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The Development of Rail Path Modelling

Corridor Capacity Assessment

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Abstract

Transport planners in Australasia have a good understanding of road corridor capacity and associated assessment techniques and have access to a wide range of commercially available, simplified and detailed traffic models. In contrast, access to rail corridor capacity analysis is often difficult and transport planners rely on outputs from detailed operational rail models, provided by a few rail sector specialists.

Strategic multi-modal transport models in Australasia rarely include rail capacity constraints and such models are either unconstrained or only apply train (passenger) crowding functions. It is very difficult for detailed operational models such as OpenTrack to provide the information required for strategic assessments, contributing to an over-reliance on subjective judgements for scenario testing. For this reason, a simplified rail path model and associated techniques to assess rail corridor capacity are demonstrated, with potential applications for strategic transport planning, preliminary scenario assessment and indicative economic appraisal.

1. Introduction

1.1 Purpose

The topic of this paper is simplified rail capacity (hourly train-throughput) analysis for strategic assessment and planning purposes, written from the point of view of a strategic transport planner or multi-modal modeller.

The paper is not aimed at rail engineers or specialist rail modellers, other than to emphasise the need for the rail sector to explain rail capacity issues as clearly as possible to strategic transport planners.

The purpose of the paper is to demonstrate simplified techniques to provide broad estimates of rail corridor capacity.

Although rail demand forecasting is very important, this is relatively well undertaken at present when compared to the application of rail capacity constraints in strategic transport planning and modelling.

Transport planners in Australasia have a good understanding of road corridor capacity (hourly vehicle-throughput), access to associated assessment techniques[1] and to a wide range of commercially available, strategic and detailed capacity constrained traffic models.

[1] Austroads, Table 5.5, 2020

In contrast, the transport planning profession has limited experience of rail corridor capacity analysis and currently relies on externally prepared estimates of capacity derived from detailed operational rail models, operated by a few specialists within the rail sector.

1.2 Scope

This paper addresses transport network (rather than total system) capacity in terms of hourly train-throughput corridor capacity. Capacity constraints associated with (say) rail junctions, stations, or patronage capacity of trains, are excluded from consideration in this paper.

Corridor capacity has been selected mainly for demonstration purposes, but also because, in certain circumstances, this has the potential to be a critical limiting factor within a rail network.

This paper discusses peak capacity along a series of rail corridor links, with reference to NZ conditions and to the Wellington Region.

The Wairarapa and Hutt Valley rail corridor (between Masterton and Wellington) was selected for model demonstration purposes as it has an interesting service mix of express, semi-express, and all-stop passenger rail services.

This paper has been developed from project experience identifying the need for rail capacity assessment techniques, although the future scenario used in this paper for increased service frequencies, is purely illustrative and does not reflect any real-world proposal.

1.3 Need for Simplified Assessment Techniques

This paper argues that strategic assessment techniques, models and traffic data are widely available and easily accessible for road corridor planning, but this is not the case for the analysis of rail corridors. This paper demonstrates one example of a simplified rail path model that, with further adaption and development, could assist in filling this void.

Simplified rail path modelling has the potential to improve the quality of preliminary rail scenario assessment, strategic transport planning and indicative economic appraisal.

Better strategic rail corridor capacity analysis would assist transport planners to:

i) Generate more balanced assessments, plans and programmes.

ii) More effectively engage with the rail sector for multi-modal transport investment planning.

Without simplified rail capacity modelling, detailed operational models are unlikely to satisfactorily provide the information required for preliminary strategic assessment and there is likely to be an over-reliance on subjective judgements when undertaking future scenario comparisons.

Conversely, if corridor capacity limitations are not identified, then strategic transport plans and forward investment programmes are unlikely to include sufficient and appropriate infrastructure investments, preventing the achievement of demand forecasts, mode split targets, emissions reductions and other required outcomes.

Despite current guidance advising; *''The transport network model, or 'supply side' component of a transport model is intended to reflect, as accurately as possible, the actual available transport network, by incorporating the following link attributes: …….as related to the number* *of lanes or available train paths…*[2]" I am unaware of any strategic multi-modal transport model (not a rail model) in Australasia incorporating a pathing based link capacity restraint function for rail. It is true that train-throughput is implicit in the number of trains allowed for in train crowding model functions, but without input from and verification by strategic planners, future train pathing assumptions can be pessimistically low or unrealistically high.

