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PERFORMANCE BASED STANDARDS ASSESSMENT OF A RIGID URBAN TRANSPORT VEHICLE

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1 Introduction

Vehicle access to road networks is regulated to ensure safe operation and minimisation of wear to infrastructure. A recent survey of vehicle regulatory practices within OECD[1] countries identified that the regulation of heavy vehicles is almost exclusively achieved by prescriptive standards that define the physical characteristics of allowable vehicles – e.g. height, width and axle loads [1]. The prescriptive standard mode of regulation provides an uncomplicated and unambiguous reference for identifying compliant vehicles, however, the link between prescriptive standards and on-road performance is indirect [2][3], and prescriptive standards have been found to be an inadequate predictor for [1]:

- Swept path variation;
- Dynamic stability in hilly terrain;
- Disparate bridge protection requirements; and,
- Dynamic stability during emergency maneuvers.

To overcome the limitations of prescriptive standards, it is has been proposed that vehicle compliance be assessed by an alternate mode of vehicle regulation, i.e. Performance Based Standards (PBS). The fundamental attribute of PBS is that the required on-road performance is specified, without direct reference to how this performance is achieved. The complexity associated with assessing PBS compliance is greater that that associated with a prescriptive standard, however, it is hypothesised that PBS would provide [3]:

- More consistent regulatory outcomes; and,
- Scope for enhanced vehicle productivity by allowing the certification of innovative vehicles.

Australian vehicles are typically regulated by a series of prescriptive constraints, for example [4]. Local government may allow non-compliant vehicles restricted access to the road network if they can be shown to match the existing infrastructure [5][2]. A series of PBS for vehicle compliance are currently in development, based on approximately potential 100 performance measures that have been assessed and refined over a five-year period [3]. The proposed PBS attempt to define appropriate on-road performance for vehicles by a series of distinct performance measures and associated performance levels required for certification [1][2][3].

[1] OECD: Organisation for Economic Cooperation and Development.

The Australian domestic mail delivery service (Australia Post) estimate that the demand for urban mail transport will double within the next two decades. In response to this predicted increase, Australia Post formed a consortium with a road transport advocacy group, the Australian Road Transport Suppliers Association (ARTSA), to investigate opportunities of increasing the payload efficiency of rigid, i.e. non-articulated, urban transport vehicles within the pending PBS regulatory framework. The objectives of this work are to:

1. Review the proposed PBS;
2. Generate a series of vehicle concepts based on the available literature, and discussion with Australia Post;
3. Identify the PBS performance levels of particular importance to the proposed concepts, i.e. the governing PBS requirements;
4. Provide a means of predicting the performance of the concept vehicles according to the governing requirements.
5. Based on the project requirements, and their associated importance, identify the optimal vehicle for the proposed role.

1.1 PBS review

The proposed Australian PBS for vehicle compliance consists of a series of performance standards and measures, and an associated performance limit (Table 1). The performance limit identifies the acceptable range of performance for access to a series of road types, each with a generalised level of access to the road network:

- Level 1 – Unrestricted access;
- Level 2 – Significant freight route;
- Level 3 – Major freight route; and,
- Level 4 – Remote area access.

1.2 Concepts vehicles

A series of meetings were convened with members of Australia Post and ARTSA in order to further understand the design requirements associated with the project, and their associated importance:

- The associated capital costs should be minimised, importance = 2;
- The technical feasibility should be maximised, importance = 2; and,
- The resultant increase in payload efficiency should be maximised, importance = 4.

A series of concepts were suggested by Australia Post, including:

- An extended rigid vehicle, i.e. maximise the length of a typical delivery vehicle within the PBS framework.
- Self-steering lazy rear axle. The rearmost axle of the rear axle group is allowed to rotate, thereby a providing load bearing function without influencing the low speed tracking.

Table 1. Proposed PBS for vehicle compliance on the Australian road network [3]. Prescriptive requirements and standards under development not shown.

