	22.72
18	12.18	13.88	15.15	17.25	18.08	19.16
20	11.33	12.86	13.95	14.69	15.50	16.38

Figure 60: Effect of Turn on Maximum Self-steer Angle for Self-steer Quad

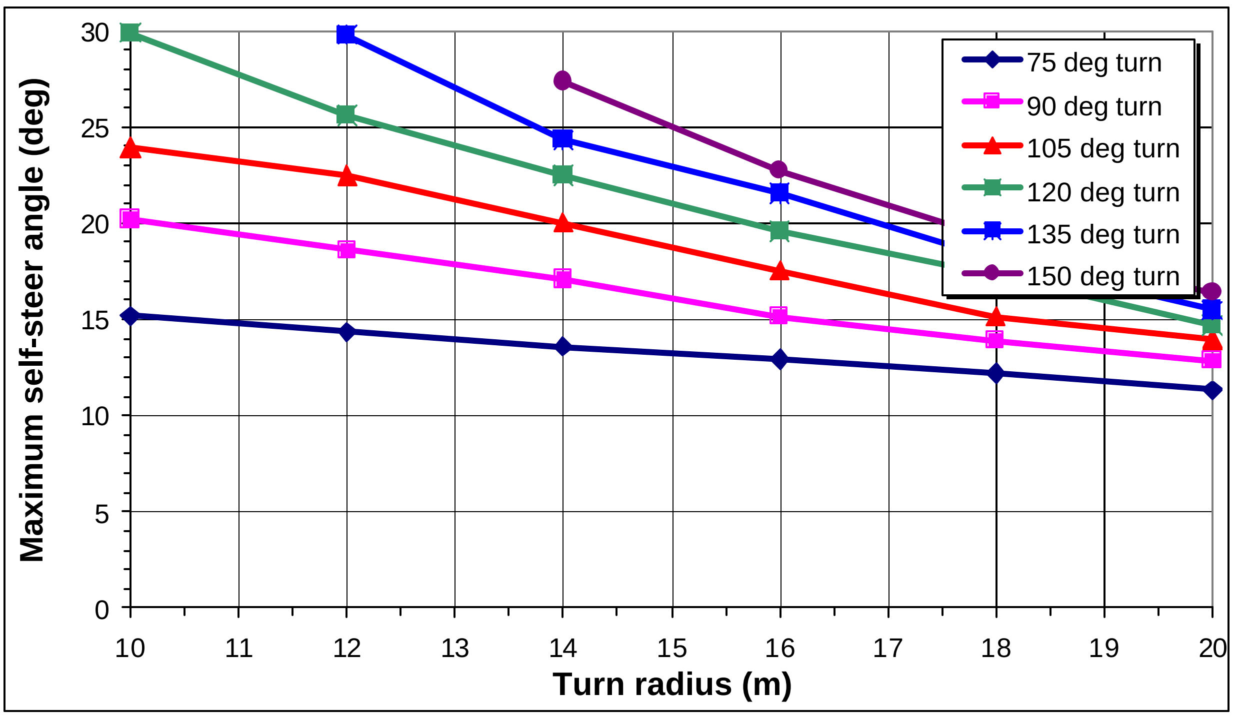


Table 80: Effect of Turn on Friction Demand for Self-steer Quad

Turn Radius (m)	Turn Angle (deg)					
	75	90	105	120	135	150
10	0.180	0.225	0.362	0.549		
12	0.170	0.200	0.278	0.410	0.545	0.943
14	0.158	0.199	0.231	0.285	0.367	0.457
16	0.149	0.182	0.192	0.223	0.259	0.288
18	0.141	0.165	0.184	0.186	0.202	0.214
20	0.136	0.147	0.157	0.174	0.185	0.187

Figure 61: Effect of Turn on Friction Demand for Self-steer Quad

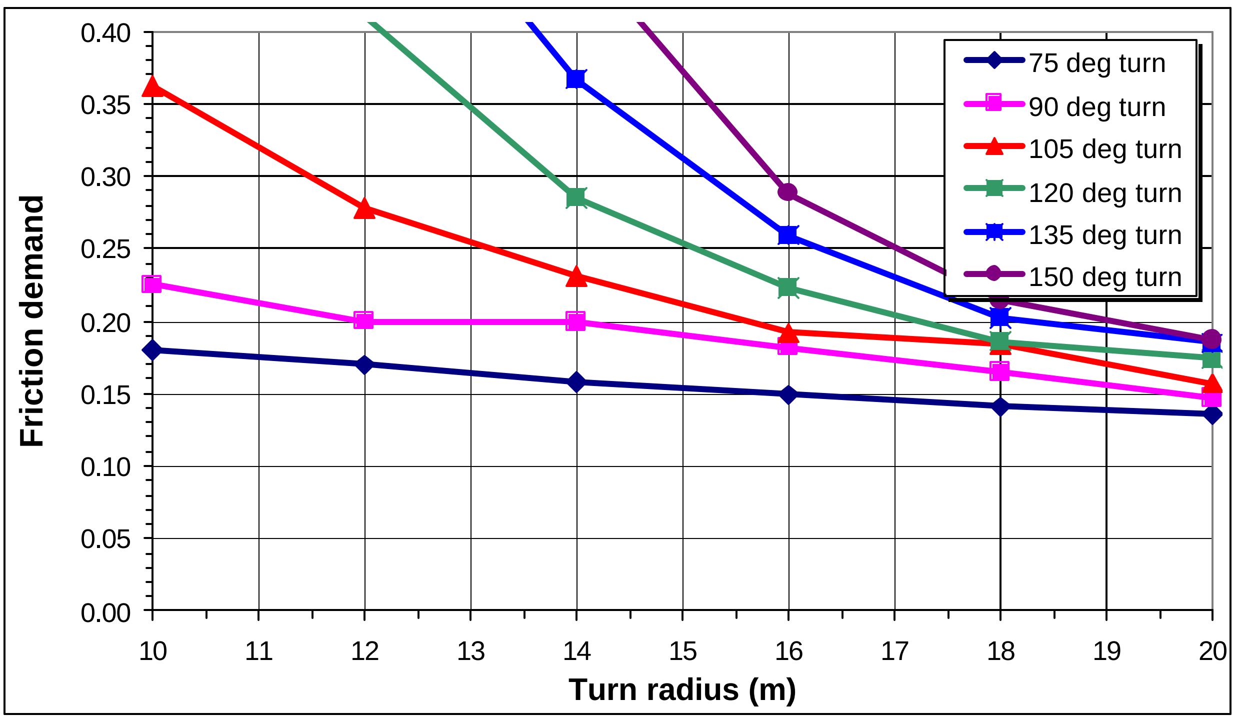
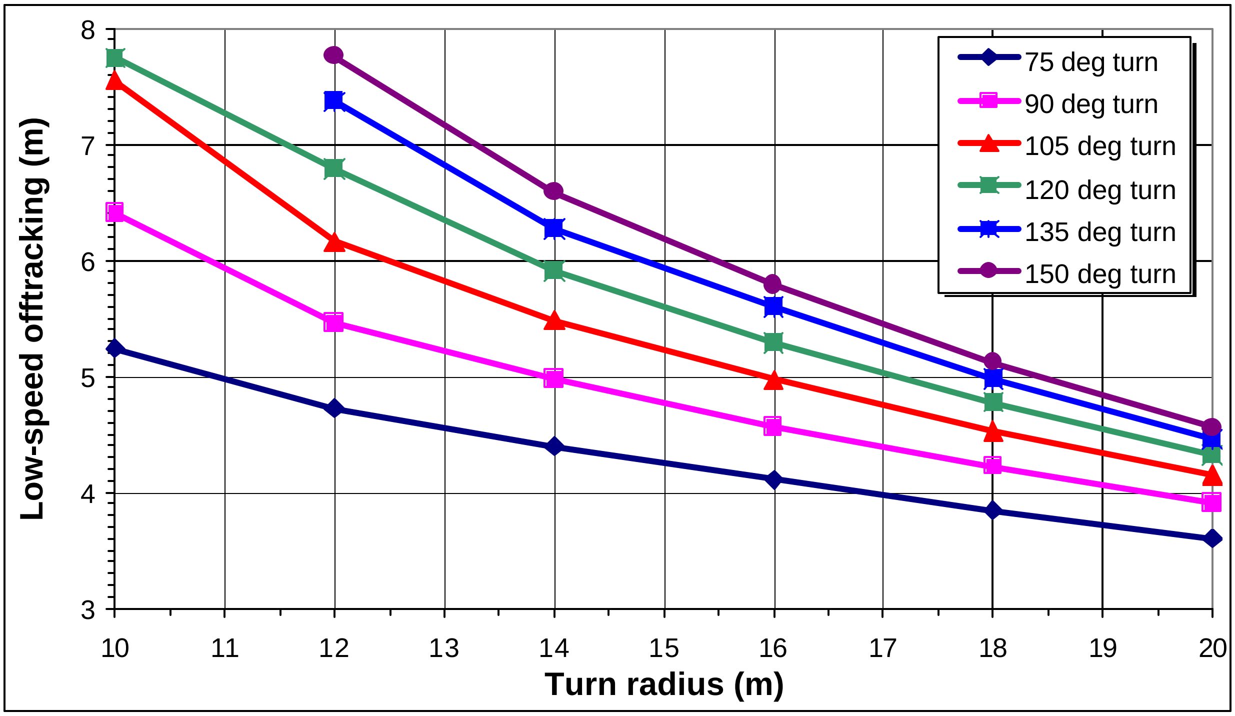


Table 81: Effect of Turn on Low-speed Offtracking for Self-steer Quad

Turn Radius (m)	Turn Angle (deg)					
	75	90	105	120	135	150
10	5.238	6.404	7.552	7.744		
12	4.725	5.456	6.157	6.785	7.369	
14	4.395	4.972	5.483	5.906	6.267	6.582
16	4.107	4.563	4.968	5.289	5.598	5.784
18	3.843	4.225	4.527	4.776	4.973	5.122
20	3.602	3.905	4.151	4.319	4.455	4.558

Figure 62: Effect of Turn on Low-speed Offtracking for Self-steer Quad



7.6 Previous Assessments of Performance of Vehicles with Self-steering Axles

A variety of forced steering and self-steering devices entered the market in Ontario in the 1970's to deal with the high friction demand that arose from the multiple widely spaced axles that became common after weight regulation was introduced by the Ontario Bridge Formula [24]. However, the need for steering axles disappeared as it became clear that use of rigid liftable axles would be tolerated. Some of the steering devices were an unmitigated disaster. Experience with those devices affected the acceptance of self-steering axles for a long time.

This chapter summarizes briefly previous assessments of the dynamic performance of vehicles equipped with self-steering axles.

MTO conducted two series of tests with a tri-axle semitrailer that was fitted with a self-steering belly axle and a two-axle bogie that was also free to steer, with the first axle on the bogie also a self-steering axle [24], [25]. The first series consisted primarily of low-speed turning tests, and lane changes at a moderate speed on a low-friction surface. The self-steering belly axle was found not to have a serious effect on dynamic performance when the bogie was locked, because it would hardly steer during a lane change manoeuvre. However, serious stability problems were found when the bogie was free to steer [24]. The second series included both low-speed and moderate-speed turning tests and braking tests, and included a slick (smooth tread) tire on the self-steering belly axle. These tests found that the self-steering belly axle had little effect on roll stability whether locked or free to steer, regardless of its offset ahead of the tandem, while lifting that axle reduced the roll stability. They also found that the self-steering axle significantly reduced tire scrub, and the slick tire was somewhat beneficial in this regard. Finally, the vehicle stopped in a shorter distance when the liftable axle was down. The report concluded that a self-steering belly axle was a viable alternative to a rigid liftable axle, and that the lift control should be outside the cab [25].

