CHALMERS

Definitions of Performance Based Characteristics for Long Heavy Vehicle Combinations

Prepared by:

Maliheh Sadeghi Kati

June 2013

Abstract

Performance Based Characteristics (PBC) can be seen as an alternative for regulating Long Heavy Vehicles and their access to the road network. PBC has potential to improve productivity gains and technological advances while controlling road safety, infrastructure impacts and environmental effects.

In order to define the standards, a number of PBC needs to be defined. This report provides and introduces the definitions of PBC for longitudinal and lateral performance of long heavy vehicles.

Acknowledgements

I would like to acknowledge the valuable feedback and discussion of the following individuals: Jonas Fredriksson, John Aurell, Bengt Jacobson, Leo Laine, Inge Johansson , Lennart Cider, Peter Lindroth, Niklas Fröjd and Lena Larsson.

Maliheh Sadeghi Kati,
Göteborg, June 2013

Nomenclature

ANRTC	Australian National Road Transport Commission
NAASRA	National Association of Australian State Road Authorities
PBS	Performance Based Standards
PBC	Performance Based Characteristics
LHV	Long Heavy Vehicle
CHV	Conventional Heavy Vehicle
SLC	Single Lane Change
SRT	Steady-state Rollover Threshold
RWA	Rearward Amplification
LSSP	Low Speed Swept Path
HSTO	High Speed Transient Offtracking
HSSO	High Speed Steady-state Offtracking
YDC	Yaw Damping Coefficient
SLO	Straight Line Offtracking
LCT	Lateral Clearance Time
DCT	Deceleration Capability in a Turn
COG	Center Of Gravity
GCM	Gross Combination Mass

Contents

Abstract **2**

Acknowledgements **3**

Contents **i**

1 Introduction **1**

2 Longitudinal Performance Based Characteristics **3**
2.1 Startability 3
2.2 Gradeability 4
2.3 Acceleration Capability 4
2.4 Stopping Distance 5
2.5 Down-grade Holding Capability 5

3 Lateral Performance Based Characteristics **7**
3.1 Steady-state Rollover Threshold (SRT) 7
3.2 Rearward Amplification (RWA) 8
3.3 Low Speed Swept Path ($LSSP$) 9
3.4 High Speed Transient Offtracking ($HSTO$) 9
3.5 High Speed Steady-state Offtracking ($HSSO$) 10
3.6 Yaw Damping Coefficient (YDC) 11
3.7 Straight Line Offtracking (SLO) 11

3.8 Deceleration Capability in a Turn (DCT) 12
3.9 Lateral Clearance Time (LCT) 13

Bibliography **14**

Introduction

The rapid increase in the goods transport demands makes Long Heavy Vehicle (LHV) combinations as an attractive alternative to the Conventional Heavy Vehicle (CHV) combinations. One obvious advantage with using this alternative is reduction in fuel consumption and consequently the emission of harmful gases. Another major advantage with LHVs is that they occupy less road space compared to CHV combinations to transport the same amount of goods. Introducing LHVs as a major part of good transportation creates a need for a approach to heavy vehicles' regulation to improve road safety, reduce environmental effect and protect road infrastructure.

There are vehicle regulations, as a series of design based requirements(prescriptive vehicle limits), which put restrictions on the vehicle design but does not directly address the performance of the vehicle combination. The vehicle's performance as a way that it interacts with the road network is the determinant factor whether a vehicle should be allowed on the road or not. Performance Based Standards (PBS) is an initiative approach introduced by the National Road Transport Commission in Australia to achieve this goal, [1].

