THE ARTSA-i HEAVY VEHICLE BRAKE CALCULATOR

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Abstract

The ARTSA-Institute (ARTSA-i) brake calculator was developed to provide a sophisticated yet easy to configure web application that vehicle technicians, engineers and regulators can use to design and check heavy vehicle, service, emergency and parking brake systems. The calculator predicts wheel lock-up during braking using a novel tyre-road friction model that can be set for different road surfaces. The mass transfer between vehicles, axle groups and within each axle group is included in the model. Thereby designs that have good brake balance and are likely to make minimal call on antilock brake intervention can be found. The tyres, foundation brakes at each axle, pneumatic control system, suspension reaction and road tyre friction can be set by the user. Outputs are primarily in graphical format as a function of brake control level. The calculator can be applied to design-rule, modification code, PBS or in-service brake performance checks.

Keywords: Heavy-vehicle brakes, brake calculations, tyre lock-up, wheel lock-up, truck safety, brake rules, truck stopping distance, truck emergency braking.

1. Overview

The ARTSA-i brake calculator allows the user to calculate the deceleration, adhesion utilization and stopping distance resulting from the service (foot) brake, the emergency brake system and parking brakes for the following types of heavy combination vehicles:

- ➢ Prime mover + Semitrailer.
- ➢ Rigid truck + two-axle (dog[1]) trailer.
- ➢ Prime mover + B-double trailer set.

Additionally, the following sub-category vehicles can be modelled:

- ➢ Semitrailer only (with the towing vehicle set to zero).
- ➢ Rigid truck only (with the trailer set to zero).
- ➢ Two-axle (dog) trailer only with rigid truck set to zero.
- ➢ Centre-axle trailer only (which is a Semitrailer with the axle group generally in the centre).

In this paper:

- ▪ 'Vehicle' or 'combination' means the total vehicle comprised of all the vehicle parts.
- ▪ 'Vehicle part' means either the motive vehicle or one of the trailers.
- ▪ Truck means the motive vehicle, which is the front vehicle.
- ▪ Axle group means 1 – 5 axles in a group. Dynamic mass is allocated to the axle group and then shared between the axles.

The purpose of the calculator project is to provide a calculator that allows Australian heavy vehicle engineers and regulators to assess compliance with brake rules, and to better understand how brake balance can be achieved. The calculator can be applied for design-rule, modification code, PBS, in-service performance checks or accident reconstruction tasks.

The calculator computes the deceleration at each of twenty brake control levels. The brake control level is static, that is, assume held. For a pneumatic brake control system the control pressure level spacings are 650 kPa/20 = 32.5 kPa apart. 1.0E control level is 650 kPa. This corresponds to the brake pedal on the motive vehicle being held successively at each of the twenty non-zero positions. The pneumatic control system can be modelled by user-specified transfer ratios between the front of the vehicle part and each axle, or to the rear brake coupling. Therefore, the brake actuation level at the foundation brake can be different to the brake control level.

Figure 1 shows the vehicle selection screen. The first step in creating a new model is to select the vehicle type. Registered users can store models and recall them. The stored models for the user will be listed on this first page and can be recalled. In Figure 1, 'Test ERC' is a model

[1]In Australia a 'dog-trailer' means a trailer with a front axle group and a rear axle group. It has an A-type coupling that does not impose mass on the towing vehicle. The front axle group can be on a separate 'dolly' trailer; however, the front axle group is part of the dog trailer for calculation purposes.

that was created and stored after selecting the ‘Semi-Trailer Only’ model. Stored models can be copied and modified.

