ARTICULATED STEERING HEAVY VEHICLE HANDLING




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Abstract

Articulated steering heavy vehicles are widely used in construction and mining for low-speed manoeuvrability. This paper uses multi-body dynamic simulations to develop handling diagrams for articulated vehicles, revealing previously unknown non-linear dynamic behaviour. Articulated cranes transition from neutral steer to oversteer and then understeer under different driving conditions, influenced by articulation angle, speed, and drivetrain mode. Heavier articulated vehicles with a longer wheelbase exhibit safer and more predictable handling. These findings provide valuable insights for driver training, articulated vehicle selection, and vehicle design to enhance safety and performance.

Keywords: Articulated Vehicles, Mobile Cranes, Handling, Rigid Body Dynamic Simulation

1. Introduction

Articulated steering heavy vehicles are commonly employed in construction and mining environments due to their exceptional low-speed manoeuvrability. Unlike conventional vehicles with Ackermann steering geometry, articulated vehicles exhibit distinct dynamic behaviours and handling characteristics. These differences arise primarily from their kinematic configuration, dynamic coupling and decoupling between vehicle units, and articulation-induced variations in stability and inertia. Understanding these dynamics is essential to ensure safe operation and effective performance, particularly when transitioning to on-road applications. Research was undertaken to inform industry and regulators as published work explicitly addressing the handling performance of these vehicles is sparce.

This report assesses the handling performance of articulated steering heavy vehicles using rigid body dynamic simulations. Handling diagrams are derived to illustrate the relationship between steering input, vehicle speed and lateral acceleration. The handling diagrams highlight unique handling characteristics of articulated vehicles operating across a range of articulation angles and speeds.

To conduct this assessment, a three-dimensional multi-body dynamic model was developed using Universal Mechanism® software. This model simulates each of the rigid bodies and joints in the vehicle using physical specification data for parameters such as mass, stiffness, and damping. Three sizes of articulated crane were modelled – 16 t, 20 t and 24 t. Each crane was simulated in front-wheel drive (FWD) and all-wheel drive (AWD).

The handling diagrams indicate that the 16 t and 20 t articulated cranes transition from neutral steer to oversteer to understeer as lateral acceleration is increased. The handling diagram for a 24 t articulated crane is more linear and transitions from neutral steer to understeer. The cranes tend to oversteer more when operating in AWD than in FWD. Oversteer and understeer are generally more pronounced at higher speeds.

Handling performance of articulated cranes is also compared to conventional rigid trucks with Ackermann steering geometry. A 4x2 and 6x4 rigid truck were assessed. The rigid trucks display similar handling characteristics to the 24 t articulated crane – more linear and tend to understeer.

2. Subject Vehicles

Conventional Ackermann steering systems rotate the steer tyres about wheel ends attached to the axle using mechanical linkages connected to the steering wheel. Rather than rotating the steer tyres, articulated cranes have a hydraulically articulated joint at the centre of the chassis which rotates the front and rear sections of the chassis relative to each other. The tyres on an articulated crane remain perpendicular to the axles. The angle of the axles relative to each other creates the cornering forces that allow the vehicle to travel on a curved path.

Compared to conventional heavy vehicles with Ackermann steering, articulated vehicles have unique dynamic characteristics including:

- **Kinematic configuration** which describes the varying positions of the two sprung masses (front and rear units) due to the articulation angle, encompassing the idea of how the relative orientations of these masses affect the vehicle's motion.
- **Articulation-Induced Dynamic Variation** which means the vehicle's dynamic properties, such as inertia, balance, and stability, vary with the articulation angle.
- **Dynamic Coupling and Decoupling** which refers to how the dynamic behaviour of the two units changes with articulation. At low articulation angles, the front and rear units are more dynamically coupled, moving more in unison. At higher angles, the units can be said to have a degree of decoupling.
- **Geometric Versatility** which describes the vehicle's ability to change its effective geometry, like track width, effective wheelbase, and orientation of the sprung masses, in response to different articulation angles.

3. Simulation Models

3.1 Articulated Vehicles

Three-dimensional multi-body dynamic models of articulated vehicles were created using Universal Mechanism® (UM) software to assess vehicle dynamic and handling performance, refer Figure 1. Three sizes of articulated crane were modelled – 16 t, 20 t and 24 t, refer Table 1. Each crane was simulated in front-wheel drive (FWD) and all-wheel drive (AWD).