Australian PBS is a solution for regulating LHV combinations by making the freight task more efficient without comprising safety or environmental protection. The following objectives and benefits are expected to be achieved by using PBS approach for regulation of heavy vehicles, [2]:

- increased productivity through innovation in vehicle design and operation
- improvements in road safety, traffic operations and asset management
- a national basis for the regulation of heavy vehicles
- consistency in the application of assessment techniques that are performance based
- better matching of the capabilities of vehicles and the road system
- consistency in permitting local and specific-use vehicles

A PBS approach to LHV combinations' regulation specify how vehicles should perform on the road (e.g. how they turn, hold the road, keep within lanes, how much road wear they cause, etc) rather than prescriptive standards and regulations regarding the dimensions and mass of vehicle that specify what a vehicle must look like not how it should be perform on the road. Some existing vehicle might not be able to fulfill some PBS levels even though they are able to fulfill prescriptive regulations, [3].

This report provides and introduces the definitions of a set of safety Performance Based Characteristics (PBC) that must be met by LHVs to enable them to participate in road transportation.

Longitudinal Performance Based Characteristics

In this chapter, the objectives and definitions of longitudinal performance based characteristics(Longitudinal PBC) of Long Heavy Vehicles (LHVs) are presented. The performance based characteristics addressed in this chapter are as follows:

- Startability
- Gradeability
- Acceleration Capability
- Stopping Distance
- Down-grade Holding Capability

Startability and gradeability characteristics indicate the ability of the vehicle combination to start from rest on an up-grade and to maintain speed on an up-grade while acceleration capability reflects the vehicle's ability to clear intersections and rail crossings etc. These first three characteristics also are powertrain-related characteristics. Stopping distance and down-grade holding capability characteristics are braking system characteristics.

2.1 Startability

To measure the traction capability of a vehicle two metrics can be used, tractive capability or startability. Tractive capability is the maximum tractive force that a vehicle is able to produce. Startability is the maximum grade a vehicle can start in. Both metrics highly depend on the same factors, [4]:

- Tyre/road friction levels
- Engine specifications (torque output versus engine speed)
- Drive train specifications (gear and final ratios)
- Vertical load on driven axles

Startability and tractive capability are highly correlated, therefore only one of them should be used, [4]. Since from a traffic aspect a vehicle should not be stuck in an uphill, startability measure which is a more general measurement is used in this work.

In addition, startability is an important measure for sizing the vehicle's powertrain components such as the engine torque, first and reverse gear ratios and so on, [5].

Definition 2.1 (Startability): *Startability is defined as the maximum grade that a fully laden [1] vehicle combination is capable to start in and maintain the forward motion at a certain friction level.*

The objective of this characteristics is to improve road safety and traffic by ensuring that a vehicle has proper starting capability on up-grades in each road condition. Otherwise, it leads to a safety risk and congestion and consequently causing other users' inconvenience. This test ensures that the fully laden vehicle will be able to start in an uphill grade and move forward, [3].

2.2 Gradeability

Gradeability is another key performance measure to evaluate the vehicle longitudinal performance and tractive capability. Gradeability measure is also largely dependent on the same parameters which were mentioned for startability.

Within Australian National Road Transport Commission (ANRTC), there have been many discussions and arguments regarding the need for both startability and gradeability standards and the possibility of combining both standards. It is argued that a vehicle that is capable of starting on a specified grade is capable of maintaining forward motion on the same grade and it is suggested that low speed gradeability is redundant. However, it was finally decided to keep both standards and it was explained that startability performance is influenced by clutch engagement torque and lower gear operation while gradeability performance is influenced by characteristics of the engine and the drive train in higher gears and therefore two performances are addressing different aspects of performance, [6].

Definition 2.2 (Gradeability): *Gradeability is defined as the maximum grade that a fully laden vehicle combination is capable to maintain the forward motion on an uphill road at a certain constant speed at a certain friction level.*

The objective of this metric is to improve road safety and traffic by ensuring that a fully laden vehicle will be able to maintain its forward motion and speed on up-grades in each road condition.

Poor gradeability performance leads to congested traffic in the road and consequently reduced traffic flow which are not desired.

2.3 Acceleration Capability

Acceleration capability of LHVs reflects their ability to clear intersections and rail crossings. LHVs typically require longer time to accelerate and experience more difficulty to reach desirable speed and maintain it compared to passenger vehicles.