A series of tests of a seven-axle tractor-semitrailer were conducted during the CCMTA/RTAC Vehicle Weights and Dimensions Study [26]. The semitrailer had two fixed axles, and two rigid liftable axles, with 2.77 m (109 in) spacing between each axle. The tests included low-speed turning tests, high-speed lane changes on low- and high-friction surfaces, and high-speed turns, with both liftable axles raised, the foremost liftable axle raised, and both down. Dynamic performance was governed by the liftable axles, which reduced the effective wheelbase, and increased the friction demand. The friction demand of the seven-axle vehicle was so high that it could not be turned sufficiently tightly to reach its roll threshold, and it clearly increased the risk of jackknife during a high-speed lane change.

A series of tests of a tri-axle semitrailer with a self-steering belly axle were conducted during the CCMTA/RTAC Vehicle Weights and Dimensions Study [6]. These tests attempted to determine whether there were conditions where the self-steering axle would determine the dynamic response of the vehicle. It was unable to determine any, and concluded that the self-steering axle had essentially no different effect on vehicle dynamic performance than a rigid liftable axle. It attempted to produce a jackknife due to friction demand, but was unable to accomplish this. Nevertheless, the researchers concluded that this mechanism was still valid.

A simulation study examined semitrailers with three to six axles with the most common widely spaced axle configurations [18]. It looked at their pavement loading and bridge loading with rigid liftable axles both down and raised, and additionally looked at their dynamic performance with self-steering axles replacing the rigid axles, with either high centering force or a near-free-catering centring characteristic. The paper found that only configurations 12S12, 12S112, 12S13 and 12S113 could meet the dynamic performance standards, and it suggested regulatory principles for configuration of semitrailers with liftable self-steering axles. These were followed by Québec when it put the original quad-axle semitrailer into regulation, then subsequently amended to require a self-steer quad semitrailer.

A study examined the use of a free-castering self-steering axle as the rearmost axle on a straight truck or semitrailer [19]. It identified that the steering property resulted in serious yaw stability issues for the straight truck, and excessive trailer swing for the semitrailer. It suggested that either a forced steering axle should be used in this position, or that a self-steering axle should have a high centring force characteristic similar to that required for a C-dolly. However, it did not include any work that could be used as the basis of regulatory principles.

A field study was conducted to assess the effect of widely spaced semitrailer axles on fuel consumption [27]. It found that increasing the axle spacing increased both fuel consumption and tire wear, more so on paved roads than gravel roads. Replacing the extreme axles by self-steering axles reduced the fuel consumption by about 4% for each axle replaced, up to two, and the payback period for this would be just over three years.

The Ministère des Transports du Québec conducted a substantial test program and on-highway demonstration of self-steering axles at the beginning of the 1990's [28]. The project conducted an exhaustive evaluation of self-steering axle technology, and selected certain axles for installation on test vehicles. They went carefully through the installation process, and concluded that self-steering axles should preferably be installed as original equipment rather than as a retrofit. The demonstration program included three pairs of tri-axle semitrailer and one pair of quad-axle semitrailer, with each pair equipped with one make and model of self-steering axle, and matched with comparison vehicles equipped with rigid liftable axles. Tilt tests showed the self-steering axle did not affect the rollover threshold of the vehicles. Dynamic tests were conducted for pairs of vehicles, with self-steering and rigid liftable axles. These showed that the dynamic responses with self-steering axles were not worse than those with rigid liftable axles. Attempts were made during winter tests to find conditions where the self-steering axle would introduce unexpected responses, and none were found. The vehicles were then followed in service for a period of time. A number of problems arose, mostly due to installation. Once these were addressed, there was essentially no difference in operation of these vehicles than the comparison vehicles equipped with rigid liftable axles. The satisfactory conclusion of this work allowed Québec to proceed with its requirement for a self-steer quad semitrailer.

A recent study from Australia has assessed the dynamic performance of straight trucks, semitrailers and B-trains with a self-steering axle [29]. In each case, the self-steering axle was fitted with dual tires and was the last axle of a three-axle group with a total spread between 2.5 and 2.80 m (98 and 110 in) and an allowable axle group load of 20,000 kg (44,092 lb). The primary intention of this work was to examine productivity benefits that would be possible from small increases in length enabled by better turning performance. The study concluded that satisfactory dynamic performance would result if the medium level of centring force used in the study would be required, though it did not specify that level. It suggested the self-steering axle should be in the rearmost position, and that load equalization requirements should be developed for the axle group. A so-called quad-axle semitrailer has also recently been assessed and approved for service in New Zealand. It is 13.71 m (45 ft) long, and has a 3.75 m (148 in) spread four- axle group, with the rearmost two axles as self-steering axles. New Zealand allows only 15,000 kg (33,069 lb) on a tandem, and 20,000 kg (44,092 lb) on the four-axle group, which are considerably lower than would be allowed in Ontario. The conclusions reached from analysis of these vehicles are undoubtedly applicable to vehicles within the restricted rules of Australia [29] and New Zealand. Friction demand is evidently not an issue for these vehicles. These conclusions may not apply for vehicles with much wider axle spreads that operate at considerably higher axle and gross weights, like the vehicles considered in this study.

7.7 Application and Experience with Self-steering Axles.

NRC/CSTT sought to determine the state-of-the-art of self-steering axle application and experience in North America by contacting:

- Self-steering axle manufacturers;
- Trailer manufacturers who install self-steering axles;
- Carriers who operate semitrailer configurations with self-steering axles; and
- Government agencies.

Interviews with manufacturers and operators were conducted primarily by telephone following a prepared interview script that was customized to each group. Many of the questions overlapped between groups.

7.7.1 Self-steering Axle Manufacturers

Self-steering axle manufacturers have experienced a considerable growth in demand for this particular product line. Previously, much of the equipment shipped ended up on vehicles operated by carriers who had experience with self-steering axles. Now, much of it is going to carriers with little or no experience with self-steering axles. Consequently, manufacturers have faced large numbers of questions, complaints and claims. Most of these have been addressed by providing more information, by training vehicle manufacturers in proper installation and setup of the axles, and by training carriers in proper maintenance procedures for the axles. In addition, manufacturers have made product and quality improvements where these would address specific issues in a cost-effective manner.

The self-steering axle wheel cut is the most significant issue that would face manufacturers if some of the candidate vehicles became popular. Most self-steering axles with a rating suitable for these applications have about 20 deg of wheel cut. At least one has 25 deg, and at least one other axle is being developed with this wheel cut. No self-steering axles are currently known with more than 25 deg of wheel cut. It may be possible to increase wheel cut of some existing models by a small amount (maybe 1-2 deg) by relatively inexpensive modifications to existing designs. However, a 5 deg increase is likely to require a new design with new structural components, which could be much more expensive. This would be a business decision, and the outcome would depend on assessment of what will probably be a relatively small potential market. Increasing the wheel cut reduces the suspension spring spread, which reduces the roll resistance of the self-steering axle. It will encourage manufacturers to reduce the frame rail spacing, which would reduce the roll resistance of the entire vehicle.

The regulatory requirement for “20 deg of steer” has led to the interpretation that 20 deg is sufficient, and commonly 20 deg is specified even though more may be required for the application. It may have been better simply to state “sufficient steer for the application”, or something equivalent.

Suspension manufacturers do not provide suspensions that can necessarily conveniently be used with self-steering axles. Previously, when the self-steering axle could be independently suspended, a suspension could be selected that would fit the axle and the application. Now that equalization is required, the same suspension is usually fitted to the self-steering axle as to the fixed axles. This may restrict installation and clearances for the axle.

Tire manufacturers do not provide tires that are designed for Ontario self-steering axle applications. The tire requirements are not well understood, and manufacturers do not know necessarily what tire will work in any particular application.

Forced steering axles are used on both power units and highway trailers in Europe, either with mechanical or hydraulic steering, but are only used on heavy haul equipment in North America. Forced steering can offer some benefits, but it would probably only be practical where a tractor and semitrailer are essentially permanently coupled, or a semitrailer is equipped with a hydraulic system for other purposes.

7.7.2 Trailer Manufacturers

Manufacturers have been building vehicles with self-steering axles for a long time, primarily as custom designs for a small number of carriers with a long commitment to operating those vehicles. All manufacturers have had to develop standard designs of self-steer tri-axle and/or self-steer quad semitrailers because of the recent changes in regulations. Manufacturers are comfortable that they can cope with a steer requirement up to 30 deg, and would use a variety of ways to accomplish this.

Almost all self-steering axles used are of the leading kingpin type. All self-steer tri-axle semitrailers are fitted with dual tires, while almost all self-steer quad semitrailers are fitted with single tires. Rapid tire wear has not been an issue with dual tires, but is a significant issue with single tires. Some self-steering axles fitted with 445/50R22.5 low-profile single tires that are dimensionally compatible with 11R22.5 dual tires have experienced significant shoulder wear. These tires exist in drive and trailer models, which are designed to roll straight ahead, so have different characteristics than a steer tire. There are other low-profile wide single tires designed as steer tires, with a width of 385 mm (15 in) or more, which may be more suitable for the self-steering axle of a self-steer quad. These tires are principally used in Europe at this time. It appears that a self-steering axle needs an appropriate tire, which may be a steer or all-position tire, but at this time there is no clear recipe for determining which tire will be suitable for a particular application. There does however appear some merit is ensuring all tires on a semitrailer have the same diameter.

The additional capital cost for a self-steering axle is in the range $3,000-$5,000. This may be in the range of 8-12% of total cost of a typical van, flatbed or dump semitrailer, and a lower percentage for a more expensive specialized semitrailer like a tanker.

The self-steering axle is a little heavier than the rigid liftable axle it replaces. However, a consequence of the self-steering axle being down and properly loaded except when raised off-road, and the need to review existing designs to accommodate a self-steering axle may allow manufacturers to improve designs and reduce weight.

Manufacturers do not report any systemic failure or warranty issues with self-steering axles. The main issues seem to be tire wear that arises because carriers that have not previously used self-steering axles do not initially realize how critical control of kingpin inclination, camber and alignment are, and lubrication of the moving parts. Once control of these becomes part of the maintenance program, these issues tend to disappear.

A self-steer tri-axle or self-steer quad semitrailer can usually meet braking standards without spring brakes on the self-steering axle. At least one of the self-steering axles on a five-or six-axle semitrailer will almost certainly require spring brakes to meet those standards. Most self-steering axles can currently accommodate spring brakes.

Manufacturers raised the issue of the need for a lift control in the cab. It is considered the simplest way to address mobility on very slippery highways, and it is also considered a way to alleviate bottoming of the self-steer during a low-speed turn. Manufacturers have no problem with providing an interlock such that the lift control would only activate at a low speed, or when the hazard warning lights are activated. Manufacturers are not fitting such devices as original equipment, but they believe some carriers are modifying vehicles to allow a clandestine lift control.

Manufacturers have faced a range of issues as they have developed designs for self-steer semitrailers, and manufactured and supported these vehicles. Some appear relatively confident that the state of the art is ready for semitrailers with two self-steering axles. Others feel it is somewhat premature to consider these vehicles at this stage, and that it would be prudent for manufacturers and carriers to resolve the design and operational issues that exist now before proceeding to more complicated vehicles

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7.7.3 Carriers

Carriers fall into two groups. A small number decided that a self-steering axle was preferable to a rigid liftable axle, and have been operating vehicles with self-steering axles for many years. A larger number have recently begun operating self-steer tri-axle or self-steer quad semitrailers because of the recent changes in regulations. Some carriers have decided to wait and see how the market shakes out before moving to this equipment. Some carriers have not been able to move to self-steer equipment, because for example, the self-steer tri-axle and quad configurations are not readily compatible with an open-top hopper, and the lift height is not sufficient for operation on logging roads.