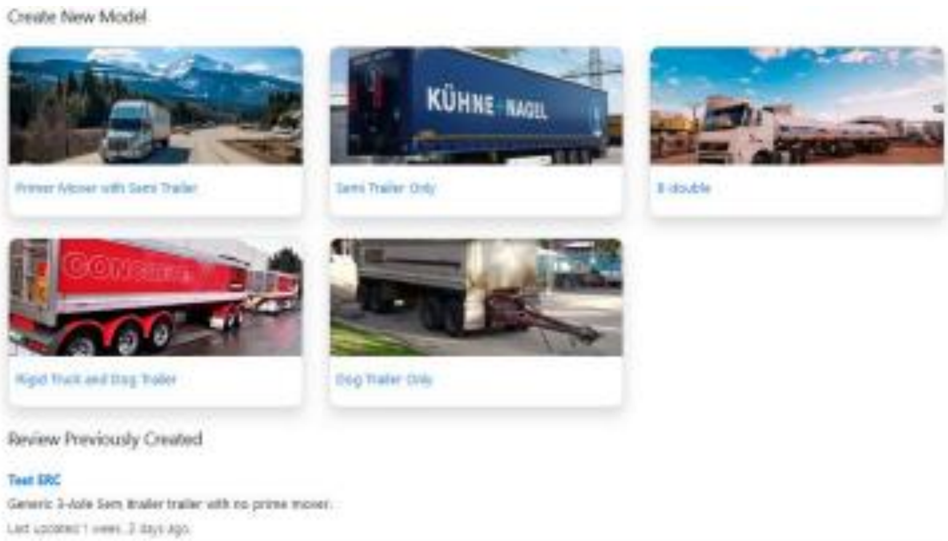

Figure 1 - Vehicle types that can be modelled.

The calculator is applicable to vehicles that have compressed-air braking systems or fully electric brakes. It is assumed that the brakes on each end of an axle have identical characteristics and that the retardation torque produced by each brake is linearly proportional to the brake actuation level (the air pressure in the brake actuator) that the brake experiences. Each axle group on a vehicle can have 5 axles or less.

The deceleration of the vehicle for both the laden and unladen conditions are calculated simultaneously and displayed on the output graphs. For each of 20 service brake control levels the primary outputs are:

- The deceleration **z** of the vehicle as a function.
- The adhesion utilization of each vehicle part.
- The adhesion utilization $\mathbf{N}_i$ of each axle.
- The mass distribution $\mathbf{M}_i$ of each axle.
- The lock-up status of each axle.
- The estimated stopping distance.

Additionally the calculator reports:

- The threshold air pressure at each axle.
- The emergency brake performance.
- The parking brake performance.

The outputs are displayed graphically. Examples are given in Figures 2, 3 and 4 below.

Most heavy vehicles have an intelligent brake system that provides antilock, brake distribution and vehicle stability functions. Despite this, it is advisable to design the service brake system to have good brake balance so that the dependence on the intelligent brake system is minimised. Furthermore, intelligent brake systems do not control emergency brakes. Emergency brake performance can be calculated.

A satisfactory heavy-vehicle brake system design should:

1. Have as high as practical brake control level for onset of wheel lock-up.
2. Produce vehicle deceleration above statutory minimum levels.
3. Produce approximately balanced braking during severe braking so the vehicle stays straight.
4. Have similar threshold pressure levels for all brakes so brake wear is balanced.
5. Have park brakes that hold the vehicle on the prescribed slope.
6. Have emergency brakes that tend to pull from the back to keep the vehicle straight.
7. Have fast signalling to the rear vehicle parts.

The calculator provides information that the user can use to check performance of each of these elements. The brake control level at which wheel lock-up occurs is a key indicator because a locked tyre provides minimal side force. Side force is essential for stable straight line braking. Therefore a wheel-lock-up model is a fundamental feature of a useful calculator. The ARTSA-i calculator has a wheel lock-up model that is described in Section 4. The average deceleration that can be achieved without wheel lock up is reported. The higher this deceleration the better, as this defines the safe stopping distance. The onset of wheel lock-up defines the safe deceleration level, which is used to assess compliance with statutory levels.

Figure 2 shows deceleration graphs for a particular prime-mover and semi-trailer combination. No wheel lock-up occurred as the lines are straight. Results for both laden and unladen vehicles are shown. The brake on this vehicle has zero ‘threshold control level’, so the curves start from the origin.

Figure 3 shows the vehicle adhesion and deceleration curves for a B-double combination. The adhesion utilization concept is explained in Section 3. Suffice to say hear, it is a measure of the extent to which each axle, axle group and vehicle part retards the mass it carries. In the example shown in Figure 3, the curves start from 0.05E (33kPa) which is the specified threshold control level. The unladen vehicle parts exhibit gross wheel lock-up behaviour for brake control levels above 0.35E (227 kPa). The unladen deceleration curve flattens out because many wheels are locked and further brake application level is inconsequential. The wheel lock-up model that is used will be explained in Section 4. Suffice to say here that the mass-transfer model and the wheel lock-up model are essential features of the calculation process (see Section 5).