[1] Fully laden vehicle means the vehicle laden to maximum gross weight/ gross mass

Definition 2.3 (Acceleration capability): *Acceleration capability is defined as the time taken for a vehicle combination to accelerate from rest and travel a certain distance while being fully laden at a certain friction level.*

The objective of acceleration capability is to assess the vehicle's ability in clearing intersections, crossings and etc. This performance charactersitics ensures that a vehicle will be able to accelerate with an appropriate rate to clear traffic lights, intersections and etc, [3].

Compared to conventional heavy vehicles (CHVs), the LHVs have a greater length, but only slightly greater engine power. The resultant power to mass ratio for longer vehicles is lower than shorter ones which results in less acceleration capability. LHVs with poor acceleration capability require longer time to accelerate which might lead to increased traffic delays and congestion in the road network, [3].

2.4 Stopping Distance

Stopping distance is one of the most important metrics to evaluate the vehicle's braking performance and accident avoidance and consequently improve the road safety. This performance characteristic ensures that a vehicle will decelerate and stop at an appropriate distance to avoids collisions.

Definition 2.4 (Stopping distance): *Stopping distance is defined as the distance traveled by a fully laden vehicle combination during straight line full braking (pedal braking or automatic braking) from a certain initial speed and it is measured from the first pedal contact or when the brake request is sent from automatic braking until the vehicle comes to a standstill at a certain friction level.*

The objective of this characteristics is to manage safety risk by requiring adequate braking efficiency of LHVs.

Poor braking performance in heavy vehicle combinations is a major factor influencing the risk of heavy vehicles' crashes and consequently can lead to severe damages for both truck drivers and other road users. In 2001 Australian studies have revealed that 4% of crashes are due to LHVs' braking problems such as skidding, jackknifing. Furthermore, it has been mentioned that improving heavy vehicle brake systems can prevent crashes or reduce severity in 13% of crashes [7].

The effective minimum stopping distance in emergency braking is generally interpreted as the minimum stopping distance or maximum deceleration that can be achieved without wheel lock. The braking performance has a major influence on stability of vehicle combination under braking and locking wheels on an axle or some axles can results in jackknifing and trailer swing instabilities. NAASRA (1985) noted that vehicle combination under extreme braking conditions are more reliable to instability situations such as jackknifing and trailer swing, [7].

2.5 Down-grade Holding Capability

Down-grade capability is the ability of a fully loaded vehicle to maintain its forward motion on a specified down-grade in different tyre/road conditions. This performance metric mostly aims at assessing the vehicle braking performance. The vehicle braking systems should be capable of holding the vehicle stationary on downhill grades over which the vehicle is required to operate.

Definition 2.5 (Down-grade holding capability): *Down-grade holding capability is defined as the maximum grade that a fully laden vehicle combination is capable to maintain a certain constant speed on a down-hill road at a certain friction level.*

The objective of this metric is to improve road safety by ensuring that the vehicle is capable of controlling its speed on downhill grades without losing its control.

Severe down-grades result in generating a large amount of potential energy that is absorbed by the combination brakes to prevent an increase in the speed. The potential energy absorbed by brakes converts to heat in braking components and results in a decrease in brake efficiency known as brake fade. In the worst situation, if the temperature continues rising, it will lead to brake failure and consequently the vehicle combination loses the control which is known as an out of control situation.

Lateral Performance Based Characteristics

In this chapter, lateral performance based characteristics(Lateral PBC) of long heavy vehicles (LHVs) are defined and discussed. The following lateral characteristics are addressed in this chapter:

- Steady-state Rollover Threshold
- Rearward Amplification
- Low Speed Swept Path
- High Speed Transient Offtracking
- High Speed Steady-state Offtracking
- Yaw Damping Coefficient
- Straight Line Offtracking
- Deceleration Capability in a Turn
- Lateral Clearance Time

Steady-state rollover threshold, yaw damping ratio and deceleration capability in a turn are vehicle combination's characteristics reflecting the vehicle lateral stability. Rearward amplification, high speed offtracking and straight line offtracking indicate the trailers dynamic characteristics. Low speed swept path is showing the vehicle combination maneuverability and insuring that the vehicle safely manoeuvres around corners. Lateral clearance time is another LHVs' lateral characteristics indicating the influence of combination's length in clearing the lane change maneuvers.