Performance Standard	Performance Measure	Level 1	Level 2	Level 3	Level 4
Startability	Ability to commence forward motion on specified grade (%).	≥ 15%	≥ 12%	≥ 10%	≥ 5%
Gradeability	Ability to maintain forward motion on specified grade (%).	≥ 20%	≥ 15%	≥ 12%	≥ 8%
	Minimum speed on 1% grade.	80 km/h	70 km/h	70 km/h	60 km/h
Acceleration	Ability to accelerate either from rest or to increase speed on a road (no grade).	Acceleration no worse than specified distance / time curves.			
Overtaking time	Time for a car to safely overtake the PBS vehicle at the specified (LoS).	LoS C	LoS C	LoS B	LoS B
Tracking ability on a Straight Path (TASP)	The swept width while traveling on a straight path.	≤ 2.9m	≤ 3.0m	≤ 3.1 m	≤ 3.3m
Low Speed Swept Path	The maximum width of the swept path in a prescribed 90 degree low speed turn.	≤ 7.4m	≤ 8.7m	≤ 10.1m	≤ 13.7m
Frontal Swing	The maximum lateral displacement in a between the path of the front outside corner of the vehicle and: (a) The outer edge of the front-outside wheel of the hauling unit or motive vehicle; (b) The outside part of a semi-trailer during a small radius turn at low speed.	Part (a) For trucks and prime movers no greater than 0.7m For buses no greater than 1.5m Part (b) No greater than 0.40 m Trailer value not to exceed prime mover value by more than 0.20m.			
Tail Swing	The maximum lateral distance that the outer rearmost point on a vehicle unit moves outwards in, perpendicular to its initial and final orientation, when the vehicle commences and completes a prescribed low-speed turn.	Not greater than 0.30m	Not greater than 0.35m	Not greater than 0.35m	Not greater than 0.50m
Steer Tyre Friction Demand.	The maximum friction level demanded of the steer tyres of the hauling unit in a prescribed low speed turn.	Not more than 80% of the maximum available tyre/road friction limit.			
Static Rollover Threshold (SRT).	The steady-state level of lateral acceleration that a vehicle can sustain during turning without rolling over.	Road tankers hauling dangerous goods in bulk and buses – no less than 0.40g All other vehicles – no less than 0.35g			
Rearward Amplification (RA).	Degree to which the trailing unit(s) amplify or exaggerate lateral motions of the hauling unit.	Rearward amplification no greater than 5.7 times the SRT of the rearmost roll–coupled unit taking account of the stability of the roll coupling			
High Speed Transient Offtracking (HSTO)	The lateral distance the last-axle on the trailer tracks outside the path of the steer axle in a sudden evasive maneuver.	≤0.6 m.	≤0.8 m.	≤1.0 m.	≤1.2 m.
Yaw Damping Coefficient.	The rate at which 'sway' or yaw oscillations decay after a steer input.	No less than 0.15 at the certified vehicle speed.			
Pavement Vertical Load.	Degree to which vertical forces are applied to the pavement.	The road wear shall not exceed the level calculated for an equivalent rigid vehicle.			
Bridge Loading.	The maximum effect on a bridge measured relative to a reference vehicle.	Bending moments and shear forces no greater than for a representative vehicle.			

Review of the available literature identified two additional vehicle concepts with the potential to enhance payload efficiency:

- The movable junction technique allows movement of the kingpin in a direction perpendicular to the longitudinal vehicle axis. This movement allows off tracking to be reduced or eliminated [6], but results in an increased lateral overhang. This technique requires active actuation. The actuation may be a proportional response based on steering input, or a control system based on intelligent analysis of multiple system inputs [7]. The authors are not aware of the practical application of vehicles of this type.
- Rear steer systems allow the rear axle group to articulate in order to minimise the vehicle off-tracking. A disadvantage associated with rear axle articulation is an increase in tail swing [3]. This articulation may be either passive or active. The performance of passive rear steer vehicles has been practically assessed [8].