The additional capital cost of a self-steer semitrailer ends up being a minor part of the annual operating cost of the trailer, usually well under 1.0%. Carriers who have been operating self-steering axles for a long time report no significant difference in maintenance costs between a semitrailer with a rigid liftable axle and a similar semitrailer with a self-steering axle in place of the rigid axle. The apparent additional maintenance requirements for the self-steering axle tend to be offset by reductions in tire, frame and suspension wear. The key issues are alignment of the self-steering axle to minimize tire wear, and lubrication of the moving parts. An automatic lubrication system costs about $2-3,000, and is a conservative approach to the issue whose cost may be offset against certain inspection and preventive maintenance activity. It may not be totally cost-effective, but it will probably reduce the risk of an unexpected kingpin replacement. Carriers who are new operators of semitrailers with self-steering axles do not anticipate any problems with additional inspection and maintenance tasks related to the self-steering axle. All these semitrailers are heavy haul vehicles that experience considerable wear-and-tear in normal use, and their operators are generally accustomed to a rigorous maintenance schedule simply to keep them operational.

Any additional operating cost is amply compensated by an additional 1,500 kg (3,307 lb) of gross weight for a self-steer tri-axle or quad end or hopper dump used for aggregate haul, or an additional 2,000 kg of gross weight (4,409 lb) for a self-steer quad operated between Ontario and Québec, or the additional volume of a 16.20 m (53 ft) quad van. In addition, a consequence of the self-steering axle being down and properly loaded except when raised for off-road operation may allow a carrier whose only off-road operation is in smooth and spacious yards to specify a lower gross axle weight rating for the semitrailer fixed axles. Ultimately, it may also allow a lower gross axle weight rating for the tractor drive axles. These may allow small cost and weight savings.

Carriers consistently raised four issues with self-steering axles: excessive tire wear, insufficient ground clearance of a liftable self-steering axle when raised, insufficient self-steer wheel cut, and additional maintenance required for a self-steering axle. The ground clearance of a liftable self-steering axle when raised ranges from 0.05 to 0.18 m (2 to 7 in). This is not a significant issue for carriers that operate on-highway and to well-maintained yards. It is an issue when a carrier operates off-road, such as for logging. Some carriers reported they no longer raise the liftable axle when entering a yard or job site, but the axle may be raised when the trailer is parked or dumped, in the case of an end dump semitrailer. The other issues have already been discussed.

Carriers are generally pleased with the on-highway performance of self-steering axles. Ontario-based carriers generally seem more pleased than Québec-based carriers, which is a little surprising since carriers have had about five years lead time to get ready for the requirement for self-steering axles in Québec. Carriers report no difficulty with the requirement that the lift control not be accessible from the cab. No-one admitted to any device that would thwart this requirement, though it was certainly implied that some such devices are in use.

Drivers are generally pleased with the on-highway performance of self-steering axles. The driver can simply make turns without having to remember to lift the axle. Drivers report no difficulty with the requirement that the lift control not be accessible from the cab. Drivers reported that self-steering axles with an adjustable centering force need to be properly adjusted. As the centring force characteristic gets stiffer, the effort to turn the vehicle increases. Driver complaints ensure that the centring force characteristic is sufficiently low that the vehicle turns without excessive effort. This seems to provide a first order limit on friction demand. Drivers also report that the self-steering axle makes it easier to change lanes than a rigid liftable axle, a further manifestation of reduced friction demand. The transition to self-steering axles might be expected to reduce the risk of a jackknife when the driver of a loaded vehicle has to make a sudden lane change on a slippery road.

Four rollovers were reported for vehicles with a self-steering axle, three for tractor-semitrailers and one for a truck-pony trailer. One occurred while the driver was trying to return to the road after driving off the road into a ditch. The self-steering axle played no part in the departure from the roadway, and the rollover would not have occurred if the driver had elected to stop in the ditch and selected a more prudent route out, or simply waited to be towed out. The second occurred when a driver swerved onto the shoulder to avoid an obstruction in the road, and the semitrailer slid across the narrow gravel shoulder into the ditch. The third occurred when the self-steering axle of a logging truck traveling on a gravel road allegedly struck a rock protruding from the road surface, which caused the axle to steer and the vehicle to roll over. Computer simulations showed that there was no difference between the responses of this vehicle if it was equipped with a rigid liftable axle or a self-steering axle. Speed and the driver's steer input determined whether the vehicle would roll over. The fourth occurred to a truck-pony trailer, with a self-steering axle in the lead position on a tri-axle pony trailer. It was reported that the truck was driving on the road, but the self-steering axle entered the soft shoulder, steered and pulled the trailer into the ditch, where it rolled over. Other details are not known. However, if the truck was on the road, the trailer would have required a considerable articulation angle that would have put its fixed axles much further off the road than the self-steering axle, where the shoulder would likely be softer and more prone to collapse. How the trailer got off the road is not known. None of these crashes was subject to a thorough investigation, and the descriptions were sketchy at best. Nothing indicated that the self-steering axle amplified in any way the actions of the driver that were primarily responsible for each of the tractor-semitrailer crashes. The pony trailer crash has some similarity to some C-train crashes that occurred on gravel roads.

It is certainly not impossible that the self-steering axle contributed to this crash, but this might not have happened if the trailer had remained on the road.

One tie-rod is known to have detached when the lugs that attach it to the steering arm failed. The driver was immediately aware of this, and stopped to strap the loose tie-rod to the axle with bungee cords. The driver left the self-steering axle down, and both wheels tracked properly as the driver returned to the maintenance shop at a reduced speed. One axle is known to have suffered a severe impact that caused the entire tie-rod to slip sideways through the clamps holding the various attachments to it. This resulted in the wheels tracking at an angle to the body of the semitrailer, which itself tracked reasonably straight. The axle was lifted for the rest of the trip, and was adjusted and aligned before returning the vehicle to service. These incidents have resulted in design changes to improve the reliability of the axles. Two cases of shimmy were reported, both occurring to the same rather poorly constructed and maintained semitrailer, which had a self-steering axle mounted on a bogie attached in a “loose and sloppy” manner to a sub-frame. On each occasion, the vehicle ended in the ditch. The mechanics of these events is not known, but the self-steering axle was removed after the second incident.

7.7.4 Government Agencies

The principal progress towards self-steering axles came from the Ministère des Transports du Québec (MTQ), which carried out an extensive test program and on-highway evaluation in the early 1990’s [28]. It has not carried out further evaluations since then. Its regulatory requirement gave industry five years to gain experience with self-steering axles, but many carriers did not make use of this opportunity. MTQ reports that carriers have experienced a number of issues with self-steering axles, including excessive tire wear and insufficient clearance when the self-steering axle is lifted. These issues could largely have been resolved if the five-year grace period had been used. MTQ are now sponsoring some analysis and testing to gain a better understanding of the mechanics and operation of self-steering axles. MTQ recognizes that self-steering axle clearance is likely to be a continuing problem for on/off-road operation, such as for log trucks, and is considering a tridem drive or twin steer tractor with a tridem semitrailer, configurations 13S3 and 22S3, as alternatives, with the same allowable gross weight as a tandem drive tractor with a self-steer quad semitrailer. MTQ determined that the weights allowed under a permit program for tractor-semitrailers with Ontario axle configurations in the late 1980’s exceeded prudent limits for bridges, so cancelled that program. MTQ would therefore not be prepared to consider a higher allowable gross weight than it currently allows on a tractor-semitrailer with seven axles for any tractor-semitrailer with more than seven axles.

After an evaluation of the dynamic performance of quad-axle log haul semitrailers, New Brunswick has been allowing a small number of these vehicles from Québec to operate in the northern part of the province under permit. The permit allows only dual tires on the self-steering axle, as New Brunswick restricts a single axle with single tires to 6,000 kg (13,227 lb). After further evaluation, it is currently considering a request for a pilot program for domestic truckers to operate quad-axle log haul semitrailers in the same region under the same conditions, though it may allow one vehicle with single tires on the self-steering axle for evaluation.

7.7.5 Regulations of Other Jurisdictions

In Europe, EEC Directive 70/311 requires that a vehicle must be able to make a circular turn with an outer radius of 12.60 m (41.3 ft) and must remain entirely outside an inner radius of 5.50 m (18 ft) [29]. This has resulted in vehicles that use self-steering axles to reduce their swept path in a turn. EEC Directive 92/62 supplements Directive 70/311, and specifies a simple test that requires high-speed rear outswing less than 0.7 m (28 in) at a lateral acceleration of 0.2 g [30]. This is not directly comparable to high-speed offtracking as used here, because it is measured at the rear corner and not the rear axle. It is also measured on a tighter turn, which will affect the criterion, and it is probably based on a typical European tridem semitrailer or pony trailer, each of which has a very large effective rear overhang. This directive also has provisions for forced steering axles and linked articulation. Most European countries have adopted such EEC directives, though they are allowed to continue with historical limits that may be more restrictive, and they may be more generous. For example, the German Road Traffic Regulations (Article 38, Steering Equipment) allow one self-steering axle on a semitrailer with three or more axles, and also have provisions for forced steering axles [29].

The Land Transport Safety Authority of New Zealand issued a steerable rear axle policy for heavy vehicles in October 1996 [29], which allowed small increases in length for a single semitrailer equipped with a self-steering axle as follows:

- Tridem axle only, with the self-steering axle in the rear position;
- A restoring moment must be provided, or the self-steering axle must lock automatically, for speeds above 40km/h;
- Maximum high-speed offtracking not more than 0.60 m (24 in);
- A test for braking stability on a wet road is required; and
- Certain maintenance and compliance requirements.

This was recently extended to include a tandem axle with one self-steering axle, or a quad-axle with a total spread of 3.75 to 4.00 m (147 to 156 in) [30]. Either the two rearmost axles, or the foremost and the rearmost axle of the quad-axle group may be self-steering, and must steer at least 15 deg.

Self-steering axles have not been widely used in Australia, and they are not addressed by regulation. However, Australia is now moving strongly towards a parallel system of regulation based on performance standards, and it is clear that steerable axles will allow modest increases in vehicle length and allowable gross weight [29]. Vehicles are now operating under permit after evaluation against the proposed performance-based standards.

The rules in the states of Idaho, Ohio and Washington, among others, allow vehicles to be configured with more than five axles for a gross weight greater than 36,287 kg (80,000 lb) according to the U.S. federal bridge formula B, and the rules in Michigan allow a similar result by a different means. Straight trucks and semitrailers with more than three axles are common in these states, and some use self-steering axles. In most cases, the additional gross weight added by each axle is relatively modest, so the gross axle weight rating of a self-steering axle is usually between 3,000 and 6,000 kg (6,613 and 13,200 lb). Other states, like New York and Pennsylvania, allow additional axles on straight trucks that may be self-steering. None of these states appear to have specific requirements for self-steering axles or the vehicles of which they may form a part.

7.7.6 Summary

A small number of carriers have successfully operated vehicles with self-steering axles for a long time. They may have had specialized applications, and have worked with the axle and trailer manufacturers to identify a combination of axle, suspension, tire and set-up that works for the application with controllable maintenance cost. A much larger number of carriers have recently begun to operate vehicles with self-steering axles in accordance with the requirements of regulations in Ontario and Québec. They have certainly benefited from the experience of the pioneers, and many report satisfactory experience, possibly after learning the need to lubricate moving parts and maintain steering alignment. However, these carriers have a much wider range of applications, and report troubles like excessive tire wear, insufficient steer and inadequate lift clearance. Québec carriers report a greater level of concern than Ontario carriers.

Drivers generally report that a self-steering axle makes it easier to handle the vehicle. Taking the lift control out of the cab is not an issue for many drivers. There remain cases, like climbing hills on very slippery roads, and tight turns at low-speed where the self-steer axle bottoms, where there remains support for a cab lift control, with suitable interlocks.