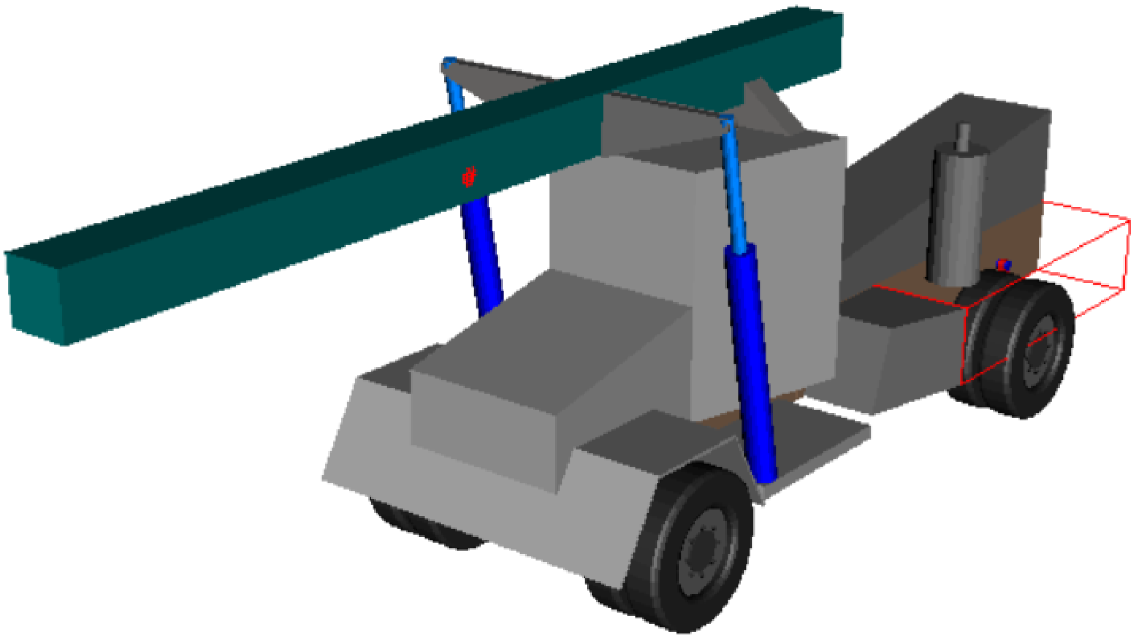

Figure 1 – Universal Mechanism® simulation model of articulated crane

This model simulates each of the rigid bodies and joints in the vehicle using parameters derived from the available data, including:

- Mass,
- Centre of gravity location,
- Moment of inertia,
- Suspension stiffness and damping,
- Hydraulic articulation joint stiffness and damping, and

- Tyre performance characteristics.

Table 1 – Articulated vehicle specifications

Tare mass	Wheelbase	Track width	Tyre size
16 t	3,900 mm	1,868 mm	11.00-20
20 t	4,450 mm	1,870 mm	12.00-20
24 t	4,750 mm	2,100 mm	14.00-20

The articulated joint was modelled using a UM bushing placed in between the front and rear chassis bodies allowing the vehicles to rotate relative to each other about the vertical axis. The vehicle steering control was implemented by applying a scalar torque to the articulation joint that acts between the front and rear halves of the chassis.

The front and rear axles were modelled as rigid axles with dual tyres installed. A scalar torque was applied to the wheels on each axle to meet velocity demands. The tyre model used is based on experimental data and includes vertical, lateral, and longitudinal stiffnesses, lateral and longitudinal forces as functions of tyre load and slip angle, plus aligning moment.

This modelling technique is widely used to simulate vehicle dynamics and has been successfully applied to heavy vehicle assessments within the Performance Based Standards (PBS) scheme which was developed by the National Transport Commission (NTC, 2020). It has also been used in research by Whitehead (1990) comparing rear wheel steering dynamics to conventional front wheel steered vehicles. Hence it is well suited for assessing handling performance of articulated vehicles.

3.2 Rigid Trucks with Ackermann Steering Geometry

Two rigid trucks with Ackermann steering geometry were also created to compare the handling of articulated cranes to conventional heavy vehicles, refer Figure 2. The rigid truck models were created in Hevi Spec®, an online tool developed by Tiger Spider that enables easy generation of UM models for heavy vehicles.

Like the articulated crane models, the rigid truck models use parameters taken from specifications of frequently used physical components, such as tyres and suspensions.

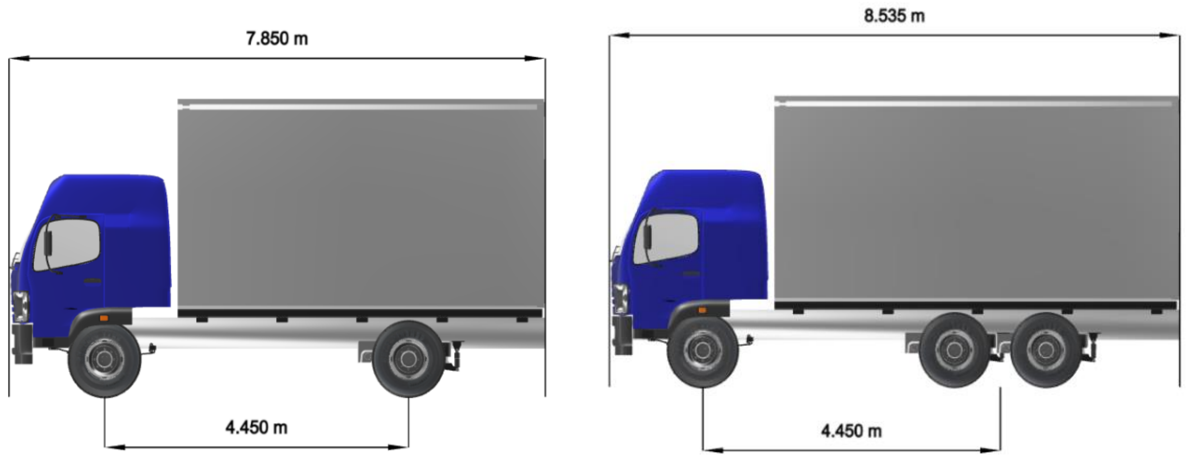

Figure 2 – Rigid trucks modelled in Hevi Spec® software – 4x2 (left) and 6x4 (right)

4. Handling Assessment Method

Handling refers to how well a vehicle responds to driver steering input during cornering. Oversteer, understeer and neutral steer are key handing concepts, and are defined as follows:

- **Oversteer:** When the vehicle turns more sharply than the driver intends, generally considered harder to control, especially for less experienced drivers.
- **Understeer:** When the vehicle steers less than the driver intends, generally considered a safer condition than oversteer as it is more predictable and easier for the driver to correct.
- **Neutral steer:** The balanced state between understeer and oversteer where the vehicle travels exactly where the driver intends.