2. CAPACITY

2.1 Capacity Overview

Capacity is absolutely central to all transport planning and without capacity analysis, little would ever get built. Concepts underlying capacity assessment for road and rail corridors have several similarities. For example, both incorporate the concepts of:

i) Desirable design capacity (with headroom for contingencies)

ii) Operational (actual) capacity, from observation.

iii) Maximum theoretical throughput capacity

Hence in reality, for any given transport corridor section, the definition of capacity is dependent on purpose and circumstances rather than being a single fixed absolute figure.

Similarities between road and rail corridor operational performance as throughput approaches capacity include, increased delays, associated decline in levels of service, increased incidence of flow breakdown and reduced operational reliability.

Transport planners, in terms of their training[3] and professional roles, are primarily road traffic focussed, with rail assessment and planning usually considered to be the territory of rail sector specialists. However, for strategic multi-modal assessment purposes, rail corridor capacity concepts are capable of being understood and applied appropriately by transport planners and modellers in possession of transferrable analytical skills.

2.2 Road Lane Capacity

Road corridor lane capacity (excluding the effect of intersections) is largely based on the characteristics of available lanes, in terms of, the number of lanes, gradients, widths, permitted speeds, incidence of side friction (parking / accesses), the composition of traffic (proportion of different vehicle types) and observed understanding of typical driver behaviour.

Road traffic headways between successive vehicles are measured in seconds, with maximum vehicle throughput for uninterrupted multi-lane flows typically in the range 1,900 to 2,200 vehicles per hour.[4] Motorways, freeways and expressways have higher ranges of lane capacities and interrupted urban road traffic flows have lower capacities.

Road traffic corridor capacity is well understood by strategic transport planners, partly because of their training and partly because of the wide availability of easily accessible guidelines, assessment techniques and analytical models.

[2] ATAPG, 3.6, 2016
[3] Bruton, 1993: Hobbs, 1974
[4] Austroads, Table 5.5 at LOS E, 2020

2.3 Rail Line Capacity

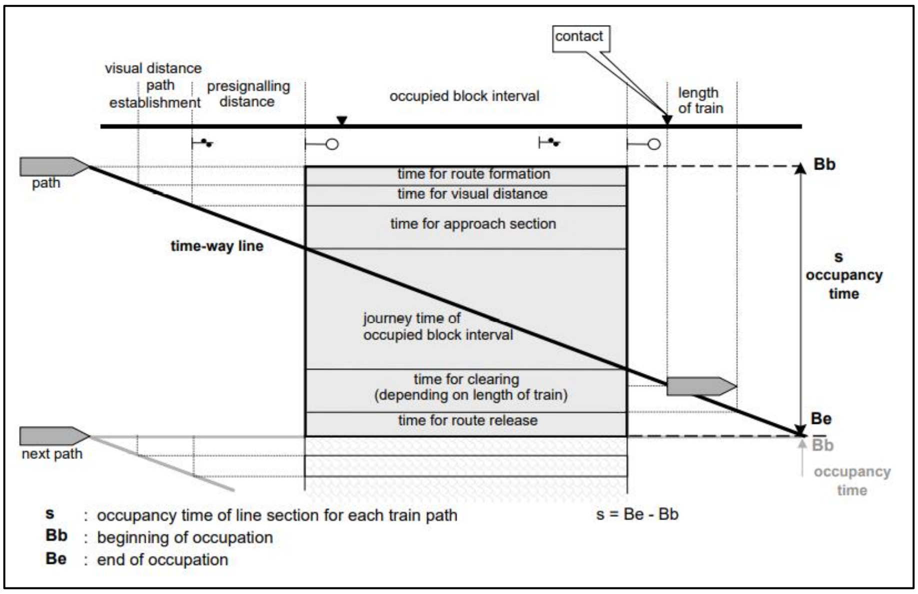
In NZ, intensive passenger rail services are only operated in Auckland and Wellington, although there are proposals to intensify some inter-regional passenger rail services and it is conceivable that rail services may in future, operate in other areas[5].

This paper references the capacity concepts of service compression, capacity consumption and additional time requirements[6] for corridors described in the International Union of Railways Code 406 Capacity leaflet and considers simplified techniques to represent versions of these concepts at a strategic level, for general transport planning purposes.

The assessment of rail line capacity often uses headways measured in minutes, to derive maximum train throughputs, typically between 6 and 30 trains per hour (tph)[7] with conventional signalling. Despite the low range of likely train-throughput volumes, the detailed assessment of rail corridor capacity involves a wide range of considerations.