There are two technical issues that affect many of the carriers without experience of self-steering axles. The first is that the clearance available from many suspensions, combined with the long wheelbase of a self-steer quad semitrailer, is not sufficient for all operations, especially off-road in such applications as logging. The second is that the set up of the self-steering axle, including caster, camber and alignment, and the tires that are used, must be compatible to minimize tire wear. There are no clear rules to determine which combination of tire and axle set-up will minimize tire wear for a particular application. It is expected this will become more clearly understood with additional experience.

Self-steering axles are still very much a work in progress. Manufacturers and carriers are gradually learning how to make them work for a wide range of applications, and they are proving cost-effective and reliable when the vehicles are operated within their capabilities. Some applications are still not amenable to the current self-steer configurations. Some carriers are waiting until the unknowns are better resolved. Depending on the perspective, the next step to two self-steering axles should not be a problem, or is premature.

7.8 Axle Load Equalization

There is a minor issue regarding load equalization between the self-steering axles and the fixed axles on a semitrailer. Assume that each axle has the same make and model of air suspension. The fixed axles will operate with a single height control valve, which will set the pressure for all the axles on the semitrailer. The air in the two airbags on an axle pushes up on the structure of the semitrailer, and down on the axle. The axle weight, which is the force applied to the roadway, is the weight of the axle plus the force due to the air. Since all the airbags are the same, the force due to the air is the same at each axle. However, the weight of each axle may not be the same. A self-steering axle is heavier than a rigid axle, due to the kingpins and bushings, tie rods and bushings, centering mechanism, lock, and other devices that are necessary on a self-steering axle but are not fitted to a rigid axle. There is also the additional weight of the lift mechanism, since a self-steering axle is invariably also a liftable axle. On the other side, a rigid axle almost certainly has spring brakes, while the self-steering axle may not. On balance, the self-steering liftable axle is likely to be about 100 kg (200 lb) or so heavier than a rigid axle. With the same air pressure, the self-steering axle will have a correspondingly higher axle load, due to its greater weight. The stated objective of axle load equalization is only realistically achievable when the same suspension airbags are used if the axle weights are the same. In practice, equalized pressure will not necessarily result in equalized axle loads. It may be appropriate to apply a modest administrative tolerance to the axle weights to allow for small differences in axle weight and rigging.

8. DRIVE OPTIONS FOR FOUR-AXLE TRACTORS

A four-axle tractor can carry more weight than a three-axle tractor, and may improve traction. The choice will depend on the particular needs. There are four possible drive configurations for a four-axle tractor:

- Single steer, tridem drive;
- Single steer, pusher, tandem drive;
- Single steer, tandem drive, tag; or
- Twin steer, tandem drive.

A significant study conducted for the Forest Engineering Research Institute of Canada (FERIC West) examined the gradability of western logging trucks [24]. Gradability is the capability of a vehicle to start or maintain speed on a grade. This study was conducted because traction on forest roads increasingly became an issue as new log truck configurations with higher allowable gross weights emerged. This study looked at the following drive configurations, which it ranked in the following decreasing order of gradability:

- Single driven steer, tandem drive;
- Single steer, tandem drive, raised tag axle;
- Single steer, tridem drive;
- Single steer, tandem drive; and
- Single steer, tandem drive, tag axle.

There was little difference between the gradability of a driven steer axle and the raised tag axle. However, the raised tag axle reduced the front axle load to such an extent that control of the vehicle would be questionable. The study did not include a pusher axle. It is expected that the gradability of a tractor with a raised pusher axle would be slightly less than that with the raised tag axle, but without the significant reduction in front axle load.

Optimum gradability requires that all axle and inter-axle differentials must be locked, to eliminate wheel spin. If any differential is not locked, the gradability may be reduced. However, locking differentials greatly reduces the ability of a vehicle to turn. Alternatives are restrictive differentials, and traction control.

In the event, the B.C. and Alberta highway authorities would not consider any form of liftable axle, tag or pusher, regardless of how it might be controlled. The only remaining options that would improve gradability were to drive the steer axle, or to use a tridem drive. Both were sound options that used existing technology, though driven steer axles were not commonly used on tractors, and tridem drives were more common on military than commercial vehicles at the time. The tridem drive was heavier, more complex and more expensive than a driven front axle, but it provided a significant increase in weight that either allowed a higher gross weight, or allowed one trailer axle to be eliminated, which reduced the weight of the trailer. This almost compensated for the additional weight, but not the additional cost, of the tractor. The benefit was significantly magnified by some of the weights allowed by permit, particularly in the winter, and in Alberta.

9. THE NEED FOR A CAB LIFT CONTROL

Industry has suggested that there is a need for a cab lift or load dump control to allow a driver to unload the liftable self-steering axle of a self-steer quad to increase the load on the drive axles in slippery conditions to provide more traction.

The key to mobility is that a vehicle has sufficient drive traction, which is defined here in simple-minded terms as the ratio of actual drive axle load to actual gross weight. Vehicle configuration and axle load data were obtained from the 1999 Commercial Vehicle Survey conducted by MTO [23] for loaded tractor-semitrailers with 12S13 configuration, and for loaded 8-axle B-trains that conform to Ontario Regulation 32/94. The tractor-semitrailers have an allowable gross weight between about 54,000 and 57,500 kg (119,048 and 126,764 lb), depending on axle configuration and base length, while the B-trains have an allowable gross weight close to 63,500 kg (139,992 lb). Both configurations use comparable tractors. In each case, a loaded vehicle was considered to have an actual gross weight greater than 50,000 kg (110,230 lb), which resulted in a sample of about 300 quads and 450 B-trains.

Figure 63 shows the drive traction data points for loaded 12S13 quad semitrailers and B-trains plotted against actual gross weight. The quad trend line, derived by a linear least squares fit, is clearly higher than the B-train trend line, because quads have a lower allowable gross weight, and generally a lower actual gross weight. From a simple-minded point of view, the drive traction of a self-steer quad loaded to its allowable gross weight is 18,000/57,500 = 31.3%, and for a B-train it is 18,000/63,500 = 28.3%. The trend lines come very close to these points. Clearly, if drivers of self-steer quads have some difficulty with traction, then drivers of B-trains would be expected to have more difficulty. Alternatively, if drivers of B-trains can operate in such conditions, then drivers of self-steer quads should also be able to operate in the same conditions without lifting any axles. If a B-train driver judges it prudent to wait for slippery conditions to pass, then a tractor-semitrailer driver should probably also wait under the same conditions.

If the self-steer quad has a traction problem, then the candidate five- and six-axle semitrailers would be expected to have more of a problem, because they will operate with an allowable gross weight up to about 61,800 kg (136,144 lb). Vehicle configuration and axle load data were obtained from the 1999 Commercial Vehicle Survey conducted by MTO [23] for loaded and empty tractor-semitrailers with a tandem drive tractor and five or more axles on the semitrailer, and for loaded and empty 8-axle B-trains that conform to Ontario Regulation 32/94. These tractor-semitrailers and B-trains have about the same allowable gross weight, and use comparable tractors. In each case, a loaded vehicle was considered to have an actual gross weight greater than 50,000 kg (110,230 lb), and an empty or lightly loaded vehicle was considered to have an actual gross weight less than 40,000 kg (88,184 lb). There were between 450 and 500 loaded vehicles, and about 230 empty vehicles, of each configuration.