The intended direction of the driver can be determined from the theoretical turning radius. The theoretical turning radius R can be calculated given the articulation angle θ and wheelbase W based on kinematic analysis. This radius aligns with neutral steering at low speed where wheels are aligned for a turn without tyre slip, refer Equation (1) and Figure 3.

$$R = \frac{W\sin(\theta)}{2(1-\cos\theta)} \quad (1)$$

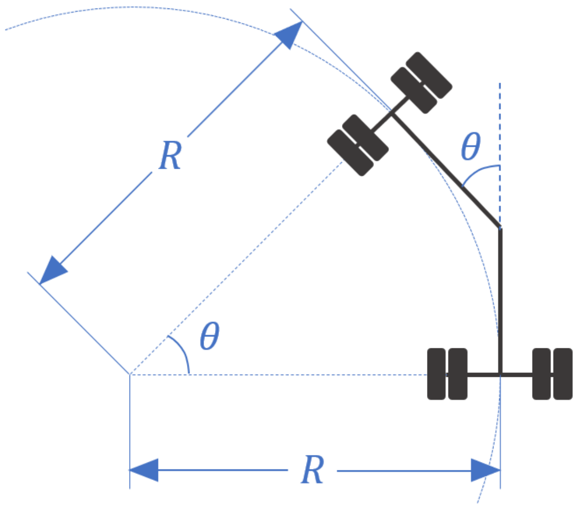

Figure 3 – Geometric relationship between turn radius and articulation angle

The vehicle speed v and theoretical turn radius can then be used to derive the theoretical lateral acceleration a_n relating to neutral steering for a given turn speed and articulation angle, refer Equation (2).

$$a_n = \frac{v^2}{R} = \frac{2v^2(1-cos\theta)}{Wsin(\theta)} \quad (2)$$

Handling can be described by the relationship between measured lateral acceleration a and theoretical lateral acceleration a_n. Equation (3), Equation (4), and Equation (5) represent understeer, oversteer and neutral steer respectively.

$$a < a_n \tag{3}$$

$$a > a_n \tag{4}$$

$$a = a_n \tag{5}$$

Handling curves were generated by simulating the articulated cranes operating at constant articulation angles 0.5°, 1°, 1.5°, 2°, 3°, 4°, 6°, 8°, 10°, 12°, 14°, and 16°, and at constant speeds of 40 km/h, 50 km/h, 60 km/h, 70 km/h and 80 km/h. The steady state lateral acceleration on the front vehicle unit was measured and plotted against the theoretical neutral steer acceleration for the corresponding articulation angle and speed.

The neutral steering line dissects the chart at a 45° angle and lateral acceleration measured from simulations at different speeds are plotted against a_n. The vehicle is oversteering when lateral acceleration is above the neutral line and understeering when below.

Analogous handling diagrams were also derived from the turning circle and steer angle of the rigid trucks with Ackermann steering.

5. Results

Articulated heavy vehicles exhibit nonlinear handling behaviour that transitions between neutral steer, oversteer and understeer under different conditions. The smaller, lighter 16 t and 20 t articulated cranes exhibit greater understeer and oversteer. The 24 t crane transitions from neutral steer to understeer at high lateral accelerations without oversteering.

Oversteer occurs at moderate lateral acceleration (0.20 g – 0.50 g) and consistently increases with vehicle speed. Understeer occurs at high lateral acceleration above 0.50 g. While understeer generally increases with vehicle speed, this trend is less predictable than for oversteer. This is because understeer occurs at very high lateral accelerations where the vehicle is in a more unstable state and behaviour is less predictable.

The articulated vehicles generally exhibit greater oversteer when operating in AWD compared to FWD due to the greater destabilising moment exerted by the rear chassis unit.

Unlike articulated cranes, rigid trucks consistently understeer, a behaviour that increases steadily with speed and lateral acceleration. The more predictable handling of rigid trucks stems from their fixed wheel alignment and single-unit chassis design which minimises dynamic coupling and decoupling effects.

The handling diagram for the 16 t articulated crane is non-linear, refer Figure 4. In FWD, the 16 t articulated crane transitions from neutral steering to oversteer at approximately 0.20 g. The vehicle tends to oversteer between 0.20 g and 0.50 g. Oversteer is more prominent at greater speeds. Beyond 0.50 g, the vehicle understeers. Understeer tends to be more significant as speed increases.

Oversteer peaks at 80 km/h at around 0.42 g where the measured acceleration is approximately 10% greater than neutral steer. Maximum understeer occurs at high lateral acceleration and is approximately 18% below neutral steer at 80 km/h and 0.68 g.

In AWD, the 16 t crane oversteers more than in FWD, particularly at 80 km/h, refer Figure 5. The crane transitions from neutral steer to oversteer at approximately 0.22 g and back to understeer at approximately 0.50 g. Oversteer and understeer are more pronounced at higher speeds. Understeer behaviour is similar operating in FWD and AWD. Maximum understeer occurs at 70 km/h and the extent of understeer does not strictly correlate to vehicle speed.

