Roll Dynamics of Long Combination Semi-Trailers with Steerable Axles

Abstract: An assessment of the dynamic performance of Long Combination Vehicles (LCV) with steerable axle systems on their trailers was undertaken by National Research Council Canada in order to facilitate the regulation of LCVs for wider use on Canadian roads. A base dry box van A-train LCV combination and four steered combinations are modeled using TruckSim, each outfitted with a different steerable axle mechanism on the trailer. TruckSim's driver logic is augmented through an optimized controller in Simulink to more accurately capture the driver's decision-making in response to LCV dynamics and the steering mechanisms. ABS and Traction control mechanisms are added to compensate for the reduced stability caused by improving the maneuverability. The modeled LCVs are run through high-speed lane change and high-speed turn simulations, the primary maneuvers that enable assessment of the roll dynamics of the truck combinations. The five configurations are compared in terms of standard performance parameters: static roll threshold, rearward amplification, high-speed off-tracking and transient off-tracking. The study shows that all of the proposed mechanisms are able to satisfy standard stability requirements.

Keywords: Long Combination Vehicles, Trailer Steerable Axles, Roll Stability, Standard Performance Measures

1 Introduction

LCVs comprised of a tractor and two or more trailers demonstrate noteworthy operational and financial benefits that make them intriguing potential candidates for transportation of cargos on roads. LCVs are capable of hauling a greater amount of cargo with better fuel efficiency on their own. By using less fuel to carry goods, LCVs have the potential to reduce the greenhouse gas emissions (GHGs) associated with shipping goods by approximately one-third [1] depending on the type of routes followed and goods transported. On the other hand, their inability to maneuver tight urban areas renders them unable to make end-to-end deliveries, requiring supporting vehicles for distribution insidedf cities and areas that are harder to reach[2]. One way to address the insufficient maneuverability is to augment the trailers with passive or active steerable axle mechanisms. Steerable axle systems, also known as forced-steel or command-steer axles, are mechanically, hydraulically or electronically controlled systems that provide steering input to trailer axles based on the forward motion of the vehicle and/or articulation of the trailer at the king pin. This can allow the LCVs to maneuver smaller roads and tighter turns. However, by improving maneuverability of the vehicle, augmented LCVs do not necessarily perform as well as comparable vehicles without steered trailer axles in high-speed maneuvers. For this reason, roll stability analysis becomes critical and traction control mechanisms become essential assets that are added to the vehicle.

Although some steerable axle mechanisms are commercially available to be mounted on LCVs, the development of functional multi-trailer LCVs is a costly endeavor for the transportation industry. There must be solid proven results from simulation and experiments on the advantages of this sort of augmentation to justify the shift from single to multi-trailer combinations. Computer simulations via commercial vehicle dynamics software or programming languages are the most reliable non-empirical tools at researchers' disposal to study the behavior of complex vehicle combinations such as LCVs with steerable axles. Gerdes et al. demonstrated the safety of Advanced Vehicle Control Systems that they developed for various operations and truck-trailer configurations through use of commercial multi-body dynamics simulation software[3] as part of the California Partners for Advanced Transit and Highways (PATH) program. TruckSim is a commercial software package for simulating the dynamics of trucks that uses a modular architecture for modeling vehicle dynamics, allowing the user to analyse the macro behavior of LCVs as multi-body systems while enabling modifying components. Duprey et al. evaluate the performance-based standards of truck configurations via simulating a 90-degree slow turn in TruckSim[4]. Cheng and Cebon developed an optimal LQR controller for the trailers to improve roll stability of tractor-semi-trailer combinations in TruckSim by optimizing a combination of the rear trailer's deviation from the target path and the lateral acceleration of the center of gravity[5]. Jujnovich and Cebon use TruckSim to compare the dynamic performance of several LCVs with different trailer axle steering mechanisms mounted on them[6]. They evaluate roll stability performance measures along with other measures by running the vehicles through common maneuvers such as low-speed corners, low-speed roundabouts, high-speed lane changes and high-speed circles, concluding that in general, trailer steering systems are capable of improving low-speed performance of LCVs in the form of better maneuverability and lower off-tracking. These benefits are partially undercut by poor high speed performance of steered trailers which have higher rearward amplification and transient off-tracking. They propose locking the steering mechanism in high speeds to prevent these downsides. Keldani and He perform Hardware/software in the loop (HIL/SIL) on-line simulations, including TruckSim simulations, to demonstrate the advantages of a robust active trailer steering system based on Linear Quadratic Regulator(LQR) in enhancing maneuverability of multi-trailer articulated heavy vehicles while also improving their lateral stability [7]. Oberoi uses anti-roll control systems to actively improve rollover stability of LCVs during high-speed maneuvers[8]. He uses Genetic Algorithm to optimize the design parameters of the LCV to achieve a proper balance between high speed stability and low speed maneuverability. They designed an electronic stability control system based on trailer differential braking in CarSim environment[9]. This system was shown to improve the safety and handling of LCVs.