Figure 63: Drive Traction of Quads and B-trains

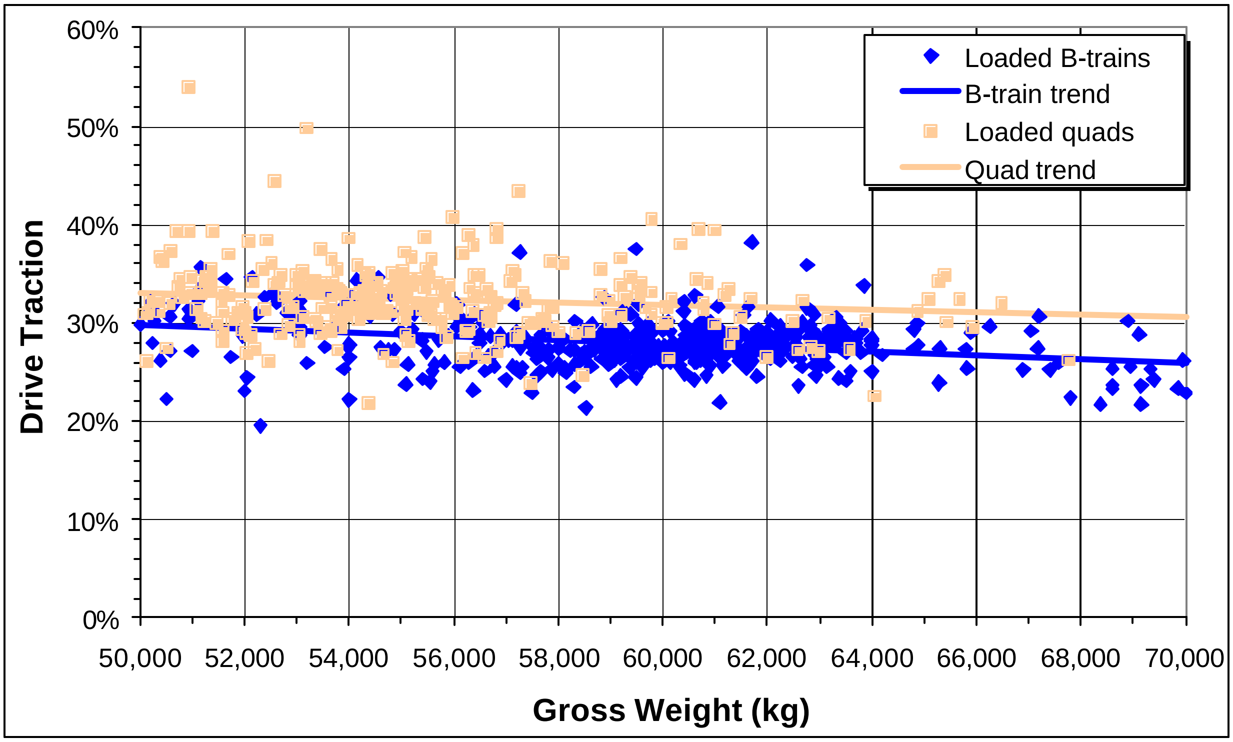


Figure 64: Distribution of Drive Traction

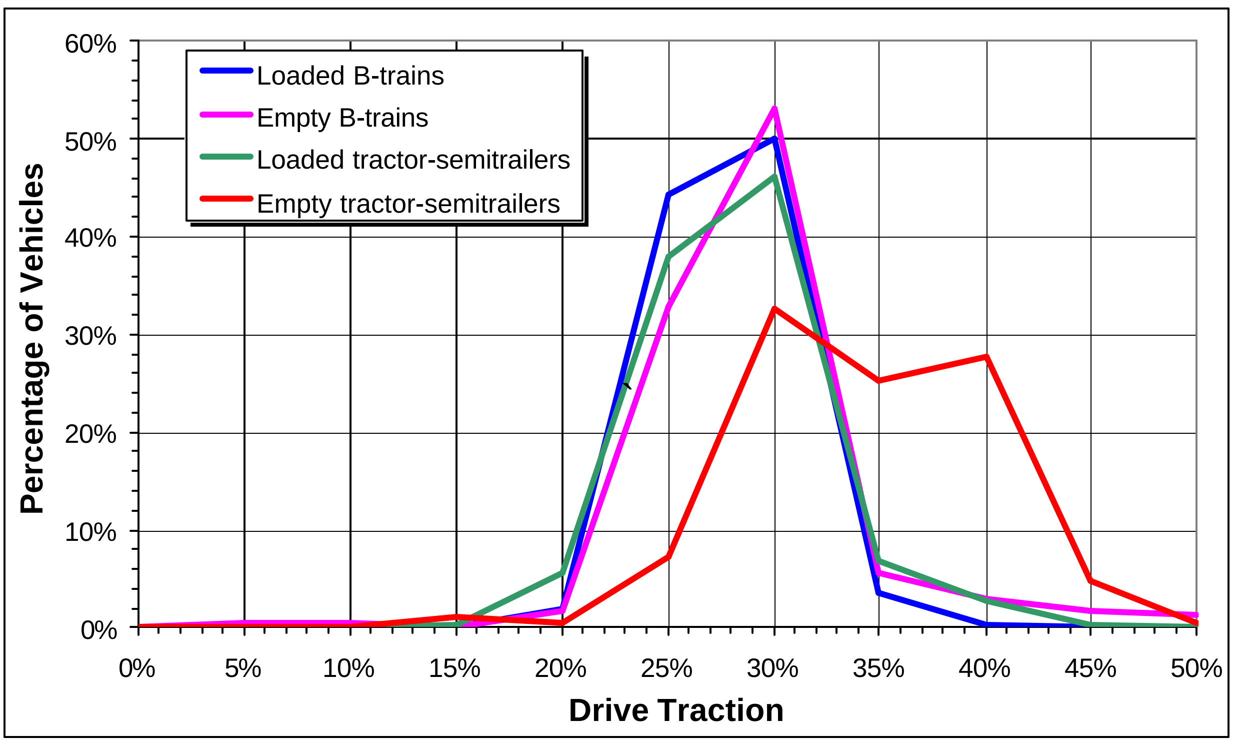


Figure 65: Distribution of Gross Weight

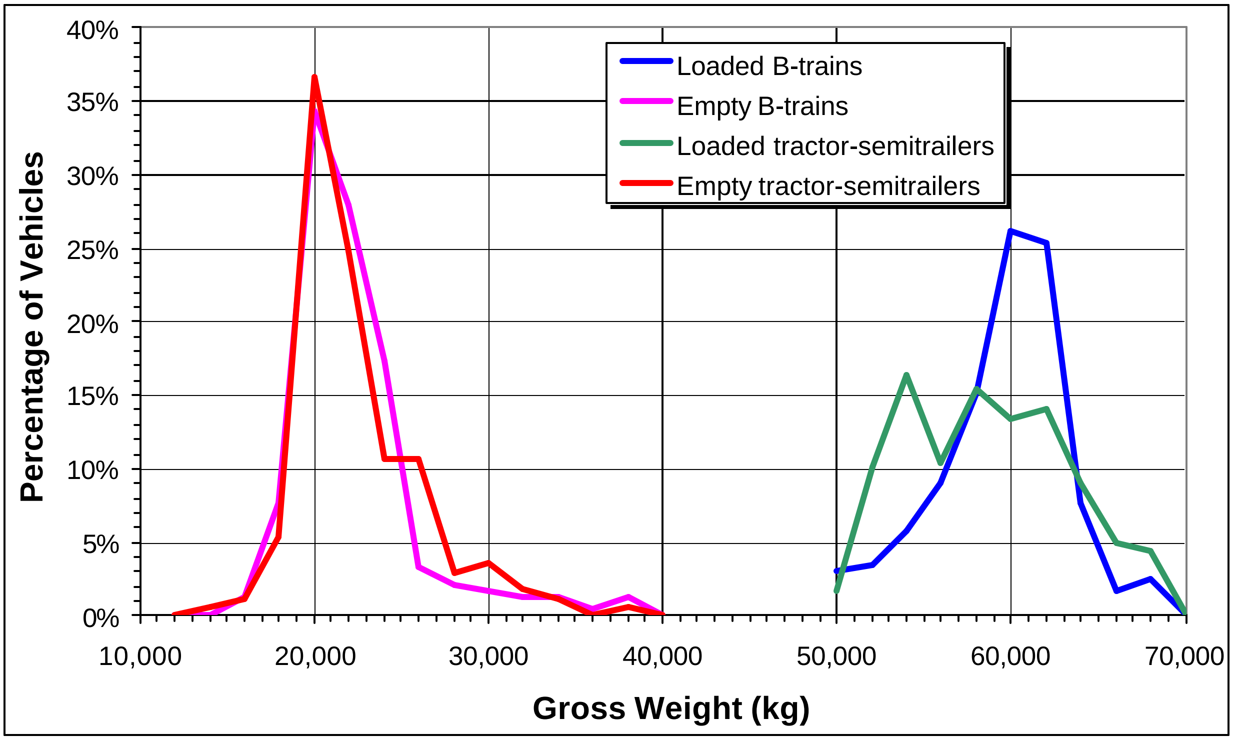


Figure 66: Drive Traction and Gross Weight of Semitrailers and B-trains

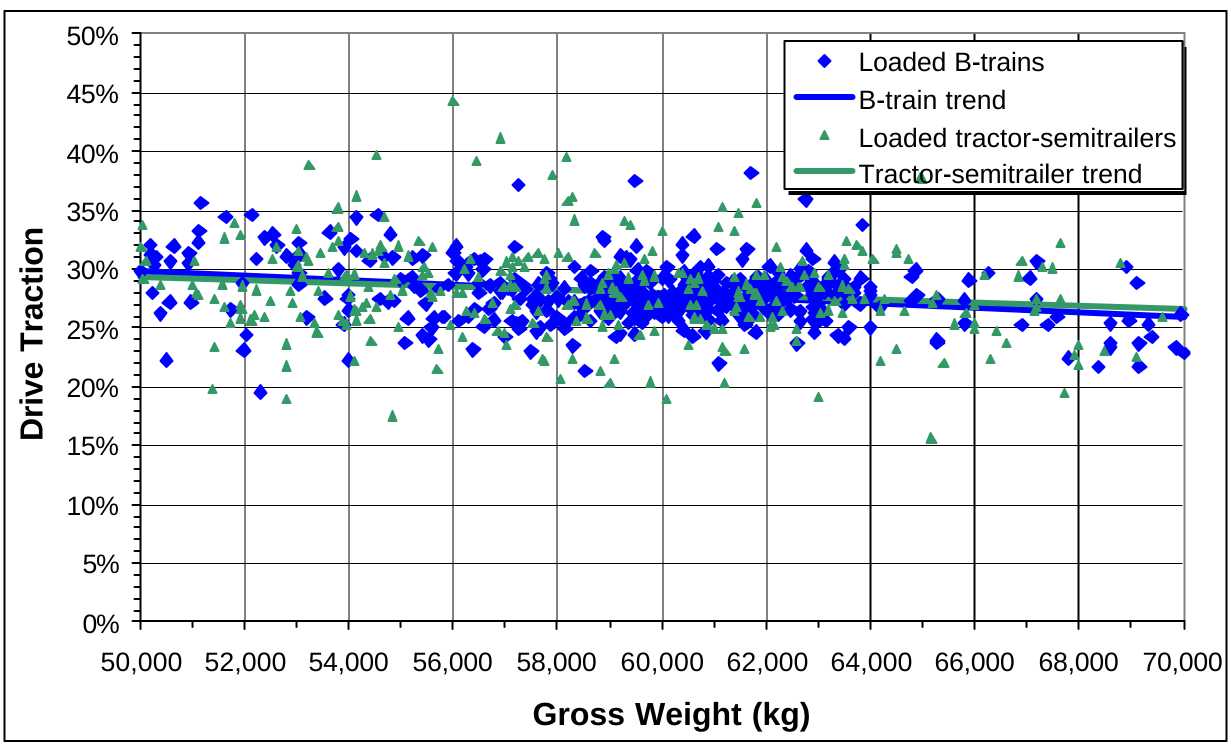


Figure 64 shows the distributions of drive traction of empty and loaded B-trains, and loaded tractor-semitrailers. All appear rather similar. The drive traction of empty tractor-semitrailers is a little more favourable, possibly because weight is transferred to the drive axles when a configuration with forward liftable axles has raised those axles. Any traction difficulties that might occur with loaded vehicles would seem to just as likely with empty or lightly loaded vehicles, when the liftable axles on vehicles so equipped are already raised.

Figure 65 shows the distributions of gross weight for empty B-trains and tractor-semitrailers are similar. The distribution of gross weight for loaded tractor-semitrailers is flatter than that for B-trains. This may be because a greater proportion of tractor-semitrailers are flatbeds that are used for general purposes, and can carry various loads on a return trip, while a greater proportion of B-trains are tankers and other body styles that only return empty.

Figure 66 shows the drive traction data points for loaded tractor-semitrailers and B-trains plotted against actual gross weight. While there is significant scatter in these data, the two trend lines, derived by a linear least squares fit, are very close. The tractor-semitrailers appear to have a greater dispersion of points on the low side of the trend line than the B-trains. Each of these low data points for tractor-semitrailers was individually examined, and they were found to fall into two groups. When the vehicle is loaded under its allowable gross weight, the weight is either distributed unduly towards the rear of the semitrailer, or the most forward liftable axle is carrying an excessive load. . When the vehicle is loaded over its allowable gross weight, the weight is invariably distributed unduly towards the rear of the semitrailer, and the drive axles are reasonably loaded. Each of these situations is arguably within the control of the driver. If they were corrected, there would be essentially no difference in drive traction between tractor-semitrailers and B-trains.

There is no doubt that a multi-axle semitrailer with a forward liftable self-steering axle can improve its drive traction if the driver stops and raises that axle. A B-train driver can accomplish the same thing, by detaching and parking the rear trailer to reduce the gross weight, moving the lead trailer forward and parking it, then returning to retrieve and re-couple the rear trailer. However, this would involve a lot of work, in the cold, so a B-train driver is only likely to consider doing it very occasionally, in dire circumstances.

The real issue is whether the driver of a multi-axle semitrailer with a forward liftable self-steering axle should be able to raise that axle from the cab under certain restricted conditions, and for a short period of time. This would certainly give these vehicles an advantage in mobility over B-trains in slippery conditions. It is appealing to think that this would improve safety. Certainly, from the point of view of a driver whose wheels start spinning on a slippery hill, it is a simple solution that has been readily available for many years. However, if the driver was simply more prudent, and was not there at all, that would also improve safety. The highway authorities recognize that drivers need to raise self-steering axles for reversing and to operate off-road, and also need to disable load equalization to comply with the axle weight regulations of other jurisdictions. However, the ability for a driver to raise an axle at will is the real issue that recent changes in regulations in Ontario, Québec and the Atlantic provinces are trying to address. Overloaded axles increase both road wear and the risk of failure of a highway structure. Driver controls that result in overloaded axles means that driver actions are controlling road wear and elevating the risk of structural failure above the level that would occur simply due to the passage of traffic.

If the real issue is that the drive traction of tractors hauling gross weights above (say) 50,000 kg (110,230 kg) is inadequate in some parts of Canada in the winter, then maybe a tractor that does provide the required traction should be used. A 6 x 6 tractor with a driven front axle, or a tridem drive, both do this. All tractors are now equipped with an antilock brake system (ABS), and all ABS vendors offer a traction control option as part of their tractor ABS, which intervenes as necessary to prevent wheels spinning. This works best with a six wheel speed sensors and six modulators to control brakes, a so-called 6S/6M configuration, which allows individual wheel control. A factory installed traction control system with a 6S/6M ABS is likely to provide greater and more reliable mobility, and greater resistance to wheel lock, than the modestly cheaper 4S/4M minimum system required by CMVSS 121. Differential locks are also available as an option with many transmissions, and can provide substantial increases in drive traction.