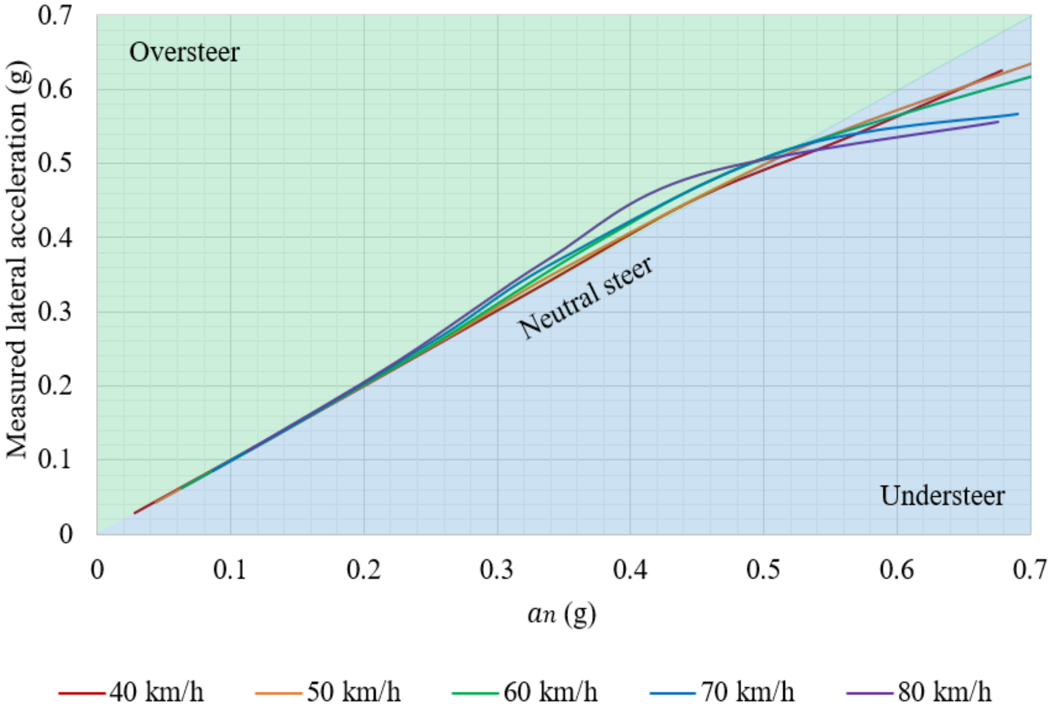

Figure 4 – Handling diagram – 16 t FWD

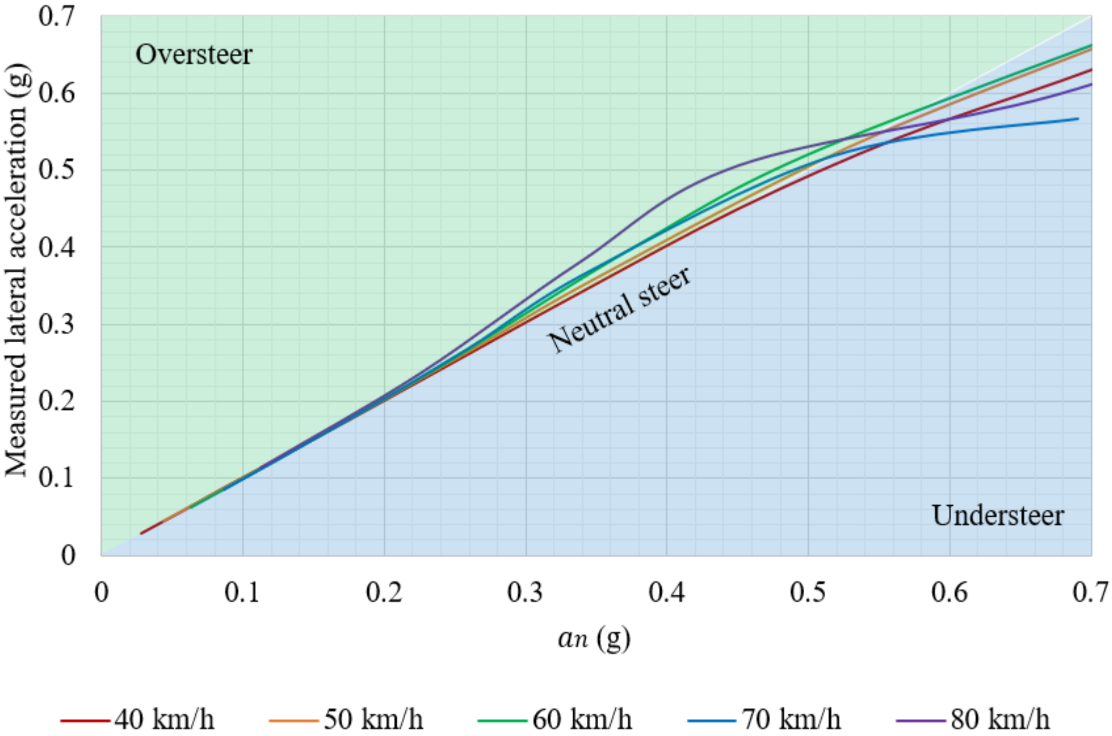

Figure 5 – Handling diagram – 16 t AWD

The 20 t crane has similar handling characteristics to the 16 t crane, refer Figure 6. The 20 t crane (FWD) transitions from neutral steering to oversteer at approximately 0.10 g, and transitions to understeer beyond 0.50 g. Oversteer uniformly increases with vehicle speed. While understeer generally increases with vehicle speed, the correlation is less clear than for oversteer. Peak oversteer occurs at 80 km/h and 0.36 g where lateral acceleration is approximately 16% more than neutral steer. Peak understeer of approximately 20% occurs at 80 km/h and 0.70 g.

In AWD, the 20 t crane transitions from neutral steering to oversteer at approximately 0.16 g, peaks at around 0.36 g and then tends to understeer beyond 0.56 g. Compared to FWD, measured lateral acceleration is generally greater, making oversteer more pronounced and reducing understeer, refer Figure 7. While oversteer steadily increases with vehicle speed, the trend for understeer is less consistent.