All the dotted red limit lines on the graphs signify vehicle deceleration performance limits in the Australian brake design rules ADRs 35/06 (2018) and 38/* (see Figures 1 & 2). These limit lines are based upon Diagram 3 in UN ECE Regulation 13, V10. The Australian rules require fully laden vehicle parts to have decelerations between the lower limit and the middle limit lines. The rules require unladen vehicles with variable proportional brake systems (i.e.

with load proportioning valves) to have curves that are lower than the upper red dotted curve. The intention of this requirement is to achieve a degree of compatibility brake balance (see Section 3).

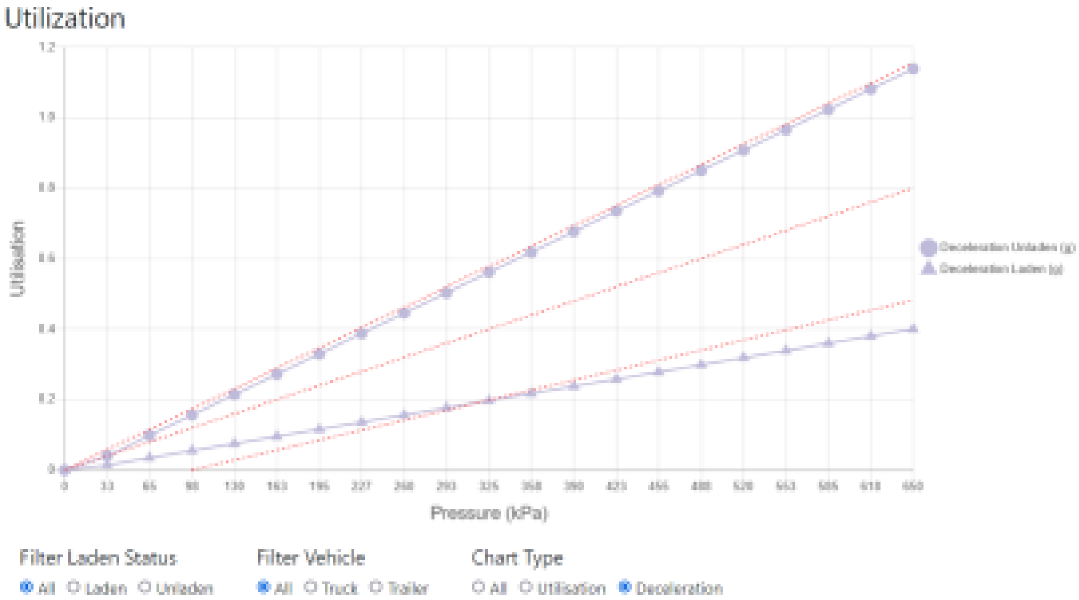

Figure 2 - Vehicle deceleration v control pressure graph for a semi-trailer combination