National Reasearch Council Canada (NRC) has developed the capability of evaluating dynamics of LCVs through commercial dynamic simulator softwares (TruckSim and Adams), tests on track and brief highway tests. NRC developed a generic 6x4 Class-8 tractor model in previous work with Transport Canada. This tractor model was updated in TruckSim for this study and NRC built a model of a 3- axle forward dry-van semi-trailer, a 2-axle A-train dolly, and assembled them to create an A-train LCV configuration as shown in Figure 1. This configuration was used in the present assessment study. The article at hand describes the procedure of modeling, simulating and analysing the standard performance measures of 4 trailer axle steering configurations in comparison to a base unsteered model. Section 2 describes the procedure of modelling the LCVs, the steering mechanisms, ABS and ECS and an augmented driver logic in TruckSim and Simulink. Section 3 provides the performance indexes of the aforementioned models going through the standard maneuvers.

2 Simulation Setup

Five different double-trailer LCVs are modeled in TruckSim. Passive trailer steering mechanisms are jointly modeled in TruckSim and Simulink. The driver control logic of the software is updated based on the logic presented by Islam and He[10]. The engine, transmission, differentials and other portions of the tractor powertrain are directly taken from existing data libraries of TruckSim and the previously developed LCV model by NRC, as they are the same for all 5 combinations and therefore do not have an impact on the roll dynamics comparisons.

Figure 1 The LCV model in TruckSim

Suspension mechanisms play an important part in roll stability of the vehicle. As they are shared among the models of this study, they do not affect the comparison that is being made here. Therefore, they must be optimized in the future experiments and be matched to their real-life counterparts in order to validate the model accuracy. This improvement can compensate the slight loss of stability caused by the increase in maneuverability.

2.1 LCV Model

The model incorporates a 3A tractor with 2A shipping container trailer from the existing lead vehicles in TruckSim. The axles on the lead unit are located at $0m$, $5.26m$ and $6.61m$ measured from the front axle. European trailer models in TruckSim are modified to capture the properties of the semi-trailers with 3 axles of the configuration. The van sprung masses have a weight of $17950lbs$, and a center of gravity positioned 357 inches ($9.07m$) from the front wall. The dimensions of the sprung mass are $2.9m \times 10.8m \times 2.59m$. The trailers have the properties of Michelin X-One tires of model 445/50R22.5, modeled with a radius of 50.165cm and weight of 4625Kg. The axles are positioned at $9.97m$, $11.80m$ and $13.63m$ from the front hitch point. The two trailers are connected via a convertor dolly. This dolly was modeled on the rear trailer, having a weight of $5285lb$, a center of gravity that lies 6 inches longitudinally forward from center point between the two tires. The dolly tires are dual Continental 11R22.5 HT3 ECO-PLUS.