Peak oversteer occurs at 80 km/h and 0.36 g where the measured acceleration is approximately 22% greater than neutral steer. Peak understeer occurs at 70 km/h and 0.70 g where lateral acceleration is 12% less than neutral steer.

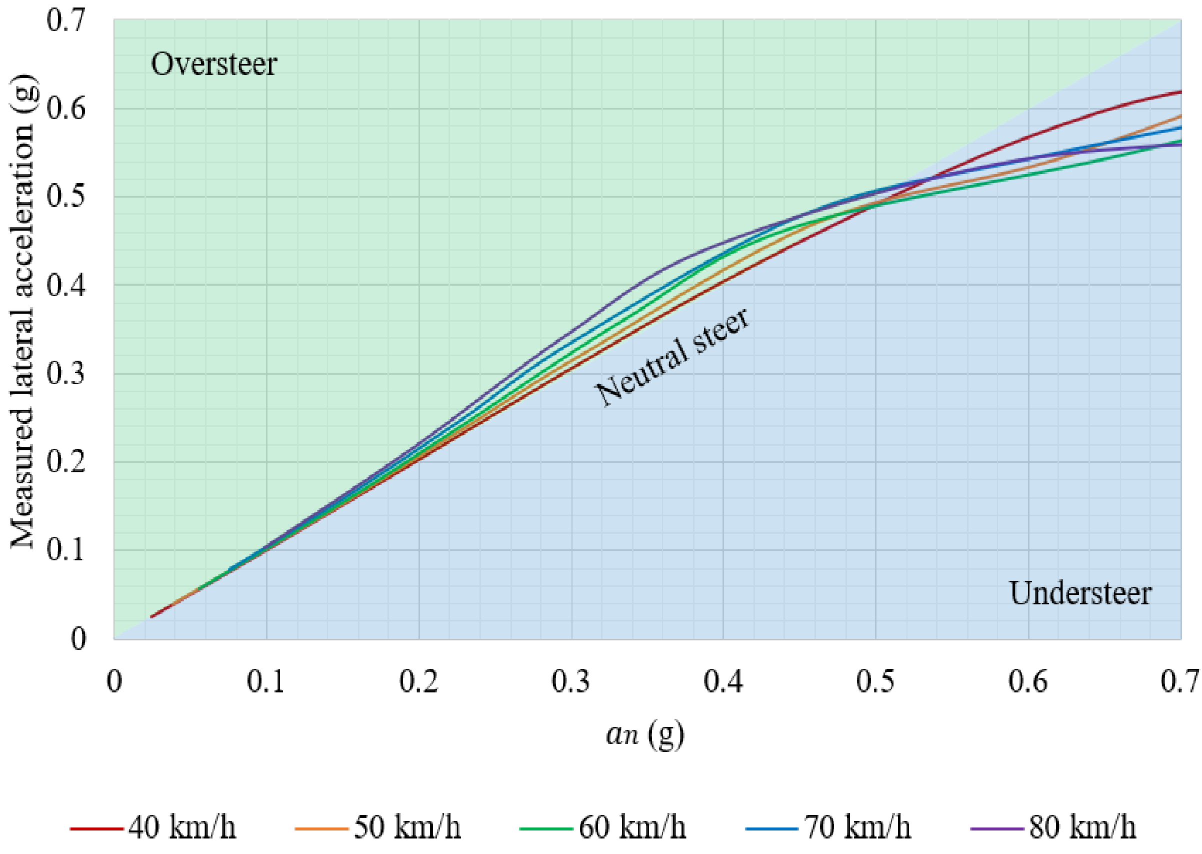

Figure 6 – Handling diagram – 20 t FWD

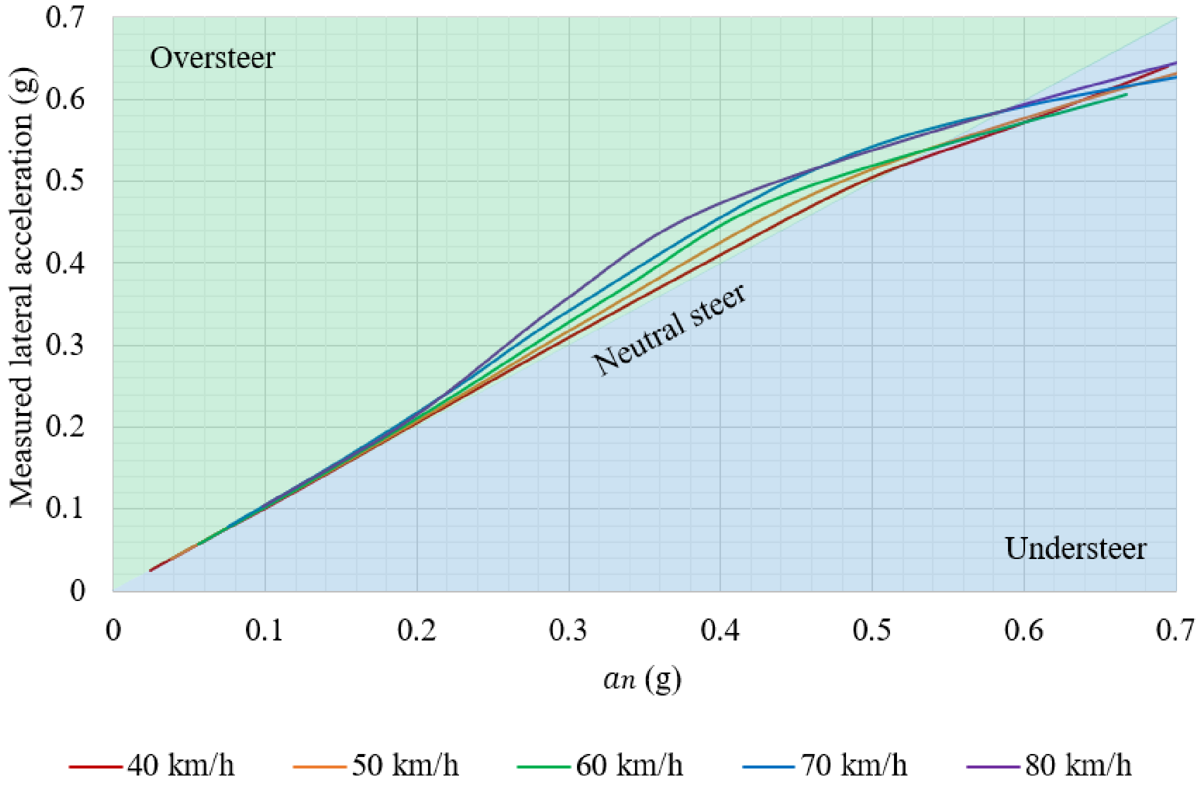

Figure 7 – Handling diagram – 20 t AWD

The 24 t crane does not exhibit any oversteer behaviour, refer Figure 8. It exhibits neutral steering until approximately 0.30 g, beyond which it slightly understeers. The 24 t crane has more predictable handling compared to the smaller cranes because of its longer wheelbase and greater track width. Unlike the smaller cranes, understeer decreases with vehicle speed. Peak understeer occurs at 40 km/h and 0.65 g, where measured acceleration is approximately 8% lower than neutral steer.

The 24 t articulated crane behaves similarly, understeers more in AWD than in FWD, except that the crane understeers more in AWD, refer Figure 9. Maximum understeer is 8% in FWD and 11% in AWD.