Frontal swing and tail swing are also introduced in Australian PBS as lateral characteristics of LHVs that are not considered in this report.

3.1 Steady-state Rollover Threshold (SRT)

Steady-state rollover threshold, which in some studies is also called as static rollover threshold, is a high speed lateral performance measure. SRT is the vehicle's lateral acceleration at which the vehicle is about to roll over in a steady state turn. SRT is considered to be the most important performance characteristics between the stability related characteristics of LHV combinations due to its strong correlation with the rollover crashes.

Definition 3.1 (Steady-state rollover threshold): *Steady-state rollover threshold is defined as the steady state level of lateral acceleration of COG that a vehicle can sustain without rolling over during steady turning.*

The main purpose of introducing this characteristic is to improve road safety by limiting the rollover tendency of a vehicle combination during steady turns.

The accidents caused by rollover of heavy vehicles are a major concern for road safety because the accident are violent and cause greater damage than the other accident. Rollover in heavy vehicle accidents is strongly dependent on the vehicle roll stability.

In New Zealand, 20% of heavy vehicle accidents were due to rollover and lateral instability and in Tasmania this rate was 16% which in both cases around 50% of rollover accidents were related to vehicle speed through curves, [8].

3.2 Rearward Amplification (*RWA*)

While making a sudden lateral movement in a LHV, each unit in the combination experiences different lateral acceleration which is amplified towards the rearmost unit of the vehicle. Lower values of rearward amplification indicates better LHVs performance where the best RWA value is one.

Definition 3.2 (Rearward amplification): *Rearward amplification is defined as the ratio of the maximum value of the motion variable of interest (e.g. yaw rate or lateral acceleration of the center of gravity) of the worst excited following vehicle unit to that of the first vehicle unit during a specified manoeuvre at a certain friction level and constant speed.*

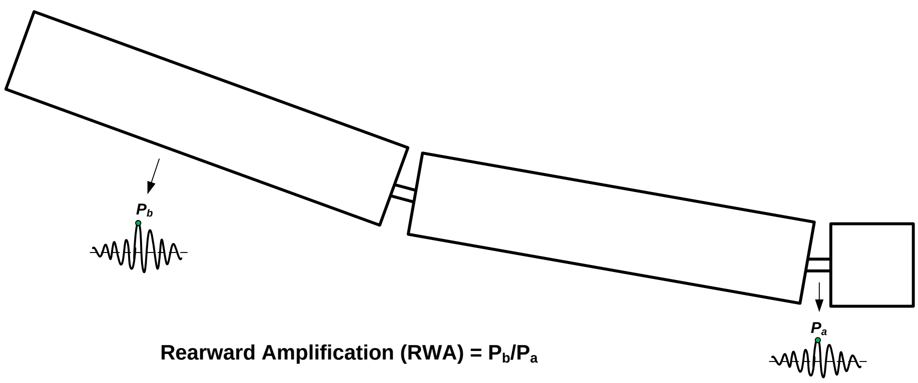

Figure 3.1: Illustration of rearward amplification

Higher values of RWA, shown in Figure 3.1, indicates higher risk of hitting other objects on the road and in a sever situation causing the rear units rollover. Therefore, the major purpose of defining this characteristics is to manage safety risks by limiting lateral response of the LHVs to sudden path-change maneuvers.

3.3 Low Speed Swept Path (*LSSP*)

Low speed swept path or low speed inboard offtracking, shown in Figure 3.2 is a lateral performance measure of LHVs while negotiating with a turn at low speeds. While a LHV is turning in a low speed, the rear wheels follows inside the path of the front wheels that is known as a low speed swept.

