INVESTIGATION OF LONGER MODULAR CONCEPT CONFIGURATIONS FOR BRITISH COLUMBIA

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Abstract
This paper gives an overview of preliminary evaluations undertaken for two potential configurations which are capable of hauling two modular containers thereby improving hauling efficiency. Steerable trailer axles were utilized so that acceptable low-speed tracking performance could be achieved for these long configurations. Simulations indicate that acceptable performance can be achieved with forced steer axles using steering control strategies which are speed dependent. Further research and optimization will be required to improve the 9-axle (tandem drive version) configuration’s performance, but the 11-axle (tridem drive version) configuration’s performance was satisfactory for immediate implementation.

Keywords: High Productivity Vehicles, Modelling, Trailer Steering System, Performance Based Standards.

1. Introduction

Long hauling distances experienced by resource industries continues to drive the need to improve transportation efficiency and remain globally competitive. Recently, the province of British Columbia[1] (BC) has approved the use of longer and heavier configurations for specific routes, provided the configurations achieve prescribed performance criteria. FPInnovations is currently cooperating with industry proponents to investigate two potential modular concept designs. The core of the design concept involves a double trailer with a quad-axle group on the lead trailer (**Error! Reference source not found.**). The quad-axle group includes a trailing tandem dolly that can be rigidly attached to the lead trailer. In order to achieve acceptable low-speed maneuverability required by existing highway networks, steerable axles will be required on the quad-axle group.

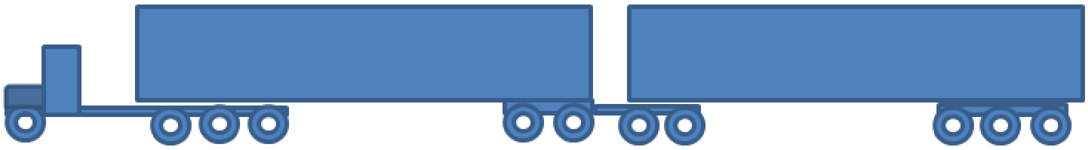

Figure 1 – Modular design concept

In Europe similar modular concept vehicles have also been investigated which incorporate the European Modular System (EMS) allowing existing loading units (modules) to be combined into longer and heavier vehicle combinations (Nijmeijer et al. 2014). Most of these proposed longer configurations will require the use of trailer steering systems which will need further development in order to achieve acceptable low-speed maneuverability, while also achieving high speed stability. At present most of the existing active steering systems are only utilized at low-speeds and are automatically locked at high speeds to provide stability. Researchers from the University of Cambridge have pioneered a sophisticated trailer steering axle control strategy known as “Conventional Tractor- Active Trailer” (CT-AT) which has addressed the high-speed rearward amplification issues as well as improving low-speed manoeuverability and eliminating the tail swing associated with standard command steering control (Odhams et al. 2010). More recently researchers from the Eindhoven University of Technology have

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[1] Western most province in Canada

developed an alternative active trailer steering control strategy known as Virtual Rigid Axle Command Steering (VRACS). This method is a simpler strategy requiring less sophisticated sensors (speed and trailer articulation) compared to the CT-AT strategy and is said to operate seamlessly at all speeds (Prati et al. 2014).

For the purposes of this paper, practical trailer steering options and configuration specifications were established which will allow the proposed configurations to achieve the prescribed performance criteria required by the BC Ministry of Transportation and Infrastructure's Commercial Vehicle Safety and Enforcement (CVSE) branch.

2. Methodology

The proposed weights and dimensions for the 9-axle and 11-axle modular concept configurations are shown in Figure 2 and Figure 3 respectively. The 9-axle configuration is a tandem drive version; designed to fit within the current maximum vehicle envelope currently permitted in BC, but at an increased Gross Combination Weight (GCW) of 68.7 tonnes. The 11-axle configuration is a tridem drive version at an extended overall length and increased GCW of 85.2 tonnes. A tridem drive power unit will be essential to negotiate the mountainous terrain prevalent in BC with the increased payload. Note that all trailer axles are equipped with super single tires[2] (445/50R22.5), with the last two axles on the lead trailer being steerable. Industry had initially proposed that the quad-axle group be spaced closer together to allow easier detachment of the two units. However CVSE required a minimum spacing of 4.1 m between the two tandem groups in order to carry the proposed axle loads due to concerns over pavement and bridge loading. Currently there is no mechanism within the BC commercial transport regulations for quad-axle groups. Further research of quad-axle bridge and pavement load allowances is therefore required before these axles can be spaced closer together.