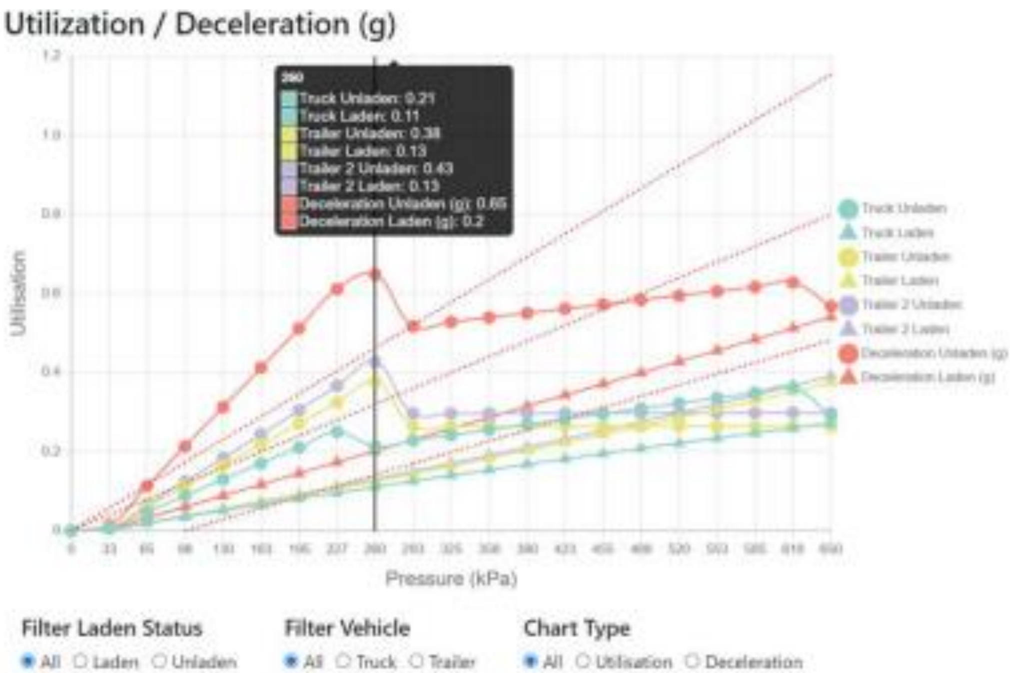

Figure 3 - Axle adhesion utilization v control pressure performance for a B-double combination.

The stopping distance for each <u>brake control level</u> is computed using the calculated deceleration for each <u>brake control level</u>. This calculation takes account of time delays specified by the user that occur when the service brake is first applied. The brake control level is kept constant during the entire stop because the calculator operates in the brake control level domain and not the time domain.. This calculation uses a single pressure build-up time delay that is calculated as an average of the individual vehicle 'pressure time delay' values that the user enters for each axle group. Additionally the user can specify a 'driver time delay' in applying the brakes. This provision may be useful for crash reconstruction calculations. An example of a stopping distance graph is shown in Figure 4. The effect of wheel lock-up for the unladen vehicle can be identified. Beyond the cursor at 0.4 (260 kPa), increases in brake control level results in increased stopping distance due to loss of adhesion due to wheel lock up.

Figure 5 illustrates the 'brake specification panel'. In this case the brakes on a 'dog trailer' with two axles in the rear group are specified. The front axle brake selection is Australian trailer brake approval 31666. The second axle has been specified to have no brakes, but it carries mass. The specified foundation brake torque is applicable at 1.0E brake application pressure. The parking brake and emergency brake torque for that axle, can be specified based upon manufacturer data for spring-brake performance and are likely to be about half the service brake torque. The threshold pressure is the brake application air pressure needed for the service brake to start to operate. Tyre radius is specifiable. The user can changes any of the values.

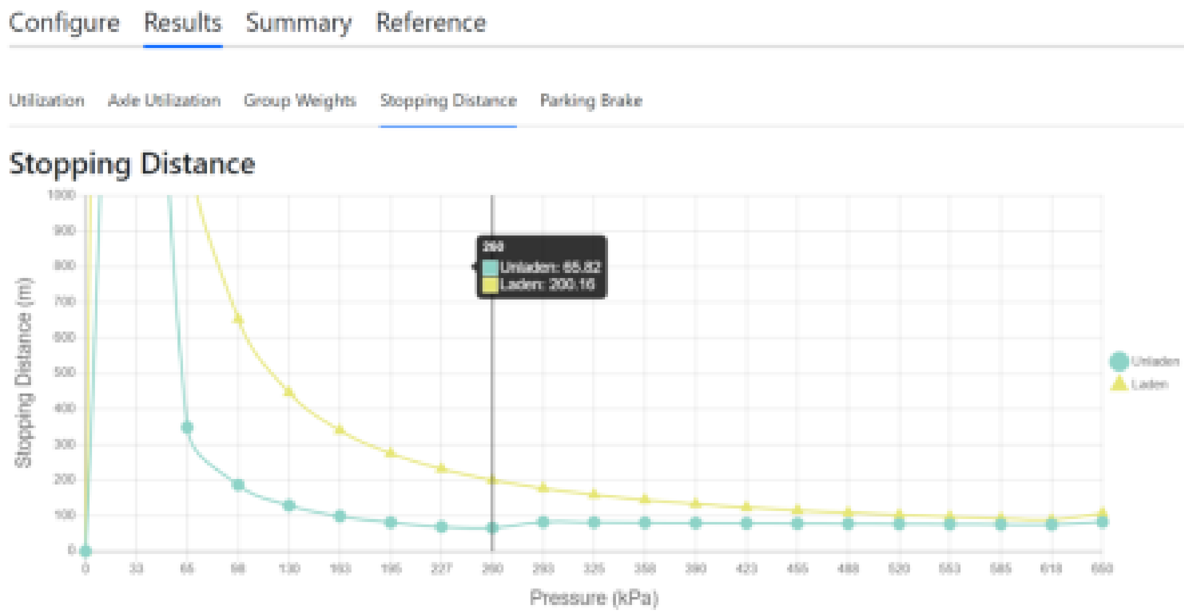

Figure 4 - Stopping distance v control pressure performance graph.