10. RECOMMENDATIONS FOR REGULATORY PRINCIPLES FOR MULTI-AXLE SEMITRAILERS

10.1 Introduction

The candidate “infrastructure-friendly” semitrailers were configured generally according to the following principles from Chapter 6.1:

- The load carried by all axles on a semitrailer must be shared equally among those axles when the semitrailer is operated in Ontario;
- Self-steering axles may be used in Ontario, provided they have sufficient steer capability for their location on the semitrailer;
- A semitrailer must have more fixed axles than self-steering axles;
- A self-steering axle may be fitted with single or dual tires;
- A self-steering axle may be liftable, but any lift or air dump control must not be accessible to a driver in the cab;
- A self-steering axle may lift automatically only when the driver reverses the vehicle;
- Rigid “invisible” liftable axles may be fitted for use in another jurisdiction, as long as they are always raised in Ontario; and
- Load equalization may be disabled for operation in other jurisdictions.

Chapter 5 shows that the high-speed dynamic characteristics of a self-steer quad are not strongly affected by the location or centring force characteristic of the self-steer axle, but friction demand and maximum self-steer angle are both strongly affected during a low-speed turn. Low-speed offtracking is not an issue. Friction demand increases as the self-steer axle spacing or self-steer centring force increase, and maximum self-steer angle increases as the self-steer axle spacing increases or self-steer centring force decreases. There are no particularly critical safety issues identifiable from this analysis. There is no apparent reason to put the self-steering axle more than 2.54 m (100 in) ahead of the tridem, or 2.77 m (109 in) for a semitrailer that will be used in Michigan. The likelihood of bottoming the steer will depend somewhat on the maximum wheel cut and the centring force characteristic of the self-steering axle used by the manufacturer. A higher centring force characteristic makes the vehicle harder to turn, and may increase wear on the self-steering axle tires even if the steer is not bottoming. The likelihood of bottoming the steer will depend much more on how the vehicle is used, both on-highway and off-road. There may be some issues that affect the operating cost of such a semitrailer, but they do not appear to affect its safety performance. There certainly does not appear to be any need for additional safety provisions for either the self-steer triaxle or self-steer quad semitrailer beyond those already in Ontario Regulation 597.

10.2 Configurations 12S113 and 12S114

The dynamic performance of configurations 12S113 and 12S114 is quite similar, so they may be considered together. The rearmost self-steering axle of these configurations responds essentially as if it were on a self-steer quad, but the foremost self-steering axle is likely to require a steer capability greater than 20 deg, and preferably up to 25 deg. There does not appear to be any particular need to require that the self-steering axles should be locked for operation at high speed. Consequently, there is no reason to go beyond the scope and level of detail already used in Ontario Regulation 597 for the self-steer triaxle and quad semitrailers.

Ontario Regulation 597 specifies that a self-steer quad semitrailer shall have a self-steering axle that “is capable of turning 20 degrees in either direction”. This could be interpreted that exactly 20 deg of steer is required, or that more than 20 deg will not be needed, though that may not be what was intended. Most self-steering axles used have about 20 deg of steer, and some have been bottomed during operation. The circumstances under which they bottom, and the level of effort to avoid bottoming, are both unknown. Ontario has no provision within the regulatory structure to provide commentary, guidance or advice related to regulatory requirements. If recent experience is not sufficient, there are several ways a self-steer requirement could be expressed that might be more helpful, such as:

- At least 20 deg of steer;
- Sufficient steer for any turn the semitrailer might make while on a highway;
- Sufficient steer for any turn the semitrailer might make; or
- Sufficient steer for any turn the semitrailer might make, but not less than 20 deg.

There are two different approaches that could be used, either specifying the vehicle tightly to ensure performance similar to that of the self-steer quad, or less tightly to allow manufacturers some flexibility to configure vehicles. The regulatory text for a tight specification for configuration 12S113, for example, could require:

- A tridem spread from 3.00 to 3.10 m (118 to 122 in);
- The rearmost self-steering axle from 2.50 to 2.80 m (98 to 110 in) ahead of the foremost axle of the tridem;
- At least 20 deg of steer on the rearmost self-steering axle;
- The foremost self-steering axle from 1.20 to 1.40 m (47 to 55 in) ahead of the rearmost self-steering axle;
- At least 25 deg of steer on the foremost self-steering axle; and
- Appropriate weights.

Alternatively, to allow manufacturers some flexibility to configure vehicles, the regulatory text could require:

- A tridem spread from 2.40 to 3.70 m (94 to 146 in);
- Two self-steering axles ahead of the tridem;
- The rearmost self-steering axle not less than 2.50 m (98 in) ahead of the foremost axle of the tridem;
- Sufficient steer on each self-steering axle for any turn the semitrailer might make; and
- Appropriate weights.

The numbers used in these examples are simply intended to be illustrative, and take no account of spacing restrictions that may be required when bridge loading is considered. The specific detail used for the self-steer triaxle and quad was probably necessary at the time, because the manufacturing and operating industries each generally had little experience in fitment and use of self-steering axles on semitrailers. Industry has now gained considerable experience in these regards. The second approach allows manufacturers to adjust axle spacings, spreads and self-steering axle wheel cuts and centring force characteristics to get both the desired payload and satisfactory dynamic performance. A manufacturer will hear about a semitrailer with a self-steering axle which bottoms too often, or whose friction demand is too high, and it may result in warranty claims.

10.3 Configurations 12S131 and 12S141

The dynamic performance of configurations 12S131 and 12S141 is quite similar, so they may also be considered together. Slightly greater self-steer wheel cut is required with configuration 12S141. The rearmost self-steering axle of both these configurations should certainly be locked for travel at highway speeds, to ensure that "ultimate" responses will be similar to those of the corresponding existing configurations. The discussion of the previous section also applies to these configurations.

10.4 Requirement for a Speed Sensitive Self-steer Lock

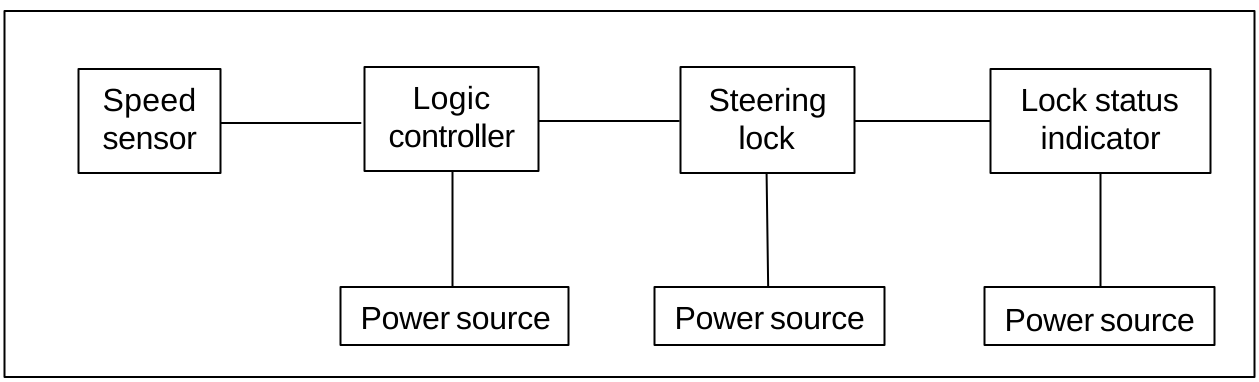
There is a requirement for a self-steer lock on configurations 12S131 and 12S141, and there is a choice to require a lock on configurations 12S113 and 12S114. The lock should be fitted entirely on the semitrailer, and should engage and disengage automatically, without any requirement for intervention by the driver. The lock must be disengaged at low speed, to allow the vehicle to turn, and should engage as speed is increased above some point at which the vehicle will not be making a tight turn. The technology to automate engagement and disengagement of the lock is straightforward and is already commercially available. It uses an ABS wheel speed sensor and the existing ABS toothed ring already installed on the semitrailer to get a wheel speed signal from one of the fixed axles. It is much more difficult to make such a device withstand the service environment than it is to provide the functionality. The lock is required in order to ensure adequate performance for this configuration.

The lock must be engaged and disengaged as necessary while the vehicle is operating. If a manual lock would be considered, there would need to be a control in the cab to allow the driver to engage and disengage the lock. There would be no guarantee that a driver would remember to engage a manual lock. Indeed, since the benefit of the lock would only be apparent in an emergency situation, there might not be any incentive for a driver to engage a manual lock at all. Such a semitrailer could also be pulled by a tractor without a suitable control to allow the driver to operate the lock from the cab. Because the lock is considered fundamental to the safety of the vehicle, it must operate regardless of the wishes or memory of the driver and the equipment of the tractor. The lock system therefore needs to be entirely self-contained within the semitrailer, so it must be automatic. This requirement is different than that for the C-dolly, where a manual lock on the dolly is required, and an automatic lock may be used [16]. This arises from a recommendation that the C-dolly should be locked when a C-train operates on a gravel road. A manual lock was considered adequate at the time, though the automatic lock was probably the preferred long-term approach, as it would also make the C-train more like a B-train at highway speed on a paved highway.

Figure 67 shows a schematic of a speed-sensitive lock for a self-steering axle, which consists of a speed sensor, a logic controller, the steering lock itself, and a lock status indicator, if required. The lock is a key safety feature of the vehicle, and should work for the life of the vehicle. The logic controller relies on a power source, usually electrical, and the steering lock relies on a power source, often pneumatic. There are a number of potential failure modes that may be associated with this device:

- The speed sensor output may fail or become intermittent;
- Power to the logic controller may fail;
- The logic controller may fail;
- Logic controller output may fail or become intermittent;
- The power source for the lock may fail;
- The lock status sensor may fail;
- The lock status indicator may fail; and
- The lock status indicator power source may fail.

Figure 67: Speed Sensitive Self-steer Lock



The status of the lock should not be allowed to be indeterminate in the event of failure of the control signal to the lock, or the power source for the lock. There are two choices in this situation, either the lock should engage, or should disengage.

If the lock is applied by a spring and held off by the power source, the lock would normally engage when a control signal shut off the power source holding off the spring, and the steer passed through centre. In this situation, if the control signal or the power source fails, the spring will engage the lock, and the axle will lock when it next passes through centre. This is a safe failure, as it maintains the desired configuration of the vehicle for high-speed operation. The vehicle will also have very high friction demand in this state, and will be difficult to turn at low speed. The driver will presumably stop, raise the axle, and proceed. With this configuration, a lock status indicator may not be necessary, because the driver will feel the increased friction demand and will know that the axle is locked and not steering. This configuration will presumably ensure that the failure will be repaired before the vehicle makes another trip.

If the lock is applied by power and held off by a spring, if the control signal or the power source fails, the spring will disengage the lock if it is engaged, or continue to hold the lock it off if it is not engaged. This failure does not maintain the desired configuration of the vehicle for high-speed operation, but it does allow it to turn at low speed. The driver may not be aware that there has been a failure, so a lock status indicator will be necessary. The status indicator, which might be a light similar to an ABS warning light, either adjacent to the axle or in the cab, should indicate when the lock is not engaged. If there is no signal when the vehicle is stationary, either the lock or the indicator needs to be repaired. If there is a signal at highway speed, the lock needs to be repaired. In this configuration, there is no sure way to ensure that a lock failure will be repaired.

It is recognized that a system could be more complicated than the simple system shown in Figure 67. This section cannot deal with potential complexity of future systems. It is simply intended to highlight that a safe condition should be identified for each self-steering axle, and the system should be designed to ensure that the self-steering axle reverts to that safe condition in the event of any failure in the system. This requires a thorough and detailed analysis of the potential failure modes of the system, and their effects.

It will be necessary to go beyond the detail already used in Ontario Regulation 597 for the self-steer triaxle and quad semitrailers, to specify performance and operational requirements for the self-steering axle lock, possibly as:

- Which self-steering axle on the semitrailer shall be equipped with a lock;
- The lock shall only engage when the steer of the axle is aligned with the centre-line of the semitrailer;
- The lock shall engage automatically when the speed of the vehicle increases over 60 km/h (36 mi/h);
- The lock shall disengage when the speed of the vehicle drops below 50 km/h (30 mi/h);
- The lock shall engage (or disengage) when the power source to the lock or the lock signal fails; and, if necessary,
- The status of the lock shall be monitored, and an indicator shall indicate that the lock is not engaged.