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[2] In BC super single tires are not allowed weight parity with duals and hence the tandem load limit is reduced to 15 400 kg from 17 000 kg (for duals).

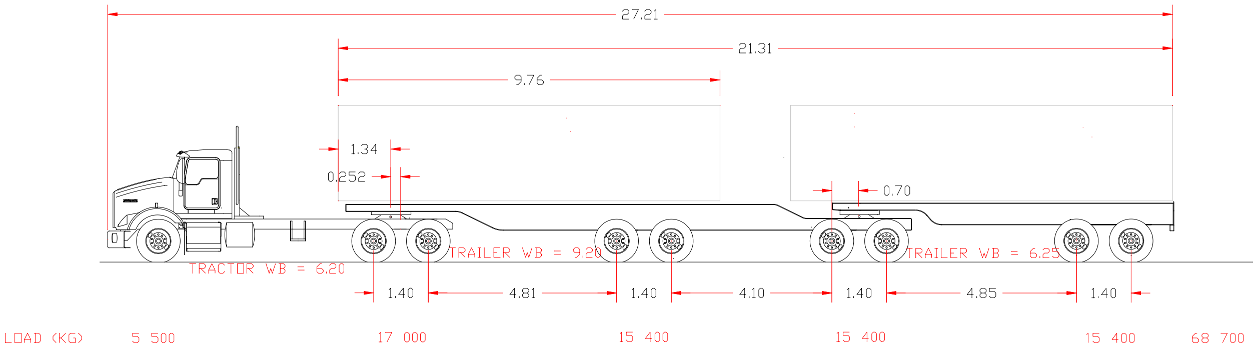

Figure 2 – Proposed 9-axle (tandem drive) weights and dimensions

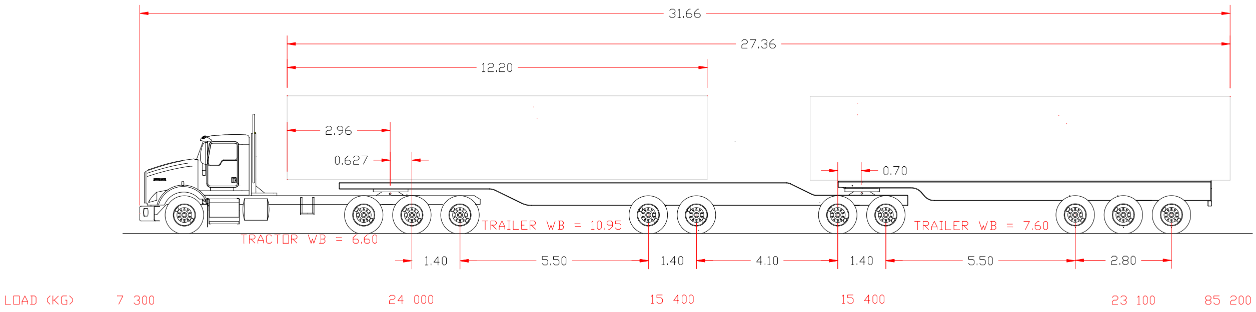

Figure 3 – Proposed 11-axle (tridem drive) weights and dimensions

The performance of the two proposed configurations was evaluated through computer modelling using Mathworks Simulink/Simmechanics™ models. The following performance measures were evaluated against the CVSE specific performance criteria:

Handling performance: Three measures are used to evaluate handling performance at steady-state conditions. These measures were developed by the National Research Council of Canada (NRC) and have only been adopted by the province of British Columbia within Canada.
The first measure (Point #1) is the lateral acceleration where the transition from understeer to over-steer (i.e. the point where the understeer coefficient is zero) takes place. The remaining two handling measures are the understeer coefficient at 0.30 g (Point #2) and 0.15 g (Point #3). Understeer coefficient is expressed in degrees per g which represents the slope of the handling diagram. Positive and negative values indicate understeer and over-steer levels respectively. This performance measure is determined during a ramp steer manoeuvre (ramp steer rate of 2 deg/sec at steering wheel) at a forward velocity of 100 km/h. The pass/fail criterion is addressed by comparing the understeer coefficient with the critical understeer coefficient, which can be expressed as $-Lg/U^2$, where U is the vehicle speed (U = 27.77 m/s or 100 km/h), L is the tractor or truck wheelbase (in metres), and g is acceleration due to gravity (9.81 m/s2). If the value of the understeer coefficient is greater than the critical value, the vehicle will meet the criterion (NRC criterion – Point #2 @ 0.30 g). The criterion for point

#1 is to be greater than 0.2 g, while the criterion for point #3 (0.15 g) is for the understeer coefficient to be greater than 0.5 but less than 2 deg/g.

Static Rollover Threshold (SRT): This is the level of steady lateral acceleration beyond which the configuration rolls over. The measure is expressed as the lateral acceleration (in g's) at which all wheels on one side, except the steer axle, lift off the ground. Configuration performance is considered satisfactory if the static rollover threshold is greater than or equal to 0.40 g. (TAC[3] and CVSE benchmark). However, internationally, a SRT of 0.35 g is considered satisfactory.

Load Transfer Ratio (LTR): The load transfer ratio is defined as the ratio of the absolute value of the difference between the sum of right wheel loads and the sum of the left wheel loads, to the sum of all the wheel loads. The front steering axle is excluded from the calculations because of its relatively high roll compliance. Configuration performance is considered satisfactory if the LTR is less than or equal to 0.60 (TAC performance standard). This performance measure is evaluated during a rapid lane change manoeuvre conducted at 88 km/h, yielding lateral acceleration amplitude of 0.15 g and a period of 2.5 seconds at the tractor's steering axle.

Rearward Amplification (RA): Rearward amplification is defined as the ratio of the peak lateral acceleration at the mass centre of the rearmost trailer to that developed at the mass centre of the tractor. Configuration performance is considered satisfactory if the RA is less than or equal to 1.6, which is the current CVSE target, but the TAC performance standard is to be less than 2.0. This performance measure is evaluated in the same manoeuvre as LTR.

Friction Demand (FD): The friction demand performance measure describes the non tractive tire friction levels required at the drive axles of a tractor. Excessive friction demand is a contributing factor to jackknife and also results in excessive tire wear. Friction demand is the absolute value of the ratio of the resultant shear force acting at the drive tires divided by the cosine of the tractor/trailer articulation angle to the vertical load on the drive tires. Configuration performance is considered satisfactory if FD is less than or equal to 0.1 (TAC performance standard). This performance measure is evaluated in a 90-degree turn at a vehicle speed of 8.25 km/h. During the manoeuvre, the centre of the front steer axle tracks an arc with a 12.8-m radius (approximately a 14-m outside-wheel-path radius).

Lateral Friction Utilization (LFU): Lateral friction utilization is a measure proposed by NRC to characterize the highest level of the lateral friction utilization at the steering axle. LFU is

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[3] TAC – Transportation Association of Canada (formerly known as RTAC)

defined as the ratio of the sum of lateral forces to the vertical load, and the peak tire/road coefficient of adhesion. The tires of a steering axle that achieves a lateral friction utilization level of 1 are said to be saturated. Configuration performance is considered satisfactory if LFU is less than or equal to 0.80 (NRC recommended performance standard). Initially this performance measure was evaluated on a high friction surface. FERIC[4] modified this measure by evaluating LFU on low friction surfaces, which are more critical for steering performance, by using low friction tire characteristics ($\mu = 0.2$). This performance measure is evaluated using the same manoeuvre as FD, but on a low friction surface.

Low Speed Off-tracking (LSOT): Low speed off-tracking is measured as the maximum lateral displacement of the centre-line of the last axle of the configuration from the path taken by the centre of the steer axle. Configuration performance is considered satisfactory if LSOT is less than or equal to 6.0 m (TAC performance standard). This performance measure is evaluated using the same manoeuvre as FD and LFU.