The brake torque is characterised by a single valve at 1.0E brake control level. The brake torque at other control pressure levels is proportioned assuming a linear relationship. This approach is needed because the Australian trailer axle approvals are characterised by a single torque number.

ARTSA-i has produced instructional training videos and a detailed manual to assist users to learn about the calculator.

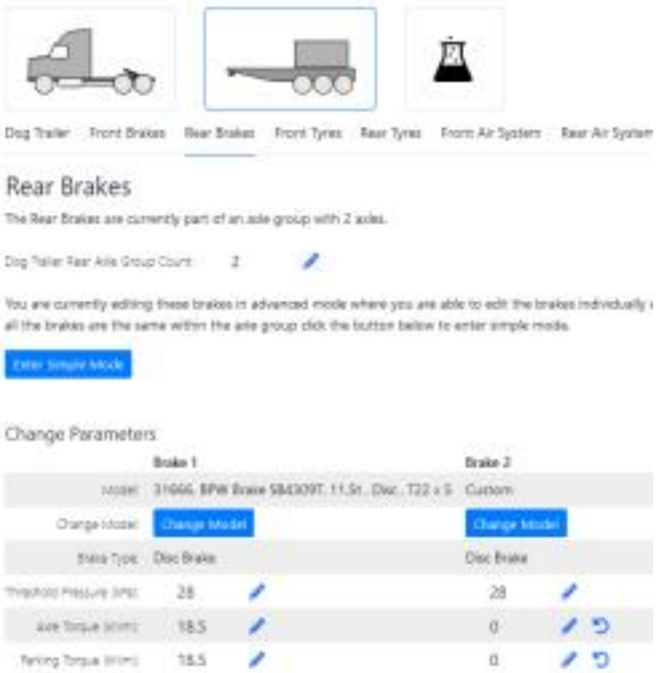

Figure 5 - Example of the brake parameter specification panel for a particular rear axle group of a particular dog-trailer.

2. The Motivation for the ARTSA-i Calculator

Brake calculations are routinely done for new trailer brake certification in Australia. The need arises because Australian trailer rule ADR 38/05 (2018) allows new trailer service and parking brake systems to be certified by approved calculations based upon the brake performance levels stated for approved brake sub-assemblies. In contrast there is no 'calculation path' for motive trucks in the Australian truck rule ADR 35/06 (2018). New truck models must have brakes certified by approved tests. No calculations need to be submitted. Consequently, vehicle engineers who work with trailers tend to have better knowledge of individual axle brakes, suspension and brake control system performance (the Australian brake sub-system categories) than do vehicle engineers who work with motive trucks only, because the former must calculate performance.

The usual path to new trailer brake homologation submissions is via 'approved calculations'. There is public controversy about the accuracy of the procedures that exist - see Hart (2023). The Federal regulator has a test example that it requires trailer calculators to satisfy. Before a trailer brake calculation can be accepted, the calculator must be successfully applied to the test example. The process is not transparent and pass/fail criteria are not published. It is unclear how wheel lock-up should be predicted because most calculators do not account for mass transfer between axles due to braking. No other Australian calculator has a wheel lock up model. Therefore, axle adhesion utilization cannot be accurately calculated.

Whilst the discussion so far has concerned the brake certification of new trailers, motive truck brake systems are sometimes modified either by addition of an axle or change of foundation brake type or set-up. There is no calculation path defined in the Australian modification code, which is Vehicle Standards Bulletin No.6 ("VSB 6"), code G3 for motive vehicles and code G4 for trailers. As written, VSB 6 requires a demonstration of compliance with the applicable Australian Design Rule 35/* and 38/* respectively. This is problematic because physical brake testing is onerous and trailer brake calculations are controversial. The ARTSA-i brake calculator is intended to provide a facility that vehicle modifiers can use to investigate the compliance of the vehicle with design rules. In time ARTSA-i hopes that the regulators will accept brake calculations to justify modified trucks and trailer brake systems.