1.3 Governing PBS requirements

The evaluation requirements were of the PBS were categorised as (Table 2):

- **Power transmission**. This category of evaluation requirements is based on the transmission of the vehicle power to overcome inertial and frictional forces in a range of scenarios. These requirements may be evaluated analytically by reference to established relationships, and empirical estimates of system efficiency [2][9].
- **Static loading.** This category identifies the forces and moments transmitted to the road surface. This may be analytically evaluated from the vehicle morphology and weight distribution [2].
- **Low speed tracking.** This category relates to the interaction of a vehicle with other road users and infrastructure during low speed maneuvers. Low speed maneuvers are nonholonomic, i.e. rolling occurs without slipping, and may be evaluated analytically from the vehicle morphology and steering inputs.
- **High speed tracking.** This category relates to the interaction of a vehicle with other road users and infrastructure during high speed maneuvers. High speed maneuvers are holonomic, i.e. slipping may occur due to inertial effects [9]. High speed tracking may be evaluated by physical testing, or by numeric analysis [3].

The objective of this work is to assess the opportunities for optimising payload efficiency of rigid, urban transport vehicles within the PBS. As Australia Post deliveries are dominantly of low density, the available delivery volume defines the payload efficiency. It was therefore assumed that the mass based evaluation requirements, i.e. power transmission and static loading will not be the governing requirements of this work. Further, it was assumed that high speed tracking would not be the governing requirement, as the high speed tracking of the proposed vehicle was assumed to be at least equivalent to that of currently certified vehicles of greater mass (e.g. vehicles with a high mass payload) and lower rigidity (e.g. articulated vehicles).

These assumptions allowed the concepts performance and optimisation to be based solely on analytic evaluation of the low speed tracking, allowing multiple concepts and associated configurations to be rapidly assessed without the computational overheads associated with numeric analysis or physical testing, i.e. as required for high speed tracking assessment. Once the final proposal was developed, these assumptions were validated by a single numeric analysis [10].

Table 2. Proposed performance standards versus required evaluation requirements

	Evaluation requirements			
Performance Standard	**Power transmission**	**Static Loading**	**Low speed tracking**	**High speed tracking**
Startability	✓			
Gradeability	✓			
Acceleration	✓			
Overtaking time				✓
TASP				✓
Low Speed Swept Path			✓	
Frontal Swing			✓	
Tail Swing			✓	
Steer Tyre Friction Demand		✓		
SRT		✓		
RA				✓
HSTO				✓
Yaw Damping Coefficient				✓
Pavement Vertical Load		✓		
Bridge Loading		✓		

The PBS associated with low speed tracking are: low speed swept path, frontal swing, and tail swing (Table 1).

- Low speed swept path is the maximum distance that a vehicle tracks inside the path taken by the steering axle in a low speed turn, plus the vehicle width (Figure 1).
- Frontal swing is the maximum lateral displacement between the path of the front outside corner of the vehicle and the outer edge of the front-outside steered wheel of the hauling unit (Figure 2).
- Tail swing is the maximum lateral distance that the outer rearmost point on a vehicle moves outwards, perpendicular to its initial orientation, when the vehicle commences a small-radius turn at low speed (Figure 3).

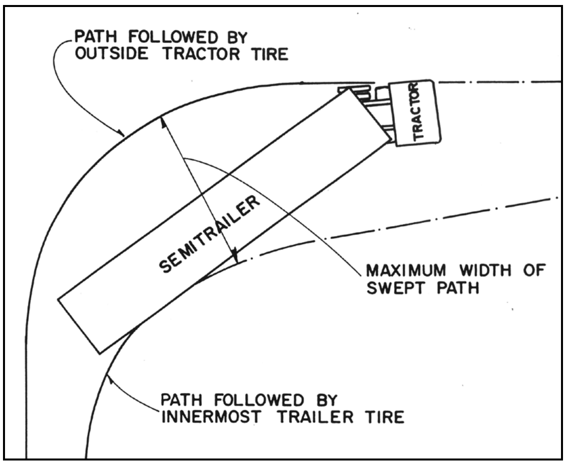

Figure 1: Diagram of swept path, after [3]