High Speed Steady State Off-tracking (HSOT): High speed off-tracking is measured as the maximum lateral displacement of the centre-line of the last axle of the configuration from the path taken by the centre of the steer axle. Configuration performance is considered satisfactory if HSOT is less than or equal to 0.46 m (TAC performance standard). This value represents a minimal clearance of 0.15 m between the trailer tires and the outside of a 3.66-m wide conventional traffic lane when the steering axle is in the centre of the lane. This performance measure is evaluated when the vehicle is operated in a 393-m curve radius, at a speed of 100 km/h, thereby attaining a steady lateral acceleration level of 0.2 g.

Transient off-tracking (TOT): Transient off-tracking is measured as the maximum lateral displacement of the centre-line of the last axle of the configuration from the path taken by the centre of the steer axle. Configuration performance is considered satisfactory if TOT is less than or equal to 0.8 m (TAC performance standard). This performance measure is evaluated in the same manoeuvre as LTR and RA.

For each of the proposed configurations the following three trailer steering options were evaluated, using steerable axles on the rear two axles of the lead trailer:

1. Forced steer axles – normal operation at low speed; locked at high-speed.
2. Forced steer axles – normal operation at low-speed; counter-steering at high-speed.
3. Self-steer axles - normal operation at low speed; locked at high-speed.

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[4] Predecessor of FPInnovations – In 2007 FERIC was amalgamated with two other Canadian forest industry research institutes (PAPRICAN and FORINTEK)

Note that for normal operation at low-speed the forced steer axle input was determined based on the axle geometry and the articulation angle between the tractor and lead trailer (Figure 4). The steering angles of the steering axles are calculated as follows:

$$\text{Steer S1} = -K\frac{b1}{a}x \quad (1)$$

$$\text{Steer S2} = -K\frac{(b1+b2)}{a}x \quad (2)$$

Where K = constant
x = articulation angle between tractor and lead trailer
a = distance from fifth wheel to rigid tandem group centre
b1 = distance from tandem group centre to steering axle S1
b2 = distance from steering axle S1 to steering axle S2

The counter-steering at high speeds is illustrated in Figure 5; where the steering axles provide lateral resistance opposing the trailer's lateral acceleration, thereby providing increased dynamic stability. For the purposes of this evaluation a constant K of 1.2 was used at low-speeds while a K value of -0.4 was used at high-speeds.