The lock and unlock speeds have been picked somewhat arbitrarily. The intention is to provide a suitable dead band to eliminate frequent lock/unlock cycles that would occur if the lock and unlock speeds were the same and the vehicle would be driving close to that speed with small speed variations.

The requirement for the rearmost self-steering axle to be locked at highway speed is clearly related to safety. There are at least three approaches that may be used to address this:

- A federal standard, along the lines of CMVSS 903 [16];
- Additional technical requirements in the Ontario regulation that defines the configuration; or
- An industry recommended practice.

The need for a self-steering axle lock is a safety issue that may affect other road users, so it would seem to fall squarely under the mandate of the Motor Vehicle Safety Act. While it is likely that these configurations would operate only in Ontario, the vehicles will undoubtedly be manufactured in a number of other provinces, and the U.S., so it might be appropriate to consider a federal standard, along the lines of CMVSS 903 [16].

It would also be possible to put the necessary technical requirements into the Ontario regulation that defines the configuration, which would add a level of detail beyond that which already exists. Alternatively, the regulation could simply require that the self-steering axle be locked at highway speed, and an industry recommended practice could be developed to contain all the necessary details, possibly under the auspices of the Canadian Transportation Equipment Association. The regulation might refer to the recommended practice, but may not need to.

From MTO's standpoint, it is probably most practical to put all the technical requirements into its own regulation. From the user's standpoint, this would also keep all the necessary technical requirements together in one place.

10.5 Configurations with Four-axle Tractors

There appears no need for any additional requirements for a self-steer quad semitrailer when it is pulled by four-axle tractor rather than a three-axle tractor. It may be necessary to relax the inter-vehicle-unit distance requirement, which may not be achievable when the semitrailer is configured for the four-axle tractor.

It is understood that four-axle tractors will be addressed in Phase 4 of MTO's program, so it is premature to suggest requirements beyond the following comments.

The tridem drive tractor is already widely used in Alberta and B.C., and there has been some interest in this power unit in other provinces. If configuration 13S13 is considered as "infrastructure-friendly", it would be helpful to industry if national specifications for a tridem drive tractor, and appropriate trailer configurations, could be added to the M.o.U. [2]. MTO's tractor specifications for configuration 13S13 could then be compatible with the national specifications.

If configuration 112S13 is considered as "infrastructure-friendly", there are a number of issues related to the self-steering pusher axle that will need to be resolved. Similar issues also arise for a straight truck with a pusher axle. MTO will consider both these configurations in the next phase of its program. The self-steer pusher axle should be positioned as closely as possible to the drive tandem, so that its weight is limited and it does not significantly reduce the front axle load. It might be allowed to venture further forward for a tractor that carries permanently mounted equipment like a hoist or a drome box that can counterbalance the effect of the pusher axle on the front axle. The load on the self-steer pusher axle should not be equalized with the drive tandem, but must be controlled to maintain sufficient front axle load. It may also be desirable to consider drive axle load in the control process. However, as noted above, it is premature to consider an appropriate control law at this time. An interim measure could limit the pusher axle load to the minimum necessary to achieve the allowable weight on the three-axle group, which would not require much more than about 3,500 kg (7,716 lb) on the pusher axle, when it would not need much more than a single light truck tire. The self-steer pusher axle should be equipped with a regulator set so that the pusher axle cannot exceed this load, or any lower value appropriate for the tractor. It may be possible to equip the self-steer pusher axle with a device that ensures the axle is down when the tractor is moving forward and its drive axle load exceeds (say) 17,000 kg (37,478 lb), and is raised when the drive axle load drops below 15,000 kg (37,478 lb), or reverse gear is selected. There may also be a manual control to raise and lower the pusher axle from outside the cab. The load range of the pusher axle is rather small, and there would seem little need to adjust the load on the pusher axle for this class of vehicle.

11. Recommendations for a Full-scale Test Program

11.1 Objectives and Scope

A test program should:

- Provide data to validate simulations against test results;
- Demonstrate "normal" dynamic performance for existing and proposed vehicle configurations;
- Demonstrate "ultimate" dynamic performance for existing and proposed vehicle configurations; and
- Explore the nature of friction demand.

Tests should consist of at least the following:

- Low-speed turning tests on high- and low-friction surfaces, with self-steering axles set with various centring force characteristics, to assess actual self-steer angles and to demonstrate the effects of friction demand and lateral friction utilization;
- High-speed lane change tests to assess transient offtracking, with self-steering axles locked and free to steer; and
- High-speed turning tests to assess high-speed offtracking and ultimate turning performance, with self-steering axles locked and free to steer; and
- Tests to assess the effect of self-steer inputs on vehicle response.

11.2 Configurations

Configurations 12S113 and 12S114 have essentially similar dynamic performance, as do configurations 12S131 and 12S141. There is no need to test all four. The five-axle semitrailers appear far more promising than the six-axle semitrailers, so these should be the primary candidates for test. These should be tested with self-steering axles locked, to represent the existing configurations, and with self-steering axles free as candidate configurations.

It would be desirable, though not necessary, to have a load equalizing suspension on each semitrailer. In practical terms, a single airbag behaves essentially as a spring under a high-rate load, such as occurs in a high-speed dynamic manoeuvre, because the time constant of the pneumatic system is much longer than the duration of most test manoeuvres. Air does not have time to pump from one side of the vehicle to the other. Thus, it would be feasible to use existing semitrailers with a steel spring suspension on the tridem and an air suspension on the self-steering liftable axles, and simply set up the air suspension so that the axle loads are approximately equalized.

It would be desirable, though not necessary, to have the same body style on each semitrailer, so that the same payload and centre of gravity height could be used. The payload should provide a centre of gravity about 2.13 to 2.44 m (84 to 96 in) above the ground.

Whatever semitrailers are used, the self-steering axles should be fitted with a manual override to any automatic speed-sensitive locking device, and with a device that allows the centring stiffness to be adjusted from a low value, near free-castering, to a value approaching that required for a C-dolly. The tires on the self-steering axles are not critical, and may be either dual or single. Locking the self-steering axles will allow the vehicle to approximate the dynamic performance of an existing configuration.

A self-steer quad semitrailer will exhibit little difference in response whether it is pulled by a three- or four-axle tractor, so there is little need to test it with a four-axle tractor. Four-axle tractors will be subject to further study in a subsequent phase, and it would be more appropriate to test them at that time.

11.3 Preparation

The same tractor should be used with each semitrailer. Instrumentation should be installed to measure at least the forward speed of the tractor, the steer angle of the tractor front axle, the lateral acceleration, roll angle and yaw rate of the tractor and each semitrailer, the articulation angle between the tractor and semitrailer, and the steer angles of the self-steering axles.

The testing will be hazardous, and will require outriggers to be fitted on the semitrailer to prevent rollover, and anti-jackknife cables to be fitted between the tractor and semitrailer to prevent jackknife. Outriggers are most easily installed on a flatbed semitrailer, but they may be installed on another body style as long as it has substantial frame rails. Anti-jackknife cables will require strong points to be installed on both the tractor and semitrailer. Probably the easiest way to install the tractor strong point is to bolt a thick steel plate to the frame rails. A thick steel tab will need to be welded to the semitrailer frame rails, as the landing gear legs are not strong enough to resist the forces that occur in a jackknife. Even so, if a hard jackknife does occur, the forces are very high, and it is possible that the tractor or semitrailer frame rails may suffer permanent deformation.

The testing outlined will be brutal for tires, especially for those on the tractor drive axles, the rear axle of the tridem, and the rearmost self-steering axle of configuration 12S131. It should be assumed that most of the tractor drive and semitrailer tires will only be useful for re-treading after the tests. Tire wear that occurs during these tests will not be representative of tire wear that occurs in normal operations.

11.4 Discussion

In terms of validation, it is not practical to measure load transfer ratio, friction demand or lateral friction utilization directly, nor is it possible to compute them from practical measurements. It is possible to derive the other performance measures from suitable test measurements. It is also possible to compare measured vehicle responses like accelerations, angles and angular rates between test and simulation. Suitable correlations between direct measurements and derived quantities from tests and simulations should give comfort that the simulations properly represent real vehicles.

It is possible to demonstrate the effects of increasing friction demand and lateral friction utilization by making a series of turns on a low-friction surface with the self-steering axles raised, with one down and steering, with both down and steering, with one down and locked, and with both down and locked. Additional points in this sequence from low to high friction demand could be generated by changing the centring force characteristic of the self-steering axles. Runs would be made at increasing speed, until the tractor is pushed out of the turn. This technique was used successfully in recent tests of a straight truck with a self-steering axle [33]. It also provides an opportunity to determine if the low-speed friction demand-induced jackknife can actually be provoked [6].

A self-steering axle may cause the vehicle to respond if it should steer for some reason when the vehicle is driving straight ahead. The mechanism by which this might occur is not important. Because it can occur, it is likely it will occur at some time, even though it might require bizarre circumstances. Tests should therefore assess vehicle responses if a self-steering axle is forced to steer while the vehicle is traveling straight ahead at high speed. . Tests should also assess whether a self-steering axle that is forced to steer away from the road while the semitrailer is traveling straight ahead on a gravel shoulder will pull the vehicle off the road. These conditions will be simulated by braking the right-hand side wheel of a self-steering axle to cause it to steer to the right, in a similar manner used for tests recently conducted on a straight truck with a self-steering axle [33].

12. CONCLUSIONS

12.1 Scope

This work has assessed the dynamic performance of:

- Ten existing tractor-semitrailer configurations, where a 3-axle tractor pulls a semitrailer with five or more axles;
- A baseline self-steer quad semitrailer, which is classified as “infrastructure-friendly” and sets an upper limit for the dynamic performance of such vehicles; and
- Six tractor-semitrailer configurations with self-steering axles and load equalization that are considered candidate “infrastructure-friendly” vehicles to replace existing configurations.

It has also assessed:

- Self-steering axle technology;
- Drive options for four-axle tractors;
- The need for a cab lift control in a self-steer multi-axle semitrailer;
- The need for regulatory principles to ensure a multi-axle semitrailer will not be likely to involved in a type of crash that does not occur for existing configurations; and
- The need for a full-scale test program involving both existing and candidate configurations.

12.2 Dynamic Performance of Existing Configurations

The dynamic performance of existing configurations that are principally used in Ontario was evaluated at Ontario weights, and the dynamic performance of existing configurations that are principally used between Ontario and Michigan was evaluated at Michigan weights. In each case, performance was evaluated with the liftable axles down, and with them raised as is commonly necessary to allow these vehicles to turn. A payload with a high centre of gravity was the critical load case for high-speed dynamic performance, and the following comments refer to this case. Payload centre of gravity height is not a factor for low-speed dynamic performance.

All configurations fail the friction demand performance standard by a wide margin, and cannot make a turn with their liftable axles down. Most also fail this standard with their liftable axles raised, though they are able to make a turn. Two configurations with a large effective rear overhang fail the rear outswing performance standard, and one with a long semitrailer wheelbase fails the low-speed offtracking performance standard. Almost all configurations fail the high-speed offtracking and load transfer ratio performance standards by a small margin, and the principal Ontario configurations fail the transient offtracking performance standard. All configurations fail the static roll threshold when their liftable axles are raised.

High-speed dynamic performance of these configurations is marginal with their liftable axles down. The problem is that none can turn with their liftable axles down, and must raise these axles in order to be able to turn. This significantly overloads some of the remaining axles. None of these configurations can be considered “infrastructure-friendly”.