Definition 3.3 (Low speed swept path): *Low speed swept path is defined as the maximum width of the swept path between outer most and inner most points of the vehicle combination in a low speed turn with a certain outer radius at a certain friction level and a certain angle between entry and exit.*

The objective of this characteristics is to manage safety risk associated with turns at intersections by limiting the road space required by a vehicle negotiating a turn in low speed, [3].

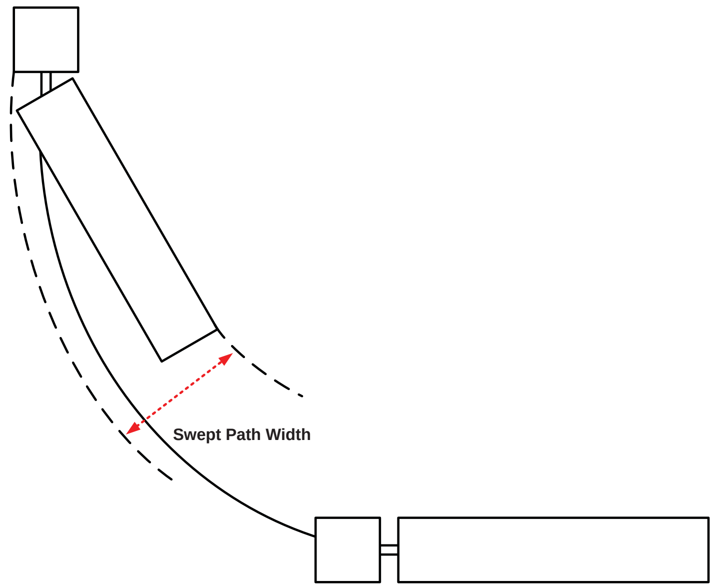

Figure 3.2: Illustration of low speed swept path

A high value of LSSP width is undesirable because the vehicle will need more road space than available space. If the maximum LSSP is greater than the width of the travel lane, the vehicle might collide with objects or other vehicles in the road or run off the road during turning manoeuver.

3.4 High Speed Transient Offtracking (*HSTO*)

When a LHV is negotiating with a turn at a high speed, there is a tendency for the rear axles to sway outside of the front axles' path. This tendency to sway outward is called high speed offtracking or outboard offtracking which is another important lateral performance characteristics of LHVs.

High speed transient offtracking (HSTO), shown in Figure 3.3, is the amount of maximum overshoot in lateral displacement of trailers of a LHV from the path of the front axle of the lead unit in a high speed abrupt turning or path-change manoeuvre. The HSTO indicates the trailers dynamic characteristics, so therefore sometimes is also referred to as trailer overshoot.

Definition 3.4 (High speed transient offtracking): *High speed transient offtracking is defined as an overshoot in the lateral distance between the paths of the center of the front axle and the center of the most severely offtracking axle of any unit in a specified maneuver at a certain friction level and a certain constant longitudinal speed.*

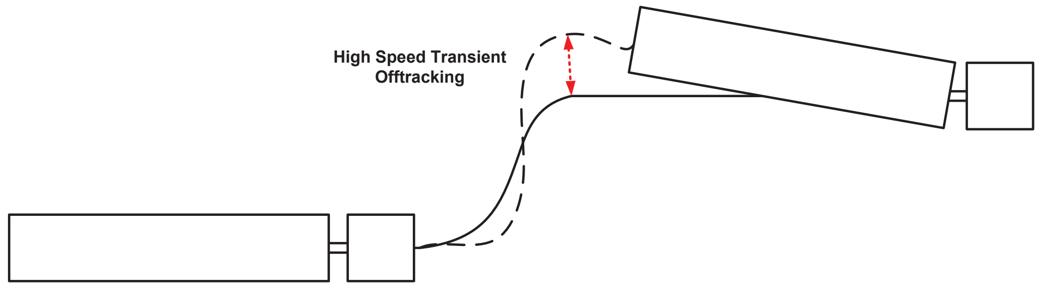

Figure 3.3: Illustration of high speed transient offtracking

The primary objective of this performance characteristics for LHVs is to manage safety risk by restricting the sway of LHVs' trailers in avoidance manoeuvres performed without braking at high speeds, [3].