The four different steerable axle mechanisms mounted on the trailers are code-named Passive Trailer Steering Mechanism type-1 (PTSM-1), PTSM-2, PTSM-2, PTSM-3 and PTSM-4. Models PTSM-1, PTSM-2 and PTSM-3 are mechanical passive steering mechanisms, meaning that they mechanically connect the hitch rotation to the rotations of two of the axles of the trailer. The relation between hitch and the axles' rotations is articulated in Simulink. PTSM-2, on the other hand, is a hydraulic passive steering mechanism that is able to rotate the wheels of the trailer instead of moving the entire axles. PTSM-3 and PTSM-4 models, similar to PTSM-1, mechanically connect the hitch angle to the axle rotations. It is worth noting that the PTSM-3 enables 5 different configurations, each with a certain approximate slope of hitch to axle angles.

2.2 ABS and ESC Models

In Canada, Antilock Braking Systems (ABS) are required on tractors since 1997 and on trailers since 1998. The internal ABS and Traction Control models of the TruckSim software were used with the dynamic performance parameters of Wabco 4S / 2M for trailers and Wabco 2S / 1M system for the dolly shown in Table 1. Traction control mechanisms are

Two Channel ABS		
Slip Off	***Slip On***	***Cut Off Speed***
0.2	0.1	6

Table 1 Built-in ABS dynamic properties

essential in preventing jackknifing, sway and rollover[9]. The LCV modeled in this research incorporates a Bendix Automatic Traction Control (ATC) system. In addition to the ABS function, many Bendix ECU models provide an Automatic Traction Control (ATC). To model the ATC, the internal ESC module in TruckSim is used based on the parameters shown in Table 2.

ESC Properties		
ESC Enabled At	***Max Brake Pressure***	***Min Active Brake Pressure***
4 Km/h	7 MPa	0.5 MPa

Rollover Protection (Full Brake at)	
Max Roll Angle	***Max Lateral Acceleration***
5 deg	0.28 MPa

Table 2 Electronic Stability Control Dynamic Properties

2.3 Driver Model

The driver model, used to drive the virtual vehicle along the prescribed path in TruckSim, was improved upon via a simple PID controller in Simulink. The updated driver acts based on the lateral distance of the front axle center from the target path and the angular error from the lead unit direction towards the target point on target path. This improved model is based upon the driver model developed by Islam, Ding and He [10]. The driver model position error ε_p, seen in Figure 2, is defined as the distance from the tractor's front axle center to the nearest point on the specified path measured along the radius of curvature. TruckSim is able to provide this value through its preview point properties. The angular error ε_a is

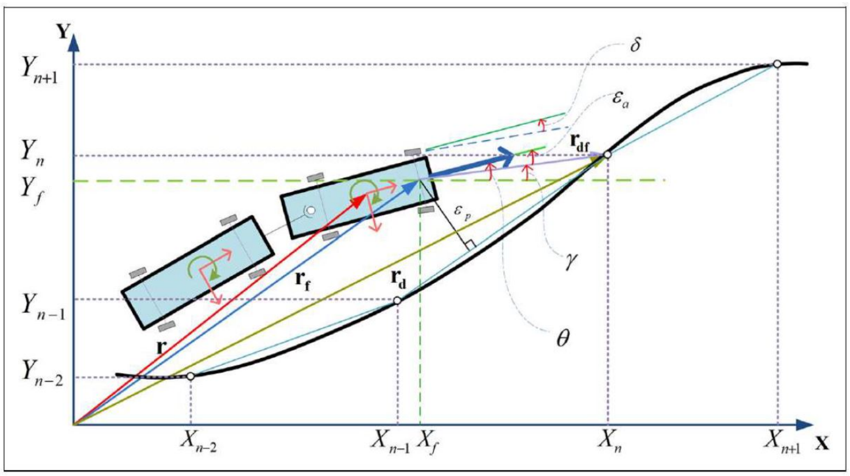

Figure 2 Geometry representation of vehicle and prescribed path[10]

defined as the angle between direction of the tractor heading (θ measured from the X axis) and the direction from the front axle center $\mathbf{r}_f$ to the target point on the prescribed path $\mathbf{r}_d$ as specified by Edelmann and Plochl[11] in Figure 3. The target point is chosen as the nearest point on the specified path measured along the radius of curvature connecting to a point that is a certain preview distance straight ahead of the front axle.