12.3 Dynamic Performance of the Self-steer Quad Semitrailer

The dynamic performance of a self-steer quad semitrailer as defined by Ontario Regulation 597 was evaluated for the range of self-steer axle location allowed by the regulation, and for self-steering axles with low, medium and high centring force characteristics. This configuration is already in regulation, so its performance may be considered as a baseline against which the dynamic performance of candidate “infrastructure-friendly” configurations may be measured.

The self-steer quad meets all performance standards, except for high-speed offtracking which it fails by about 0.02-0.05 m (1-2 in), and friction demand, where it is at the high end of the range for tridem semitrailers with a 3.66 m (144 in) spread tridem. The self-steer angle in a low-speed turn of 14.00 m (46 ft) radius is 17-19 deg. Tighter turns, or turns through an angle greater than 90 deg, will require a larger self-steer angle. Self-steer angle and friction demand are both minimized if the self-steering axle is as close to the tridem as possible. It is probably best to use as low a self-steering axle centring force characteristic as possible. An increase in centring force reduces the self-steer angle in a turn, but significantly increases friction demand.

Ontario Regulation 597 requires 20 deg of steer on the self-steering axle of a self-steer triaxle or quad semitrailer. Most self-steer quad semitrailers have just about this self-steer capability. Manufacturers and carriers report tire wear and other damage that is likely due to bottoming of the self-steer axle in tight turns. While no objective data are available, it appears that there is a significant probability that 20 deg of self-steer will be exceeded. This probability can be reduced if a greater self-steer capability would be provided, or if these vehicles are only scheduled on routes within the turning capability of the vehicle, and drivers meticulously raise the self-steering axle when tight turns are made in yards and otherwise off public roads. Carriers should not modify a self-steering axle to increase its self-steer angle without consulting its manufacturer.

12.4 Dynamic Performance of Candidate Configurations

There are no other obvious candidate configurations that would have greater merit than those identified as the principal candidates for this study.

None of the candidate configurations meets all of the performance standards, so choices arise among options that are often conflicting. This report has attempted to present data and discussion to allow options to be identified and evaluated so that these choices may be made.

Each of the candidate “infrastructure-friendly” configurations in its preferred configuration fails the high-speed offtracking performance standard by 0.03-0.08 m (1-3 in), which is comparable to the self-steer quad. Each configuration also fails the friction demand performance standard. Configurations with a three-axle tractor have higher friction demand than a self-steer quad, while configurations with a four-axle tractor have friction demand that ranges from better than any tridem to better than a self-steer quad.

Configuration 13S13 comes closest to meeting the performance standards. There is little difference in most performance measures for a self-steer quad semitrailer between a tandem and tridem drive tractor. The drive tridem significantly reduces friction demand, but increases lateral friction utilization, and the greater tractor wheelbase causes a minor increase in low-speed offtracking. Tractor specifications for this configuration should be compatible with those of other provinces.

The best performance for Configuration 12S113 is achieved if it is fitted with a 3.05 m (120 in) spread tridem, and the two self-steering axles are as close to each other and the tridem as possible. The foremost self-steering axle requires almost 20 deg of steer in a low-speed turn of 14.00 m (46 ft) radius, 5 deg or more than that of the rearmost self-steering axle. Tighter turns, or turns through an angle greater than 90 deg, will require a larger self-steer angle. This axle probably needs close to 25 deg of steer, considering that self-steer quads with 20 deg of steer are bottoming the self-steering axle in turns. Even with 25 deg of steer, the vehicle will need to be operated very carefully to avoid bottoming the steer if the axle is anywhere other than as close to the tridem as possible. It should be fitted with self-steering axles with a low centring force characteristic, to moderate friction demand. The self-steering axles do not appear to need to be locked at highway speed. This configuration does not appear to need special requirements beyond those already used to specify the self-steer quad.

The best performance for Configuration 12S131 is achieved if the tridem is positioned to the rear of centre between the two self-steering axles, to reduce the large effective rear overhang. It should be fitted with self-steering axles with a low centring force characteristic, to moderate friction demand. Its self-steering axles should have at least 20 deg of steer. The rearmost self-steering axle must be locked at highway speed, which is a requirement beyond those already used for the self-steer quad. The lock should engage and disengage automatically according to vehicle speed.

The requirement for load equalization increases the spread of the fixed axles on candidate configuration 12S131 compared to the existing configuration, and the requirement for self-steering axles limits the spacing of these axles for configurations 12S113 and 12S113. Existing configurations 12S114 and 12S141 have proven versatile alternatives to existing configurations 12S113 and 12S131 as a compromise for operation into Michigan, but this will no longer be the case as the axle spreads required for load equalization and the axle spacings required for self-steering axles will result in a much reduced payload in Michigan. Configurations 12S114 and 12S141 will have no evident benefits over the five-axle semitrailer configurations for operation in Ontario, and offer no benefit in performance. It will therefore be necessary to add two “invisible” liftable axles to candidate configurations 12S113 or 12S131 as a compromise for operation into Michigan, so there will be seven axles on these semitrailers.

It is likely that the allowable gross weight of Configurations 12S113 and 12S131will be closer to the sum of their allowable axle weights than for existing vehicles. This should prevent excessive rearward placement of the payload, which deteriorates both dynamic performance and drive traction. However carriers regard the large difference between axe capacity and gross weight available with existing configurations as a buffer to avoid axle overloads, and some may elect to reduce payloads to control the risk of exceeding an allowable axle group weight.

The high-speed dynamic performance of Configurations 12S113 and 12S131 becomes similar to that of the existing configurations if the two self-steering axles on Configuration 12S113, and the foremost self-steering axle on Configuration 12S131, would also be locked at highway speed. Locking these axles reduces high-speed offtracking slightly, but slightly increases the tendency to roll over, as measured by the static rollover threshold and load transfer ratio. Locking these axles also eliminates the possibility of hazard that may arise if an axle would be forced to some steer angle by some means.

The pusher axle of configuration 112S13 causes particular difficulties, and the twin-steer configuration 22S13 appears to be difficult to load. While the performance of these configurations is comparable to other candidates, both tractors require considerably more work to make them practical options. This is beyond the scope of this phase of MTO's program.

12.5 Self-steering Axle Technology

Previous research and testing has not identified any hazard introduced by a self-steering axle in the belly position. A self-steering axle as the rear-most axle can introduce serious stability concerns, but these may be addressed by locking that axle at highway speed.

A small number of carriers have successfully operated vehicles with self-steering axles for a long time. They may have had specialized applications, and have worked with the axle and trailer manufacturers to identify a combination of axle, suspension, tire and set-up that works for the application with controllable maintenance cost. A much larger number of carriers have recently begun to operate vehicles with self-steering axles in accordance with the requirements of regulations in Ontario and Québec. They have certainly benefited from the experience of the pioneers, and many report satisfactory experience, possibly after learning the need to lubricate moving parts and maintain steering alignment. However, these carriers have a much wider range of applications, and report troubles like excessive tire wear, insufficient steer angle and inadequate liftable axle clearance. These issues are gradually being resolved with improved understanding of operational and maintenance needs. Québec carriers report a somewhat greater level of concern than Ontario carriers. Drivers generally report that a self-steering axle makes it easier to handle the vehicle. Taking the lift control out of the cab is not an issue for many drivers. There remain cases, like climbing hills on very slippery roads, and tight turns at low-speed where the self-steer axle bottoms, where there remains support for a cab lift control, with suitable interlocks.

The candidate configurations will require more than the 20 deg of steer commonly fitted to self-steer quads. At least one self-steering axle is available that provides 25 deg of steer, and at least one more is being developed. It may be possible to gain a degree or two of steer by modest adjustments to existing designs. A greater gain in steer that requires new components could be much more expensive.

Self-steering axles are still very much a work in progress. Manufacturers and carriers are gradually learning how to make them work for a wide range of applications, and they are proving cost-effective and reliable when the vehicles are operated within their capabilities. Some applications, like hoppers and log trucks, are still not amenable to the current self-steer configurations. Some carriers are waiting until the unknowns are better resolved. Depending on the perspective, the next step to two self-steering axles should not be a problem, or is premature.

12.6 Drive Options for Four-axle Tractors

The issue of additional drive traction from a fourth axle on the power unit is not easily separated from the additional weight that it accrues. If greater drive traction is required, then a 6 x 6 tractor can provide it. A tridem drive provides more consistent traction than fitting either a liftable pusher or liftable tag axle to a tandem drive tractor. Whatever drive arrangement is selected, optimum traction requires locking all axle and inter-axle differentials, to eliminate wheel spin. However, locking differentials greatly reduces the ability of a vehicle to turn. Alternatives are restrictive differentials, and traction control.

12.7 The Need for a Cab Lift Control

Self-steer quad semitrailers have better drive traction than 8-axle B-trains. If the self-steer quad semitrailer has traction problems, then the B-trains would be expected to have more severe traction problems. There is no evidence of this.

The candidate semitrailers considered here would have very similar drive traction characteristics to 8-axle B-trains that do not have any liftable axles. If these B-trains can operate satisfactorily in slippery conditions, then the tractor-semitrailers should also be able to operate in the same conditions without lifting any axles.

It has been suggested that a driver of a tractor with a self-steer semitrailer should be able to lift the self-steer axle from the cab when necessary to maintain progress in slippery conditions. If the driver operates in the same manner as the driver of a B-train, then presumably traction should not be an issue. If it is, there are other options. A tridem drive, a driven front axle, locking differentials, or a traction control system available with all antilock brake systems all address the need for additional traction without the need to raise any liftable axle. A traction control system works best if it is allied with an antilock brake system with a speed sensor and modulator for each wheel on the tractor.

12.8 Recommendations for Regulatory Principles for Multi-Axle Semitrailers

Ontario Regulation 597 specifies that a self-steer quad semitrailer shall have a self-steering axle capable of turning “20 degrees in either direction”. This has been taken to mean that 20 deg of steer should be adequate. Carriers have found that some applications may require more than 20 deg of steer. It may be helpful to specify the steer requirement in a different way.

The form of regulation used for the self-steer quad is suitable for Configurations 12S113 and 12S114, though specified values will need to change.

The form of regulation used for the self-steer quad is also suitable for Configurations 12S131 and 12S141, and additionally the rearmost self-steering axle must be locked at highway speed. Detailed specifications are required to prescribe operation of a speed-sensitive automatic lock. These may be addressed under the mandate of the Motor Vehicle Safety Act, within an Ontario Regulation, by an industry recommended practice, or by these two latter means together.

If all self-steering axles on these configurations are locked, they become similar to existing vehicles. The high-speed offtracking is improved, but the roll performance is deteriorated.

A tridem drive tractor should be specified in a manner that is compatible with other provinces, and most especially Alberta and B.C.

A tractor with a self-steering pusher axle should not equalize axle loads with the drive tandem. The issue of how the load on the pusher axle should be controlled should be addressed in the next phase of MTO’s weight and dimension reform program.

12.9 Recommendations for a Full-scale Test Program

A test program should demonstrate the effects of self-steering axles on vehicle dynamic performance. It will allow validation of simulations against test results, demonstrate “normal” and “ultimate dynamic performance for existing and proposed vehicle configurations, and explore friction demand.

Configurations 12S113 and 12S131 are the primary candidates for testing. These tests will be hazardous. Outriggers should be fitted on the semitrailer to prevent rollover, and anti-jackknife cables should be fitted between the tractor and semitrailer to prevent jackknife. It would be desirable, though not necessary, to have a load equalizing suspension on each semitrailer, so it would be feasible to use existing semitrailers with a steel spring suspension on the tridem and an air suspension on the self-steering liftable axles. Whatever semitrailers are used, the self-steering axles should be fitted with a manual override to an automatic locking device, and with a device that allows the self-steer centring stiffness to be adjusted. The self-steer quad semitrailers have little difference in response whether they are pulled by a three- or four-axle tractor, so there is little need to test them.

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