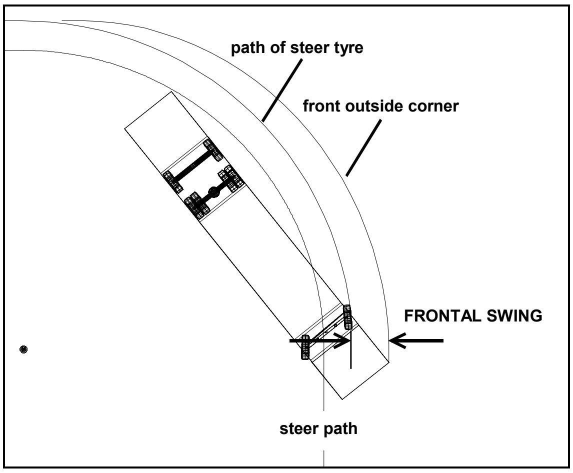

Figure 2: Frontal swing, after [3]

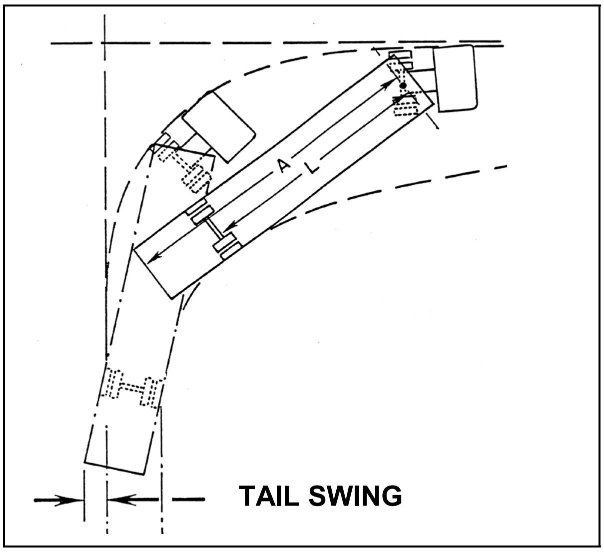

Figure 3: Tail swing, after [3]

The PBS based on low speed tracking are defined according to a prescribed 90º turn [3]. As low speed vehicle tracking is subject to nonholonomic constraints, i.e. rolling occurs without slipping, the low speed tracking may be analytically modelled by reference to the vehicle morphology and the steering input [6][11]. Based on these nonholonomic constraints, the authors developed custom software, *ProPath*, to quantify the low speed tracking behaviour of a range of vehicles and steering input (Figure 4). The accuracy of the proposed software was confirmed against "Swept Path" templates used to define the allowable low speed tracking of Australian vehicles [12].