To achieve the desired vehicle heading direction $\mathbf{r}_{df}$, the vehicle steering angle command δ is calculated from

$$\delta(t) = \varepsilon_a(t).k(t), \tag{1}$$

where k is calculated from the PID controller gain

$$k = k_{pl}\varepsilon_p(t) + k_{il}\int \varepsilon_p(\tau)d\tau + k_{dl}\frac{d}{dt}\varepsilon_p(t). \tag{2}$$

The three proportional k_p, integral k_{il} and derivative k_{pl} gain values in the above equation are optimized for each different maneuver. The lateral acceleration of the CGs of the truck becomes spiky at critical parts of the maneuvers using this driver. The optimization algorithm chooses the PID controller configurations that minimize this spike. The driver controller

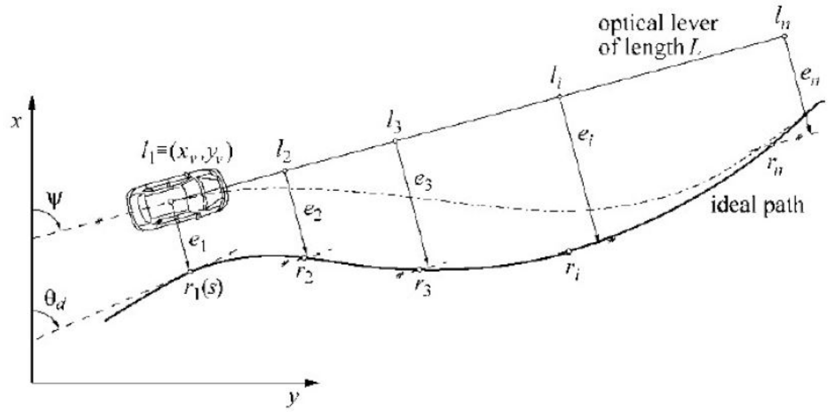

Figure 3 Target point geometric definition[11]

Design Variable	**Nominal**	**Lower Bound**	**Upper Bound**
K_P	4.2	3	5.5
K_D	0.12	0	0.25
K_I	0.12	0	0.25
t_{pv}	0.18	0.1	0.4

Table 3 Driver Configuration Optimization Range

optimization algorithm uses batch runs in Simulink and TruckSim over the regions specified in Table 3

where t_{pv} is the preview time, specifying the preview distance in front of the front axle corresponding the target point. This search, for each maneuver, generates the optimal PID configuration and the preview distance values that avoid exerting high spiky lateral accelerations to the vehicle. The optimized configurations chosen for each maneuver are shown in Table 4.

	Scenario	K_p	K_i	K_d	t_{pv}(s)
Base Model	High-Speed Lane Change	4	0.08	0.18	0.18
	High-Speed Turn	5.4	0.14	0.12	0.18
PTSM-1	High-Speed Lane Change	4.6	0.09	0.11	0.18
	High-Speed Turn	5.4	0.18	0.18	0.3
PTSM-2	High-Speed Lane Change	5.5	0.19	0.2	0.18
	High-Speed Turn	5.5	0.18	0.18	0.18
PTSM-3	High-Speed Lane Change	5.5	0.19	0.2	0.18
	High-Speed Turn	5.5	0.18	0.18	0.18
PTSM-4	High-Speed Lane Change	4.5	0.11	0.12	0.3
	High-Speed Turn	5.2	0.1	0.18	0.18

Table 4 Optimal Driver Controller Configurations

3 Performance Measures

The approach recommended by the CCMTA / RTAC Vehicle Weight and Dimensions Study[12] was followed to assess vehicle dynamic performance measures. The performance measures are responses of the vehicle to a set of maneuvers specified by RTAC[13] which has been followed for new vehicle regulations in Canada since 1985. Consistent performance thresholds are also recommended by RTAC that determine the boundaries of satisfactory and unsatisfactory performance.