A high value of this overshoot might lead to collision with the road objects or other vehicles especially when the lane width is narrow and traffic flow on the road is high, [3].

3.5 High Speed Steady-state Offtracking (*HSSO*)

Likewise High speed transient offtracking, high speed steady-state offtracking, shown in Figure 3.4, which is refereed to the lateral displacement of the rear end of the last trailer of a long vehicle combination from the final path of the front axle of the hauling unit can lead to collision with the road objects or other vehicles especially when the road lane width is narrow and traffic flow on the road is high.

Definition 3.5 (High speed steady-state offtracking): *High speed steady-state offtracking is defined as the lateral offset between the paths of the center of the front axle and the center of the most severely offtracking axle of any unit in a steady turn at a certain friction level and a certain constant longitudinal speed.*

The main objective of introducing this characteristics is to manage safety risk associated with high speed turns by limiting the road space required by a vehicle turning in a high speed.

Trailers of an articulated vehicle may track the outside of the path of the first unit and drop off the road or in a worse case collide with other vehicles on the road. Therefore, high speed offtracking in undesirable and should be minimized.

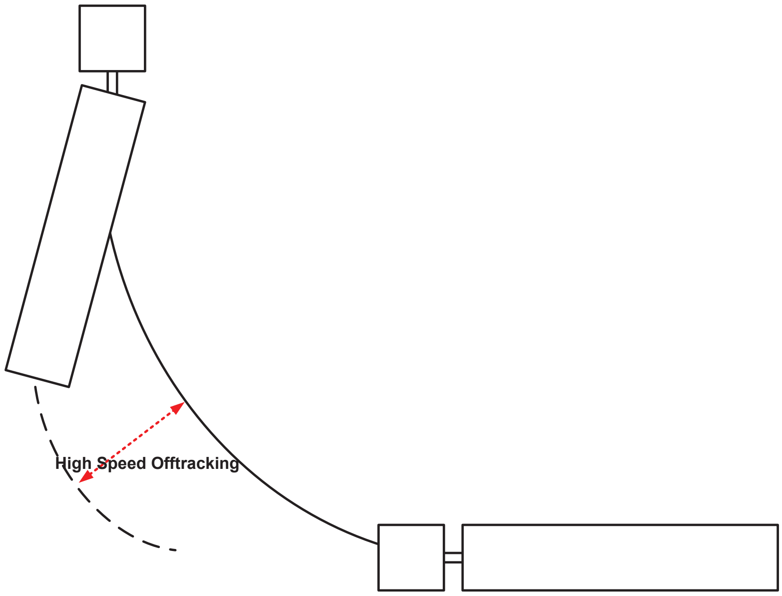

Figure 3.4: Illustration of high speed steady state offtracking

3.6 Yaw Damping Coefficient (YDC)

An important consideration in the stability and handling of LHVs is how quickly yaw oscillations of articulation joints take to settle after a severe manoeuvre. Vehicles that take a longer time to decay these oscillations might increase the driver workload and result in a higher safety risk to other road users , [3].

Definition 3.6 (Yaw damping coefficient): *Yaw damping coefficient is defined as the damping ratio of the least damped articulation joint's angle of the vehicle combination during free oscillations excited by actuating the steering wheel with a certain pulse or a certain sine-wave steer input at a certain friction level.*

The main purpose of this metric is to improve road safety by requiring acceptable decay rate of any sway oscillations of articulation joints of multi-articulated vehicles. This standard is more aim at the combination vehicles with more than one articulation joint.