Excluding other limitations such as terminal or train capacities, rail corridor line capacity is determined by, the number of rail lines / passing loops, permitted line speeds, signalling systems, signal protocols / block section lengths, train types (stopping patterns / lengths), acceleration / braking performance, required station dwell times and safety requirements[8]. Minimum headways between successive trains are defined by the components of the occupancy time for a given section of line, as shown below.

Figure 1 Occupancy Time[9]



Under most signalling regimes, a train cannot enter a defined section until the preceding train has passed through it. The speed of the following train, once it can enter a section, and when design-capacity is being approached (in busy peak periods) is determined (primarily) by the progress of the preceding train, although it should be noted that this limitation may well not

[5] Brett A, Ch 9, 2021
[6] UIC,2.3, 3.3, 5.2.1, 2013
[7] Typical values: TRB, 2013.
[8] TAIC, 2016
[9] UIC, 2013

apply during off-peak operation or where throughput is deliberately kept well below the design-capacity.

Transmission based signalling (TBS) systems[10] such as the European Train Control System (ETCS) can increase capacity,[11] especially if used in combination with other measures, such as shortening signal block lengths. However, TBS is not a panacea for all congestion problems experienced on busy rail networks.

In summary, rail corridor capacity techniques tend to be well understood by professionals within the rail sector, but because of the technical nature of rail operations, it can be difficult to convey this to a wider professional audience. As a result, rail capacity factors and associated investment requirements are often poorly understood by strategic transport planners and multi-modal modellers.

2.4 Headway-based Rail Capacity Estimation

An initial estimate of maximum train throughput along a rail corridor, assuming the corridor is operating at capacity, may use current main directional (operational) peak timetables to establish the number of trains able to utilise any particular section of line[12]. However, this is a very basic approach, only relates to current conditions, may be inaccurate and cannot be used to assess different future scenarios, including testing combinations of train stopping patterns and frequencies on particular corridor sections.

Headways, defining the minimum required headway separation (occupancy time, including safety requirements, dwell times and operating margin) between successive trains can be thought of as encompassing all the complexities referred to earlier, in Figure 1 above.

Train headways vary by section of line, depending on the mix of services (especially where service patterns involve faster trains following slower trains), the type of signalling system and associated train progression protocols.

Headway requirements between trains also vary depending on whether trains are assumed to pass signals at green, at yellow with no need to brake, or if braking to a halt is needed. Although it may appear counter-intuitive, passing a signal at green involves the longest headway, passing a signal at yellow tends to incur the second longest headway, and the minimum headway required is where following trains are expected to stop at the next signals.

The longest headway does not necessarily imply highest speed, as maximum train speed is set by a variety of factors, principally rolling stock capability and track features. In theory, the speed of trains travelling under caution through yellow signals could be the same as for passing at green, until braking becomes necessary, although in practice, line speeds after a caution signal tend to be lower.

Driving on yellows increases the risk of inadvertently passing signals at red, so is not generally designed-for in timetable-planning.

Within the parameters of this paper, namely, to assess the capacity of a single directional rail line, the maximum-train throughput capacity can be determined by the required headways between successive services within any given time-period. For example, if (say) a ten-minute

[10] Briso-Rodríguez, Ch. 9, 2017
[11] UNIFE, 2021
[12] Douglas, 3.6.2, 2006

headway has to be maintained between all trains, then 6 trains an hour will be able to use this section of line.

However, for any given mix of services and prevailing conditions on a given section of line, an average headway, and therefore an associated train-throughput capacity can be estimated. If (say) a headway of 9 minutes is required for a fast train following a slow train and a one-minute headway for a slow train following a fast train is required, the average headway would be 5 minutes.

The combination of all headways, on any section, in any given hour, can then be used to estimate the maximum theoretical train throughput capacity. A mix of fast and slow services has a potentially large capacity impact as differential speeds mean greater margins are needed and to allow for braking distances.

Detailed headway information for current conditions is held in rail models, such as OpenTrack, but headways can also be derived in approximate terms, using a simplified pathing model and in turn this can be used to derive throughput capacities along rail corridors.

Train throughput capacity can therefore be calculated (in approximate terms) for all trains, for any given scenario for strategic assessment purposes, within any given period for sections of line by dividing the time-period by the average directional headway.

2.5 Rail Capacity Thresholds

Capacity thresholds for rail corridors can be described as follows:

i) Design Capacity: The threshold beyond which the planned mix of service types can no-longer operate on an all-green signal progression basis. An allowance for some spare[13] train paths or a buffer between paths, may also be included in the estimated design capacity.

ii) Operational Capacity: In practice, train throughput may exceed design capacity, should unplanned bunching or occasional intentional overloading occur, and if any associated reliability trade-off[14] can be tolerated. Under such circumstances, trains may often pass signals at yellow, during normal operating conditions.

iii) Maximum Capacity: The theoretical point beyond which the planned mix of service types cannot operate without trains routinely needing to brake for signals, even when everything is running on schedule. In these circumstances trains may be delayed into the next available time-period, although the effect of braking continuously is clearly not a desirable one.