3.1 High-Speed Lane Change

This maneuver is made at the speed of 90Km/h. It is equivalent to a maneuver made in order to avoid an obstacle in front of the vehicle and is used to evaluate the Rearward Amplification, Load Transfer Ratio and Transient Off-tracking performance measures. The path, as seen in Figure 4, consists of a single side step of 3.5m, equal to a single cycle of lateral acceleration sinusoidal input with a value of 0.15g lasting for 3 seconds at the front axle of the lead vehicle. The RTAC study specifies that this be run on a high friction surface to obtain the required vehicle performance parameters [13].

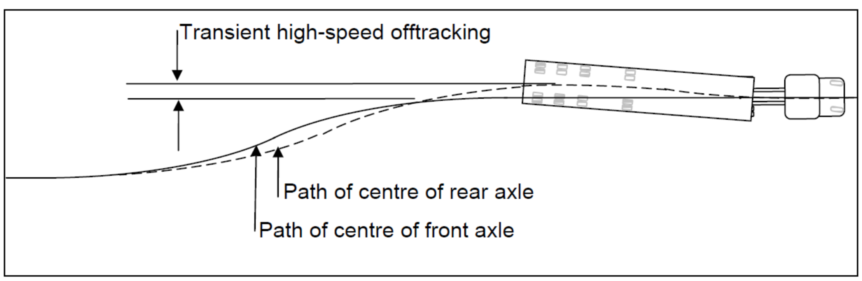

Figure 4 High-Speed Lane Change and a graphical representation of the Transient high-speed offtracking[12]

The RWA is defined as the ratio of the peak lateral acceleration at the rearmost trailer's centre of gravity (CG) to that at the CG of the lead unit during a lane-change maneuver. Table 5 shows the values of rearward amplification observed through the high speed lane change maneuver at a speed of 90 km/h. From this table, it is clear that adding the steerable axle mechanisms had a negative effect on the stability as evidenced by the increase in the RWA. It is also noteworthy that, despite the reduction of stability for the high friction scenario, all of the models were still in the acceptable range of RWA based on the RTAC limit of 1.6. This limit is only applied to the high friction scenario, as specified in RTAC for this maneuver[13].

	Trailer Configuration				
Friction	Not steered	PTSM-1	PTSM-2	PTSM-3	PTSM-4
0.9	1.157	1.538	1.512	1.171	1.403

Table 5 Rearward Amplification

Transient high-speed offtracking is a measure of how far the path of the centreline of the rearmost axle of the trailer deviates laterally from the path of the centreline of the front axle of the tractor as can be seen in Figure 4. This measure is defined as the peak overshoot in lateral position of the rear axle of the last trailer over the path of the front axle of the lead vehicle in a high-speed single lane change maneuver. As defined, the Transient high-speed off-tracking should not exceed 0.8m which is a crucial parameter for double trailer combinations. An example output of the transient high-speed off-tracking can be seen in Figure 5. The plot shows the path of the front and rear axles. The greatest difference between paths was recorded as the transient high-speed off-tracking value.

Figure 5 Sample output of transient high-speed off-tracking in a high-speed lane change maneuver

From Table 6, it can be seen that the addition of steerable axles on trailers results in an increase in transient high-speed offtracking. This trend of higher off-tracking values for the cases with steerable axles is true for both friction cases, but is more extreme in the low friction case. However, the important takeaway from this table is that since this maneuver is meant to be performed on a high friction surface as specified by RTAC[13], all of the results from the high friction case were still below the limit of 0.8 m.