Yaw damping, shown in Figure 3.5, decreases with increasing speed and at higher speed the oscillation might take more time to decay which can lead to rollover situation in extreme cases or a collision with a vehicle in an adjacent or opposite lane or with roadside objects.

3.7 Straight Line Offtracking (SLO)

Straight line offtracking is a performance criterion for tracking ability of LHVs which describes how well a LHV combinations trailers tracks the path of the leading unit on a straight banked road. When a LHV combination travels on a straight path, the trailers might not necessarily follow the same path of lead unit due to road condition such as lateral slope and unevenness and external disturbances such as cross wind. Consequently, each trailer in a combination might experience a small lateral offset from the path of the lead unit, [3].

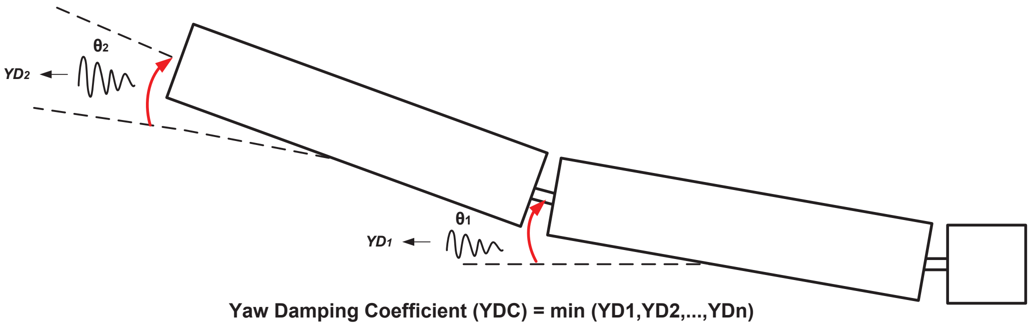

Figure 3.5: Illustration of calculating yaw damping coefficient for an articulated combination

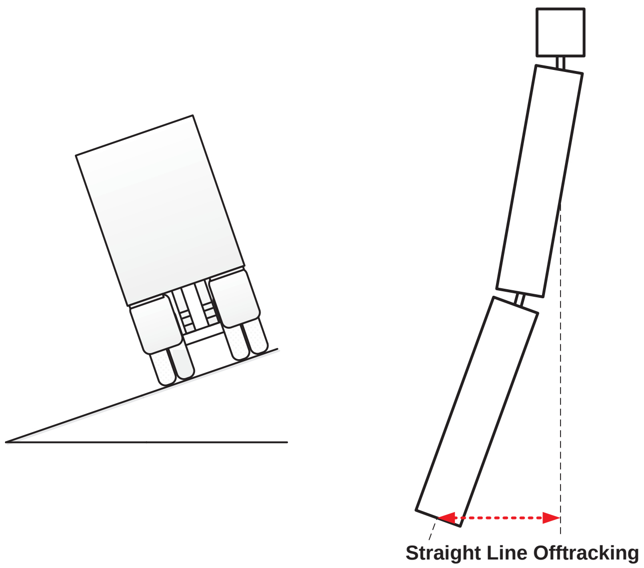

Figure 3.6: Illustration of straight line offtracking on a banked road from backside and upper view

Definition 3.7 (Straight line Offtracking): *Straight line offtracking is defined as the maximum offtracking between the paths of the center of the front axle and the center of the most severely offtracking axle of any unit while traveling straight on a banked road with a certain lateral slope at a certain friction level.*

The purpose of this characteristic is to improve road safety by ensuring that a vehicle remains within its traffic lane when traveling at high speed on straight banked roads.

3.8 Deceleration Capability in a Turn (DCT)

Deceleration capability in a turn is a measure of LHVs' braking mechanism efficiency. LHVs with a good deceleration capability are able to hold the desired path and have a stable directional behavior during braking.