In the mid -1990s I became aware that New Zealand had introduced a Heavy-vehicle brake specification that was applicable to some high-mass (combination) heavy-vehicles. Because the NZ brake specification was applicable to individual vehicles, proof of compliance was based upon approved brake calculations. The New Zealand authority issued a brake calculator that it required New Zealand heavy vehicle certifiers to use. The brake systems on some North American trucks had to be changed to meet the New Zealand requirements. The problems was with the distribution brake balance on the trucks.

The calculator works for both single vehicles and for some combinations. This provides a tool that vehicle engineers can use to investigate the braking performance of combination vehicles. The Australian Performance Based Standards ("PBS") scheme has a braking standard, which is 'Directional Stability Under Braking'. To maintain directional control a heavy vehicle should exhibit minimal wheel lock-up under heavy braking. The standard has a performance path, which requires demonstration that the (combination) vehicle does not exhibit "gross wheel lock-up" during a severe braking event for which the vehicle stopping distance is no more than twice the theoretical minimum stopping distance on a dry sealed road. The rule also has a 'deemed to comply path' via which the rule is satisfied using an intelligent brake control with prescribed features, such as Antilock and Electronic Brake Distribution, without further justification. If the 'deemed to comply path' is followed (which is usual), no tests or calculations are required. However, a well set-up service brake system will make minimal call on the intelligent brake system intervention, because the vehicle will make good use of the available road-tyre friction. Therefore, the brake calculator should be useful for identifying acceptable brake set-ups on combination vehicles.

3. Definition of Brake Balance

Perfect brake balance occurs when the brakes on each axle produce a retardation force F that satisfies Newton's second law:

$\mathbf{F = M.\ z.\ g}$ (1) where M is the mass on the axle, z is the normalised vehicle deceleration and $g = 9.8061$ m/s^2.

A vehicle with perfect brake balance can use all the available tyre-road friction and will achieve a vehicle deceleration equal to the road friction coefficient µ. That is:

$$\mathbf{z} = \boldsymbol{\mu} \quad (2)$$

The extent to which each axle retards the mass it carries determines the brake balance. Brake balance is assessed based upon the axle adhesion utilization values. The adhesion utilization of axle i is

$$\mathbf{Ɲ}_{\mathbf{i}} = \mathbf{F}_{\mathbf{i}}/\mathbf{M}_{\mathbf{i}} \quad (3)$$

In this definition both F_i and M_i and dynamic quantities. A combination vehicle with perfect brake balance has the same axle adhesion utilization at each brake control level. Prefect brake balance is impossible to achieve because the mass M changes during the brake event due to load transfer under deceleration. Furthermore, retardation force F changes as the brake heats up, but is otherwise not directly dependent on deceleration.

Brake balance has two aspects, which are distribution brake balance and combination brake balance. Distribution brake balance pertains to the range of axle utilization values on each vehicle part. Combination brake balance pertains to the range of utilization values of each vehicle part. In this context vehicle adhesion utilization is the total retardation force of all the vehicle axles divided by the total mass carried by the vehicle axles. The adhesion utilization values change with the severity of the braking event because mass transfers between axle groups depending upon deceleration level. The ARTSA-i brake calculator graphs both axle and vehicle- adhesion utilization as a function of brake control level. The user can assess the extent of both distribution and combination brake balance. The consequence of poor brake balance is wheel lock-up at low brake control levels. This is obvious on the calculator output graphs because deviations show when wheel lock-up is occurring. Safe braking requires good brake balance.

The ARTSA-i calculator allows the user to specify the brake retardation torque produced by each axle at 20 brake control levels in the range 0 – 1.0E where E = 650 kPa control level on vehicle part 1. The retardation torque is characterised by a single value at 1.0E. The user can base this value on manufacturer's data, statutory approval data or arbitrarily specify the value. The calculator also has generic brake torque values that are automatically entered at start-up so that the user can make quick progress. All settings can later be altered and the calculator will respond instantaneously. Because the user can specify the brake torque axle-by-axle, each axle can have a different brake set-up. The emergency brake performance can also be studied by specifying the emergency brake (spring-brake) torque level on axles that have spring brakes. The emergency (spring) brake retardation is not dependent on the air control system and the ARTSA-i calculator treats spring brakes separately from service brakes. The wheel lock-up model is applied to both service and emergency (spring) brakes.