	Trailer Configuration				
Friction	Not steered	PTSM-1	PTSM-2	PTSM-3	PTSM-4
0.9	0.235m	0.420 m	0.440m	0.415m	0.220m
0.5	0.455m	0.750m	2.08m	2.050m	0.455m

Table 6 Transient Off-Tracking

The load transfer ratio represents the portion of the original load that shifts from the tires on one side of the truck to the tires on the other side of the truck, a determining factor in whether the vehicle will rollover. RTAC requires LTR to be below 0.6 to be deemed safe. This value corresponds to one tire carrying 80 percent of the load and the other carrying the remaining 20 percent. Figure 6 shows sample vertical forces on the wheels of two different axles.

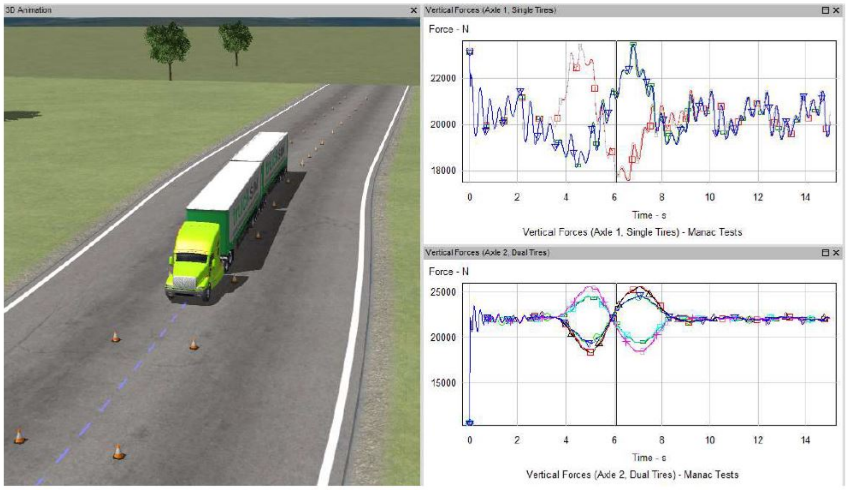

Figure 6 Sample output of load transfer ratio in the high-speed lane change maneuver

None of the steerable axle mechanisms are causing drastic increases in LTR as seen in Table 7. All of the LTR values remain safely below the RTAC limit, despite the increase in LTR observed by adding the steered axle mechanisms.

	Trailer Configuration				
Friction	Not steered	PTSM-1	PTSM-2	PTSM-3	PTSM-4
0.9	0.22	0.27	0.27	0.26	0.25
0.5	0.38	0.51	0.47	0.48	0.43

Table 7 Load Transfer Ratio

3.2 High-Speed Turn

A High-Speed Turn, shown in Figure 7 with a radius of 393 m was navigated at a speed of 90 km/h with a centrifugal acceleration of 0.2g in this maneuver. The maneuver is used to evaluate static rollover threshold performance measure which is where the vehicle becomes unstable in Yaw. To evaluate the static rollover threshold, the curve radius was gradually decreased until the truck rolled over.

High-Speed Off-tracking is defined as the lateral offset between the path of the center of the front axle of the tractor vehicle and the path of the center of the last axle of the rear trailer. This measure is expected to remain below $0.46m$ out of the path of the lead unit vehicle.

In each high friction case, the steerable axle systems result in off-tracking values that are more than double those of the baseline vehicle. They also perform worse in the low friction case. Since this maneuver is meant to be performed on a high friction surface, the limit of $0.46m$ only applies to the high friction case, and it is clear that all of the configurations remain below this limit.