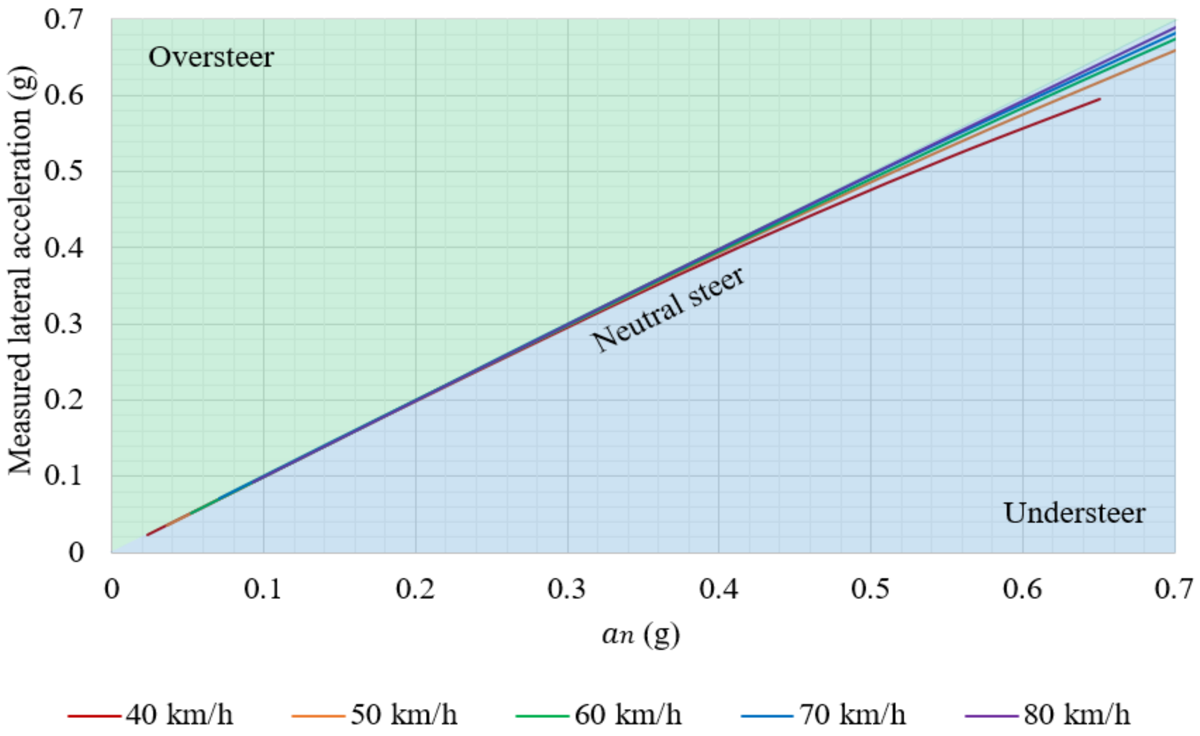

Figure 8 – Handling diagram – 24 t FWD

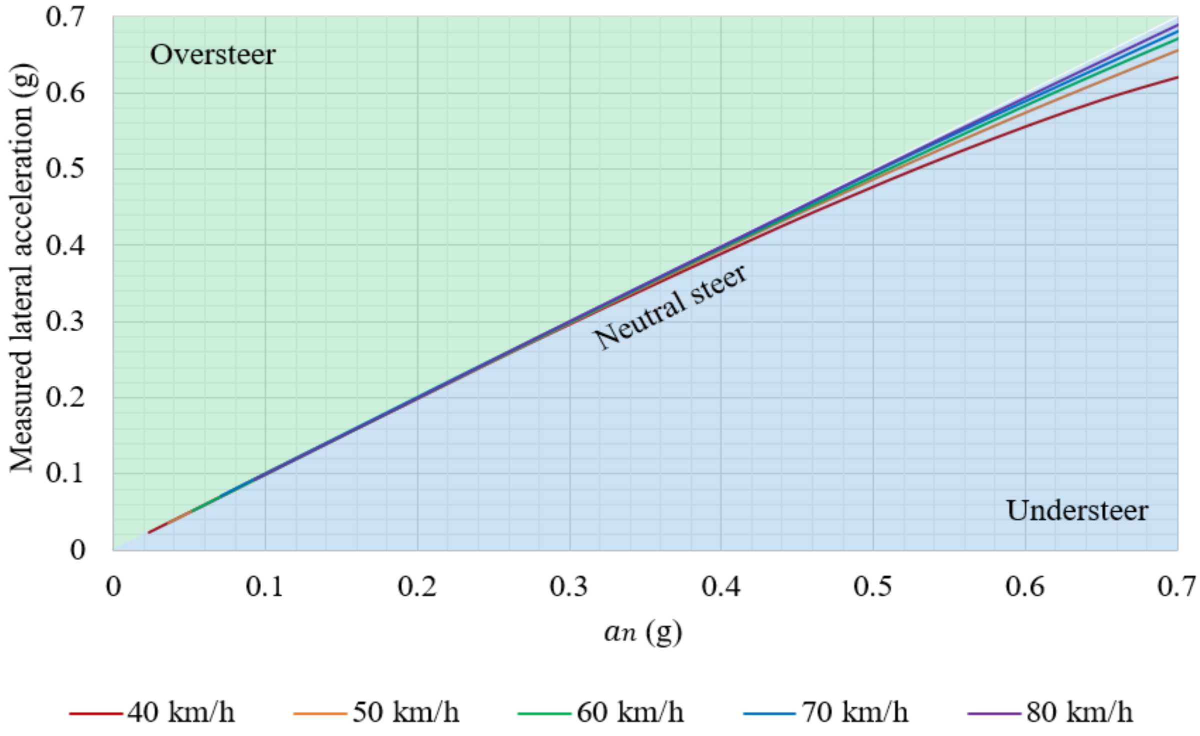

Figure 9 – Handling diagram – 24 t AWD

Handling diagrams for 4x2 and 6x4 rigid trucks with conventional Ackermann steering geometry are close to linear and consistenly understeer at a range of speeds, refer Figure 10 and Figure 11. The rigid trucks do not exhibit oversteer like the articulated cranes, partly because there are fewer tyres at the front of the rigid trucks, which means the steer axle loses traction more easily than the drive axle group.

Understeer consistently increases with vehicle speed for the rigid trucks. This trend is more consistent than the understeer behaviour of the articulated cranes. These handling diagrams indicate that the dynamic response of the rigid trucks is generally more predictable and consistent than articulated cranes.