4. The Wheel Lock-Up Model

The tyre slip characteristic is assumed to be the same each tyre. The road friction is specified by the user. Typical values are 0.7 for a truck tyre on a dry road, 0.4 for a truck tyre on a wet road and 0.25 for a truck tyre on a loose surface gravel road. Peak axle retardation occurs when the axle adhesion utilization Ɲi equals the available tyre-road friction:

Ɲi = µ (4)

If the axle adhesion utilization Ɲi > µ then the wheels on the axle are predicted to lock up. The retardation force that the brake can generate because the calculated force cannot be applied to the road as the tyres will slip. The retardation force used in the calculator must be reduced so that the axle adhesion utilization is less that the lock-up value µ**.** The previously calculated retardation force for which Ɲi ≤ µ is used as the basis for a force correction. The locked-axle force is constant. The corrected retardation force, which is illustrated in Figure 6, for all higher brake control levels that are predicted to cause wheel lock-up is constant and is calculated as follows:

Retardation Force Axle i = Factor x max. retardation force with Ɲi ≤ µ (5)

The default value of Factor = 0.7. The user can change this value and the friction value µ in 'Settings'. By using a substantial value of Factor, the onset of wheel lock-up in an axle group becomes obvious on the utilization graphs (see for example Figure 3).

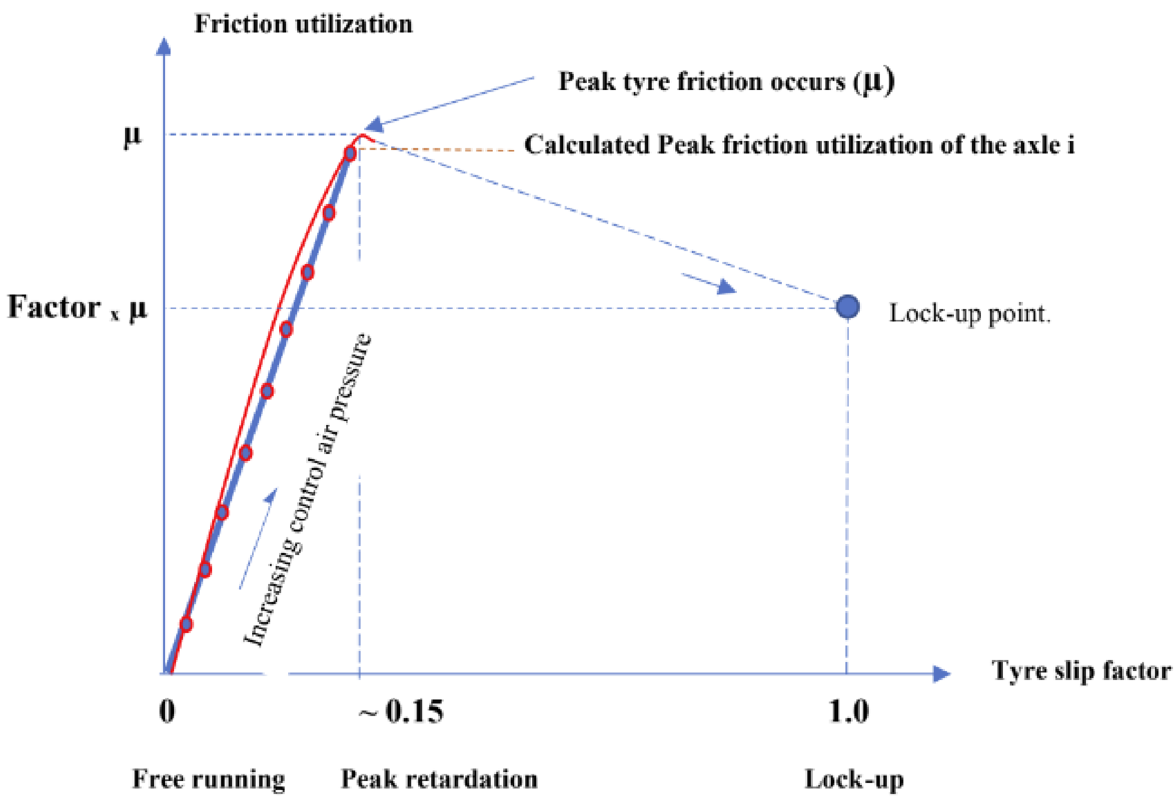

Figure 6 - Wheel lock-up model characteristic.