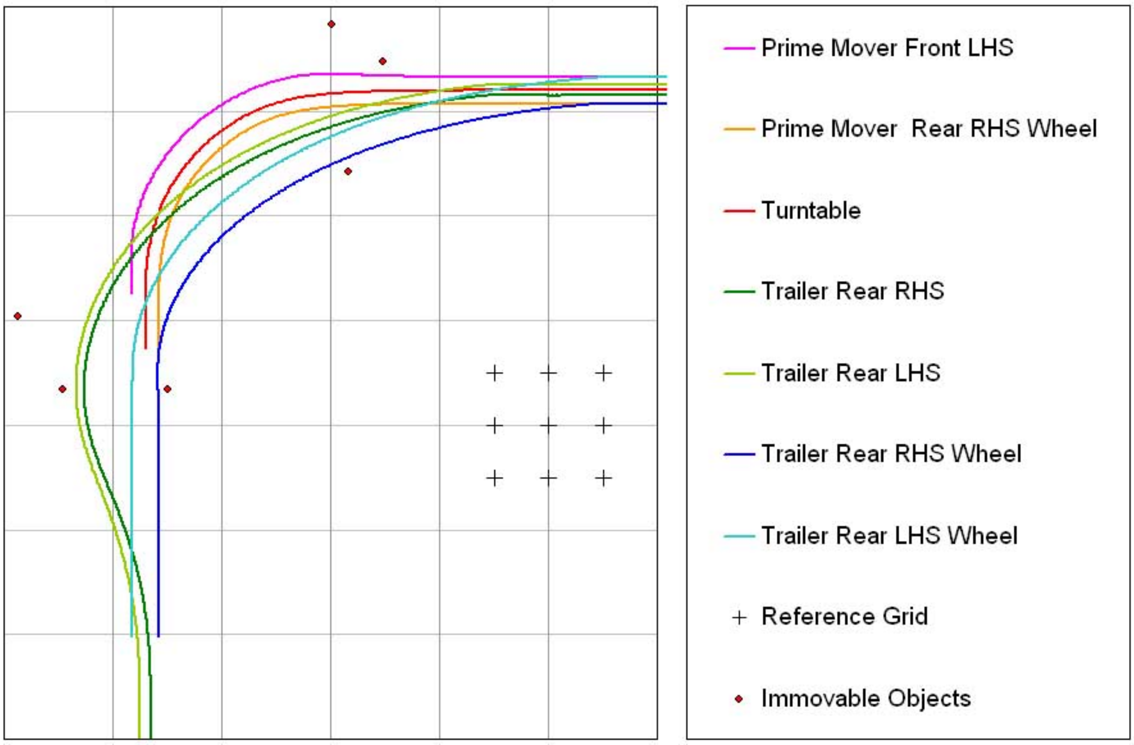

Figure 4. Typical *ProPath* analysis. This scenario indicates the low speed tracking of vehicle with active rear steering.

ProPath is highly flexible in terms of allowable vehicle characteristics and steering input, and allowed rapid evaluation of the feasibility and performance of the proposed vehicles before engaging in more complex and time consuming numeric analyses. Based on these analyses, the achievable payload efficiency of the concept vehicles was defined (Table 3).

2 Results

The payload efficiency, and a subjective evaluation of the other project requirements were incorporated in a decision matrix (Table 3). Based on the outcomes of the decision matrix, both the movable junction concept and the active steer axle have a lower net performance that the existing vehicle. This is due to the high unit cost and low technical feasibility associated with these concepts. Both these concepts have an excellent payload efficiency, and should be reassessed for the proposed role if they can be shown to be technically feasible. The performance of the self-steer lazy axle is equivalent to that of the existing vehicle as it allows an increase in payload efficiency that is partly offset by the increased unit cost. The passive steer rear axle provides a good compromise between payload efficiency and unit cost, but exhibits a low technical feasibility. If the technically feasibility of this concept can be increased it should be reassessed for the proposed role. Based on the current project requirements and their associated importance, the optimal concept for the rigid, urban transport vehicle is the extended rigid.

Table 3. Decision matrix design considerations versus concept vehicles. The performance of the concepts was evaluated relative to the existing vehicle for each of the project requirements.

Project requirements	Importance	Existing vehicle	Extended rigid	Self-steer lazy axle	Movable junction	Passive steer axle	Active steer axle
Unit cost	2	0	-1	-2	-4	-3	-5
Technical feasibility	4	0	0	0	-4	-2	-5
Payload efficiency	4	0	2	2	4	4	5
		0	6	4	-8	2	-10

3 Conclusions

Rigid vehicles may be considered a special case when assessed against the proposed PBS standards for urban operation: their performance is governed by their low speed tracking characteristics. Low speed tracking is subject to nonholonomic constraints that may be evaluated analytically. This simplification allows rapid assessment of the performance and optimisation of proposed rigid vehicles without the complexity or expense associated with numeric analysis or physical testing, i.e. as is required to assess the high speed tracking components of the proposed PBS.

Custom software for assessing low speed tracking has been developed and verified by the authors. This software has been applied to assess the performance of a range of concepts for use as a high productivity, rigid urban transport vehicle.

A decision matrix was applied to assess the net performance of the proposed concepts according to the current project requirements and their associated importance. For the current scenario, the optimal concept for the proposed role is an extended vehicle with a rigid rear axle group.

Based on the relative importance of the associated project requirements, urban transport operators can systematically select the optimal rigid urban transport vehicle for their particular application. For example, the feasibility of potentially highly productive vehicles, e.g. active rear steering, is limited in the current scenario, but would be optimal for a transport operator willing to accept a decrease in the associated technically feasibility.

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