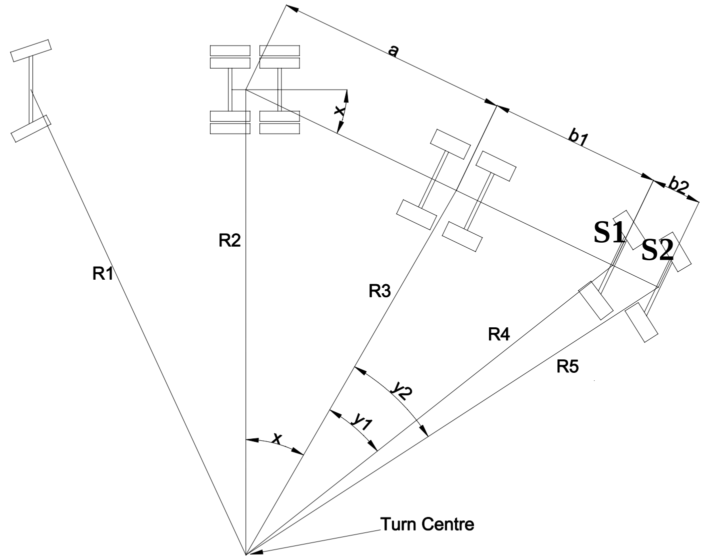

Figure 4. Axle steering geometry at low-speed

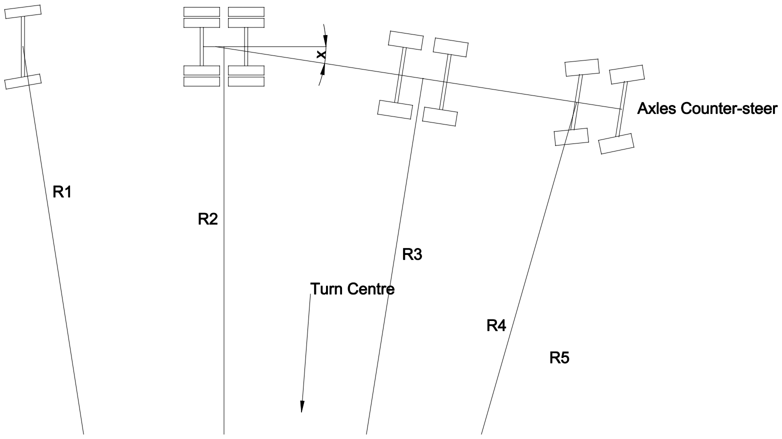

Figure 5. Forced steer axles counter-steering at high-speeds

3. Results and Discussion

3.1 9-axle configuration

The simulation results of the three 9-axle configuration steering options are summarized in

Table 1. The best overall performance was achieved when forced steer axles were utilized with a counter-steering strategy at high speeds; particularly for the dynamic performance measures of rearward amplification (RA), load transfer ratio (LTR), and high-speed off-tracking (HSOT). The use of forced steering axles significantly improved the low-speed off-tracking (LSOT) performance relative to self-steering axles, reducing LSOT by 1.8 m. However, there were handling issues with the counter steering strategy; with levels of oversteer occurring from a very low level of lateral acceleration. Similarly, locking the forced steer axles at high speeds or using self-steer axles instead of the forced steer axles also resulted in handling issues. The use of self-steer axles resulted in inconsistent handling characteristics; with multiple transitions between understeer and oversteer zones – a situation that is difficult for drivers to control and react to. As well, the use of self-steering axles resulted in higher than recommended levels of friction demand (FD).

Table 1 – Simulation Results – 9-axle configuration

Performance Measure	Performance Standard	Forced-steer Locked high speed	Forced-steer Counter-steer high speed	Self-steer Locked high speed
Handling Performance (P1) Oversteer transition	> 0.20 g	**0.067**	**0.058**	**0.075**
Handling Performance (P2) USC @0.3 g	>-4.44 degrees/g	-0.150	-3.267	0.571
Handling Performance (P3) USC @0.15 g	>0.50 degrees/g < 2.0 degrees/g	**-0.762**	**-2.520**	**-0.408**
Static Rollover Threshold	>0.40 g	0.403	0.403	0.403
Load Transfer Ratio	< 0.60	0.291	0.238	0.266
Rearward Amplification	<1.6	1.449	1.018	1.380
Lateral Friction Utilization	<0.80	0.625	0.625	0.510
Friction Demand	<0.10	0.055	0.055	**0.107**
Low-speed off-tracking	<6.00 m	3.234	3.234	4.993
High-speed off-tracking	<0.46 m	**0.531**	0.401	**0.583**
Transient off-tracking	<0.80 m	0.453	0.035	0.418

Red bold text indicates performance measure not met

It should be noted that the three point handling measure used in this study has never been widely adopted, due to concerns of its sensitivity to vehicle parameters and the ability to accurately characterize these vehicle parameters in computer models. However, despite the noted shortcomings of this handling performance measure, it can be used to determine the tractor's relative handling performance as to whether it is reasonably behaved or can quickly become a highly oversteered vehicle (Billing, Patten, 2010).

In the case of the proposed 9-axle configuration, all three trailer steering options suggest that oversteer tendencies will occur at relatively low lateral accelerations. Therefore, further research and optimization of appropriate steering strategies are recommended for this configuration before it can be successfully implemented. One potential solution may be the VRACS approach proposed by the Eindhoven University of Technology, which should be investigated further to determine its suitability.

Despite the identified handling issues, the 9-axle modular concept configuration utilizing forced steer axles at the rear two axles of the lead trailer shows promise for future implementation. The use of a counter steering strategy for the trailer steering axles at high speeds shows significant improvements in its dynamic performance, with an RA approaching unity as well as reduced levels of high-speed off-tracking (both transient and steady state). Further optimization and research is recommended to address the identified handling issues and determine the appropriate control strategies and transitions between high and low speed.