Static rollover threshold is defined as the minimum lateral acceleration at which the truck will start to roll over while performing a steady curve[13]. It is the lateral acceleration

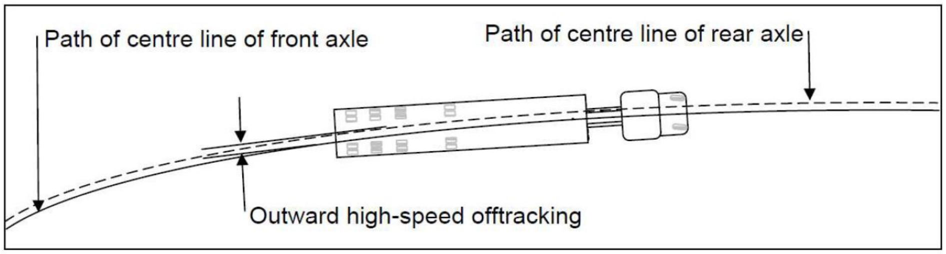

Figure 7 High-Speed Turn Maneuver[12]

	Trailer Configuration				
Friction	Not steered	PTSM-1	PTSM-2	PTSM-3	PTSM-4
0.9	0.171m	0.457m	0.413m	0.436m	0.39m
0.5	0.461m	0.806m	0.650m	0.565m	0.64m

Table 8 High Speed Off-Tracking

in terms of gravitational acceleration on Earth's surface (g) at which the vehicle rolls over in a turn. A sample output of the static rollover threshold simulation can be seen in Figure 8. Once the right wheel lifted off on both of these axles, the truck would roll over and, therefore, this is where the lateral acceleration was recorded for the static rollover threshold.

Figure 8 Output sample of static rollover threshold from the high-speed turn with increasing curvature maneuver

The RTAC vehicle weights and dimensions study provides a limit value for Static Roll Threshold of $0.4g$. A comparison of the static rollover threshold of LCV configurations with trailer steerable axle systems is shown in the Table 9. This table does not show results for the base vehicle because while the other LCVs equipped with the steered axles rolled over when subjected to this same maneuver, the baseline LCV did not. These results demonstrate that the baseline LCV without steered axles is more resistant to rollover. However, all of

	Trailer Configuration				
Friction	Not steered	PTSM-1	PTSM-2	PTSM-3	PTSM-4
0.9	-	0.57g	0.542g	0.54g	0.52g
0.5	-	0.475g	0.485g	0.46g	0.44g

Table 9 Static Rollover Threshold

the results for steered configurations pass the minimum value of 0.4 g that is required by RTAC for the high friction surfaces.

4 Conclusion

The main contribution of this article is to compare the stability of LCVs equipped with steered axle systems to a baseline LCV with no such system. Additionally, efforts were made to compare the performance measures to known standards. The steering mechanisms are added to the LCVs since they are capable of facilitating tighter turning radii with improved off-tracking which may be of interest to regulators tasked with determining the extent of the allowable LCV road networks. While dynamic stability remained within the accepted performance standards for the high speed manoeuvers assessed in this work, there were observed impacts to stability margins when steerable axle systems were present. It was found that the addition of the steerable axle systems on the high friction surface would decrease the stability at high speeds. All configurations also underperformed the baseline LCV in terms of high-speed off-tracking and static roll thresholds. All of the configurations still met acceptable performance standards for RWA, transient off-tracking, high-speed off-tracking, static roll threshold and LTR. On the other hand, the main benefit of the steerable axle systems will be realized in terms of the maneuverability at low speeds. The fact that these configurations pass the standard limitations by RTAC is very important as, along with low-speed advantages of it, it will enable regulation of LCVs on both roads and urban areas. Therefore, this could be an indication that the use of steerable axles could help make the case for extension of the allowable LCV road network. Since low-speed maneuverability can be improved, but appears to be accompanied by a reduction of stability during high-speed maneuvers, it is recommended that further investigation be undertaken on locking the steerable axles on the trailer in the forward position when the LCV is travelling at high speeds, allowing for the advantages of low-speed maneuverability without the accompanying reduction of high-speed stability. Another option would be to further study active steering systems. A more advanced active steering system could help further improve the performance at both high and low speeds.

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