Because the adhesion utilization is only known at the calculation control levels, the peak tyre adhesion utilization is based upon the peak friction utilization that does not exceed µ. This may slightly under-estimate the peak point of the tyre friction curve (see Figure 6).

The user must specify the payload and the centre-of-mass height for each vehicle part. The calculator allocates the static mass of each vehicle part to the axle group(s) and to the kingpin for semi-trailer type vehicles. The dynamic weight distribution is different to the static mass distribution because load transfers forward during braking. The dynamic load transfer is proportional to deceleration and centre-of-mass height above the axle hub level. The calculation is based upon basic physical principles, but needs to iterated because wheel lock up reduces the road friction that can be used, which in turn reduces the deceleration that can be achieved, which consequently affects the mass transferred forward during braking. The process is described below.

5. Calculation Process

Because wheel lock-up depends upon axle weight and hence deceleration, the calculation procedure must be iterated. Th e calculator implements the following process:

a) The application pressure at each axle is calculated for each of the twenty control air pressure levels.

b) Assuming no wheel lock-up occurs, the brake torque on each axle and then the retardation force on each axle is calculated. An estimate of the vehicle deceleration is obtained. At this stage it is assumed that no tyres have locked up. (‘**first deceleration estimate**’)

c) The weight distribution on each axle is calculated for the first estimate of the vehicle deceleration (obtained from step b). (‘**first axle mass estimates’**).

d) The adhesion utilization for each axle **Ni** is calculated using the first deceleration and axle mass estimates.

e) If the adhesion utilization of tyres on an axle exceeds the available road friction, **Ni** > **μ**, then the retardation force for that axle is reduced according to the wheel lock-up model, as stated in Equation (5).

f) Because the axle retardation forces may have changed due to step e., a new estimate of vehicle deceleration must be obtained. (‘**second deceleration estimate**’). g) The weight distribution on the axles is recalculated using the second deceleration estimate. (‘second axle weights estimate’).

h) The friction utilization of each axle is recalculated using the forces from step e), and the mass estimates for each axle from step g).

i) Using the revised adhesion utilization values for each axle, a new assessment of whether the wheels on an axle have locked-up is made.

j) The axle retardation forces are recalculated using the new assessments of wheel lock up. That is, the wheel lock-up model is reapplied.

k) Because the axle retardation forces may have changed due to step j), a new estimate of vehicle deceleration is obtained. (‘**third deceleration estimate’**).

l) The weight distribution on the axles is recalculated using the third deceleration estimate. (‘**third axle weights estimate’**).

m) The adhesion utilization of each axle is recalculated using the forces from step k) and the weight estimates of step l).

n) The calculation ceases when the third (and final) estimate of deceleration is obtained for each of the twenty control pressure levels.

o) The graphs are created for axle service brake adhesion utilization as a function of the brake control level.
p) The stopping distance can then be calculated, taking account of user specified time delays.

7. Novel Features

The ARTSA-i brake calculator differs from many other brake calculators because:

1. It has an easy to use interface that allows a complex vehicle to be specified in minutes. Generic vehicle set-ups can be chosen to make a ‘quick start’. The specification can be easily altered.
2. It calculates the mass on each axle group during braking and uses this information to predict tyre lock-up model.
3. It distributes the mass within an brake-reactive axle group during braking according to a user-specified (linear) distribution.
4. It contains a drum brake discount that predicts heating up of the drum brake on the laden vehicle and reduces the torque available from the drum brake as a function of deceleration. This discount does not apply to a disk brake.
5. The air system characterises can be specified between the brake control location and each brake group. Therefore, non-unity transfers between the front brake coupling and the rear brake coupling can be modelled.
6. The user can alter the brake set-up of the service or parking brakes by calculating an amended value for the torque values.
7. The user can specify a trailer brake valve characteristic for the through air-path.
8. It can be used to predict brake performance of modified vehicles, which is not otherwise available in Australia.

8. Acknowledgment

ARTSA-i gratefully acknowledges that the brake calculator project is funded by the National Heavy Vehicle Regulator’s (NHVR) Heavy Vehicle Safety Initiative (HVSI), supported by the Australian Government.

9. References

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