3.2 11-axle configuration

The simulation results of the three 11-axle configuration steering options are summarized in Table 2. Again, as noted for the 9-axle configuration, the best overall performance was achieved when forced steer axles were utilized with a counter-steering strategy at high speeds. The use of forced steering axles resulted in improved levels of LSOT relative to self-steer axles by up to 1.4 m, easily meeting the performance standard. There were only minor handling issues for this configuration; with lower than recommended understeer levels under normal driving conditions (0.15 g) for the self-steer axles and forced steer axles utilizing the counter-steering option at high speeds. However, the use of self-steering axles caused excessive levels of LSOT and lateral friction utilization (LFU). All three trailer axle steering options resulted in higher than recommended levels of HSOT, with the self-steering axle yielding very high HSOT levels of 0.624 m.

Table 2 – Simulation Results – 11-axle modular concept configuration

Performance Measure	Performance Standard	Forced-steer Locked high speed	Forced-steer Counter-steer high speed	Self-steer Locked high speed
Handling Performance (P1) Oversteer transition	> 0.20 g	0.435	0.495	0.461
Handling Performance (P2) USC @0.3 g	>-4.88 degrees/g	0.788	0.420	1.091
Handling Performance (P3) USC @0.15 g	>0.50 degrees/g < 2.0 degrees/g	0.512	**0.161**	**0.461**
Static Rollover Threshold	>0.40 g	0.400	0.400	0.400
Load Transfer Ratio	< 0.60	0.214	0.205	0.187
Rearward Amplification	<1.6	1.230	1.014	1.147
Lateral Friction Utilization	<0.80	0.786	0.786	**0.865**
Friction Demand	<0.10	0.057	0.057	0.066
Low-speed off-tracking	<6.00 m	4.687	4.687	**6.113**
High-speed off-tracking	<0.46 m	**0.556**	**0.494**	**0.624**
Transient off-tracking	<0.80 m	0.344	0.166	0.303

Red bold text indicates performance measure not met

The 11-axle modular concept configuration yielded less handling performance issues than the 9-axle and therefore can be implemented with the proposed dimensions and axle loads. The benefits of using the counter-steering strategy at high speeds is not as dramatic as seen with the 9-axle. Apart from the HSOT deficiency, locking the forced steer axles at high speeds resulted in relatively good dynamic performance. Therefore this configuration can be implemented on approved routes utilizing this trailer axle steering strategy (locking at high-speed) in the short term. In the longer term it is recommended that further research be conducted into alternative high-speed strategies such as the VRACS approach which will result in improved performance.

4. Conclusions

1. The use of forced steer axles on the last two axles of the lead trailer resulted in improved low-speed manoeuverability compared to self-steering axles (reduced low speed off-tracking) for both the proposed 9-axle and 11-axle configurations.
2. The application of a counter-steering strategy at high-speeds for the forced steer axles improved the dynamic performance (load transfer ratio, rearward amplification, and transient off-tracking) as well as high-speed off-tracking for both configurations. The benefits of using the counter-steering strategy were most pronounced for the 9-axle configuration.
3. A number of handling issues were identified for the 9-axle configuration, including oversteer tendencies at low lateral accelerations. Therefore, further research and review of alternative trailer axle steering strategies is recommended to resolve these issues for the 9-axle configuration before this configuration may be implemented.
4. The three point handling measure used in this study has never been widely adopted, due to concerns of its sensitivity to vehicle parameters and the ability to accurately characterize these vehicle parameters in computer models. However, despite the noted shortcomings of this handling performance measure, it can be used to determine the tractor's relative handling performance as to whether it is reasonably behaved or can quickly become a highly oversteer vehicle. Therefore, this measure provides important additional information on which to assess a configuration's performance.
5. The 11-axle configuration performance was satisfactory, with only minor handling issues; and therefore this configuration can be implemented with the proposed dimensions and axle loads. For this configuration it is recommended that, in the short term, locking the forced steer axles at high-speeds be used.
6. In the longer term it is recommended that further research be conducted into alternative high-speed strategies such as the VRACS approach which will result in improved performance for both configurations.

5. References

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