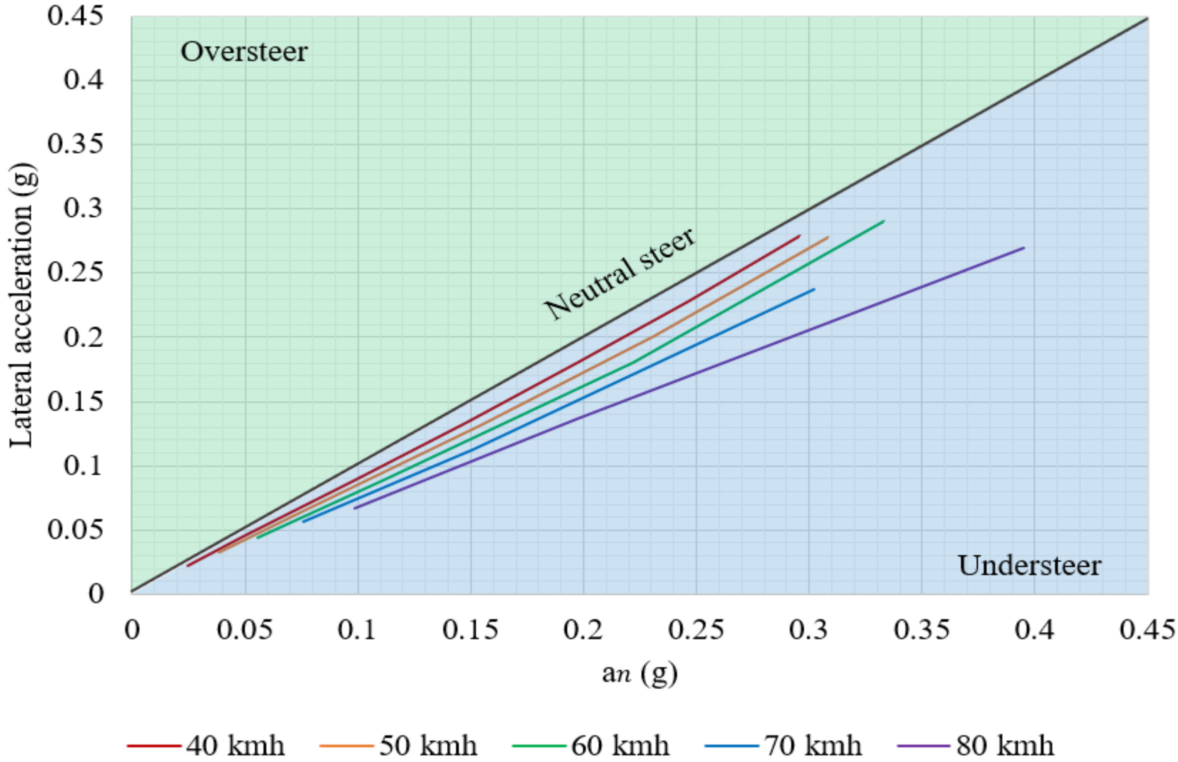

Figure 10 – Handling diagram – 4x2 rigid truck

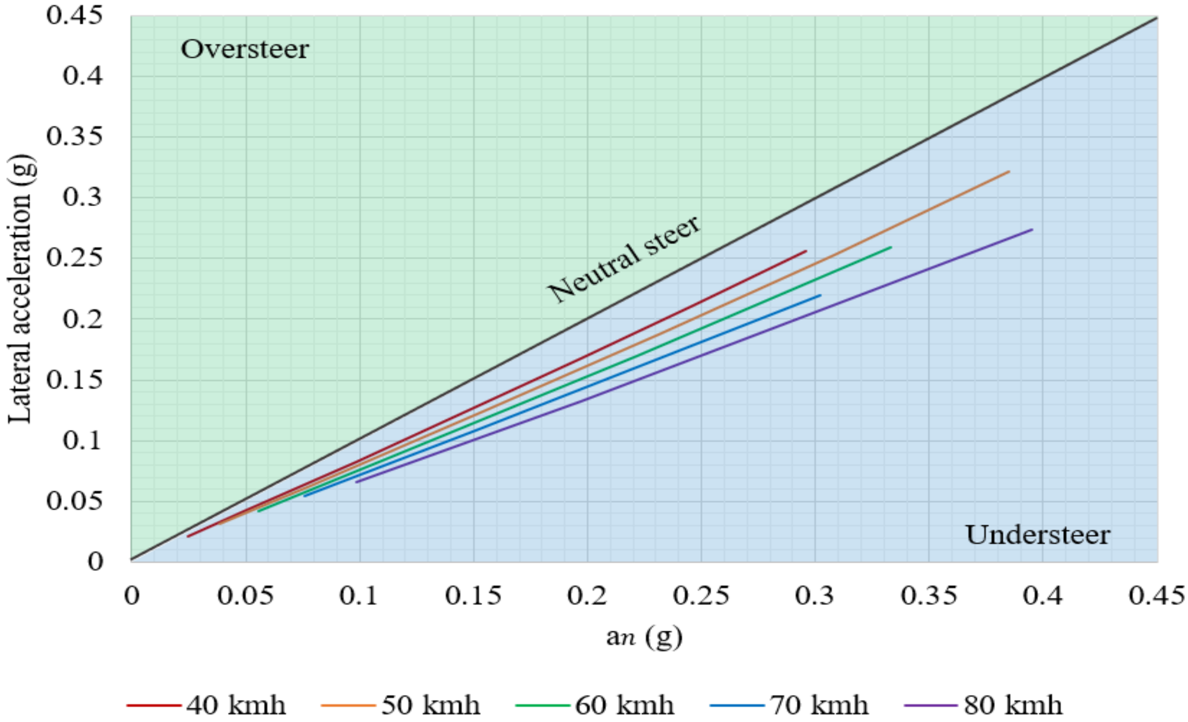

Figure 11 – Handling diagram – 6x4 rigid truck

6. Conclusions

This paper investigated the handling behaviour of articulated steering heavy vehicles by deriving handling diagrams that illustrate understeer, oversteer and neutral steer. The handling performance of articulated mobile cranes was compared to that of rigid trucks with conventional Ackermann steering. Our analysis highlights the unique dynamic properties of articulated vehicles, details previously unknown non-linear handling behaviour, and offers insights into the underlying causes.

Articulated cranes exhibit nonlinear handling behaviour due to their central hydraulic joint, which dynamically alters the vehicle's inertial properties and geometry. This articulation induces variations in stability and cornering forces, resulting in transitions between oversteer and understeer. Dynamic coupling and decoupling of the front and rear sections at varying articulation angles create complex interactions that amplify the nonlinear behaviour.

At high speeds, significant lateral acceleration can be generated at small articulation angles, and tyre cornering forces are relatively high compared to the inertial forces of the rear unit, causing a tendency to oversteer. Oversteer is greater in AWD mode because the additional drive forces from the rear unit exerts a greater destabilising yaw moment. As articulation angle and tyre slip angle increase, inertial forces begin to dominate tyre cornering forces which leads to understeer.

The handling diagrams show that the 24 t crane has more linear handling and transitions from neutral steer to understeer without oversteering. The results show the significant influence of wheelbase and vehicle mass on handling performance of articulated vehicles, indicating larger articulated vehicles with more uniform weight distribution exhibit safer and more predictable handling.

The variation in handling performance is greater for the articulated vehicles than conventional Ackermann geometry vehicles. The handling diagrams of conventional rigid trucks are linear and consistently understeer. This stems from their fixed wheel alignment and single-unit chassis design which minimises dynamic coupling and decoupling effects.

This paper reveals unique handling characteristics of articulated vehicles that transition from neutral steer to oversteer to understeer under different driving conditions. The handling diagrams may be used to inform driver training for safe operation and understanding of vehicle behaviour in different operational scenarios. The results may also assist in articulated vehicle design and selection as they indicate that larger articulated vehicles with a longer wheelbase generally exhibit more predictable and safer handling characteristics.

7. References

- National Transport Commission (NTC) (2020), "Performance-Based Standards Scheme – the Standards and Vehicle Assessment Rules," Brisbane.
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