Definition 3.8 (Deceleration capability in a turn): *Deceleration capability during turning is defined as the maximum deceleration rate that makes a vehicle combination capable to stay inside a certain curve lane during full braking (pedal braking or automatic braking) at a certain friction level.*

The main purpose of measuring braking efficiency and evaluating its performance in a turn is to characterize the quality of the vehicle combination's braking system as the primary accident avoidance mechanism in turning manoeuvres.

3.9 Lateral Clearance Time (LCT)

Longer combinations require more time to clear intersections, crossings, lane changes and etc than shorter length combinations which might cause congestion and delays in the road traffic flow. Lateral clearance time, shown in Figure 3.7, is highly dependent on the length of LHVs and reflects LHVs' capability to clear intersection, rail crossing and etc in an adequate time.

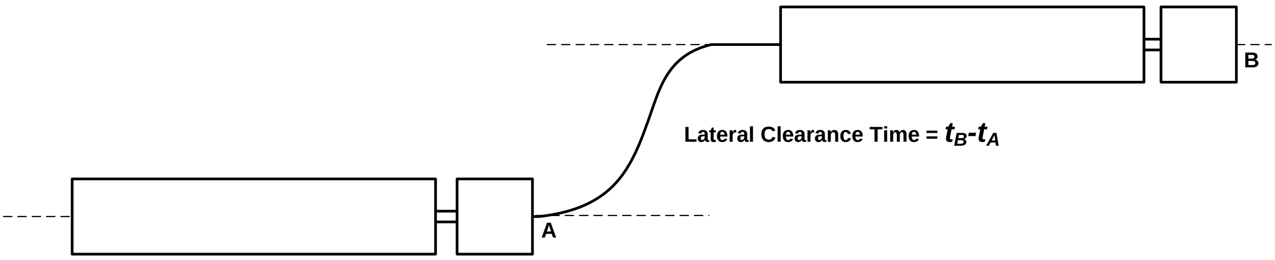

Figure 3.7: Illustration of lateral clearance time

Definition 3.9 (Lateral clearance time): *Lateral clearance time is defined as the time taken by a combination to clear a certain lateral distance and to have the paths of the center of the front axle and the center of all units in the same line at a certain friction level and a certain constant longitudinal speed.*

The primary purpose of introducing this characteristics is to improve road safety and traffic flow by requiring acceptable lateral clearance time for LHVs. Satisfying this characteristics increases the safety level during a fast multiple lane changes especially during a heavy traffic situation.

Bibliography

[1] A. Germanchev, L. Bruzsa, Hybrid Testing Method to Prove the Compliance of Heavy Vehicles, 9th International Symposium on Heavy Vehicle Weights and Dimensions (2006).

[2] J. Edgar, H. Prem, F. Calvert, Applying Performance Standards to the Australian Heavy Vehicle Fleet, 7th International Symposium on Heavy Vehicle Weights and Dimensions (2002).

[3] Performance Based Standards Scheme, the Standards and Vehicle Assessment Rules, Tech. rep., Australian National Transport Commission (2008).

[4] H. Prem, E. Ramsay, J. McLean, B. Pearson, J. de Pont, J. Woodrooffe, D. Yeo, Report on Initial Selection of Potential Performance Measures, NATIONAL ROAD TRANSPORT COMMISSION (2001).

[5] J. F. Junior, Simulating and Correlation of Vehicle Startability on Grade Maneuvers, SAE International (2010).

[6] K. Sharp, H. Prem, Report on Workshops on Performance Based Standards, NRTC Austroads Project A3 and A4, Tech. rep., ARRB Transport Research Ltd (2001).

[7] M. Haldane, J. Bunker, Assessing the Impacts of Multi Combination Vehicles on Traffic Operations and Safety, A Literature Review, Gueensland Government, Department of Main Road.

[8] S. Kharrazi, Seering based lateral performance control of long heavy vehicle combinations, Ph.D. thesis, Depatrment of Applied Mechanics, Chalmers University of Technology YEAR = 2012,.

Appendices