In theory, establishing the approximate capacity of a single directional rail line should be relatively straightforward. However, in practice it is not, mainly due to difficulties in obtaining required data, such as headway requirements for the rail system, in a suitable form for rapid assessment purposes.

[13] UIC, Tables 1 and 2, 2013
[14] Dicembre, Fig 1, 2011

3. MODELLING

3.1 Strategic Modelling

Until relatively recently, the strategic assessment of rail in NZ (post-privatisation and since the establishment of KiwiRail in 2008) has been largely concerned with justifying subsidy levels and promoting marginal improvements in rail system efficiency.[15]

Following the acceptance that the NZ rail network needs to be retained largely intact in order to secure network benefits,[16] the *'value of rail'* reports[17] recognised the substantial economic contribution made by rail, resulting in the current NZ Rail Plan.[18]

Where improvements to services are expected to be relatively marginal and incremental, then strategic modelling may not be required. If, however there is ambition to consider substantial changes to service patterns, frequencies or to introduce new services, then as a minimum, corridor capacity modelling will be needed.

Road, rail and other modes are currently modelled at the strategic level using four-stage[19] (trip generation, distribution, mode split and assignment) multi-modal transport models, in Auckland on the Macro Strategic Model (MSM) and in Wellington on the Transport Strategy Model (WTSM).

In Auckland, a rail crowding function, based on unit seating and standing ratios, is represented in the MSM and this can be activated to be included in generalised cost calculations. It is understood there is an intention to adopt a similar approach in WTSM in the future.

Whilst crowding functions are useful in making demand forecasts more realistic in respect of available train capacity, rail corridors also have limited train-throughput capacity. The number of trains per hour included in strategic models may or may not reflect the realistic potential of rail to accommodate the assumed growth in test scenarios. In contrast, link capacity constraints are almost universally applied to road networks within strategic models.

This is not to suggest that, useful though they are, strategic four-stage multi-modal transport models are necessarily the only or best tools to use for rail planning purposes, especially as they are known to have the potential to under-represent public transport potential[20].

Rail corridor capacity constraints are particularly relevant in strategic modelling when testing major changes in rail operations, wherever existing infrastructure is inadequate and especially when a different mixes of services, stopping patterns and train types are under consideration.

The danger arising from not incorporating rail line capacity into strategic transport models is that required train-throughput capacity enhancement needs on rail corridors may not be identified by strategic modellers or planners.

The lack of capacity representation in strategic models has tended to lead to an over-reliance on demand-based forecasting, subjective judgement, difficulties in quantifying mode change,

[15] KiwiRail, 2010
[16] KiwiRail, 2012
[17] NZTA, 2016: MoT, February 2021
[18] MoT, April 2021
[19] Hensher, Ch. 3, 2008
[20] DfT, 2007

associated emissions reduction potential and lack of rail infrastructure investment in forward transport plans and programmes.

Ideally, existing strategic models would be adapted to incorporate train-throughput capacity constraint functions. However, prior to modifying strategic models, or as an alternative, simplified corridor modelling[21] could play a role in assessing strategic rail capacity investment requirements.

3.2 Detailed Rail Modelling

The railway simulation tool OpenTrack[22] began in the mid-1990s as a research project at the Swiss Federal Institute of Technology and is now the industry standard for detailed rail capacity work.

OpenTrack can be thought of as the railway equivalent of a road traffic micro-simulation model, where individual vehicle movements are modelled on a detailed representation of the transport network. Such models are resource intensive and limited in terms of being able to represent radically different future scenarios without extensive modelling work to ensure realism. This is due to the need for the detailed infrastructure represented in the model to be able to accommodate individual train movements.

There has been substantial new investment in the Auckland rail network in recent years, including the construction of the Britomart terminus, passenger rail electrification and the ongoing implementation of the City Rail Link (CRL). Substantial increases in train frequency are planned for the post-CRL Auckland network. These plans have been subject to extensive assessment[23] and detailed modelling using OpenTrack.

In Wellington, high (pre-COVID) rail patronage levels following high growth rates[24], meant that in the primary northern approach sector (Ngauranga Gorge to Wellington CBD), by 2019 peak commuting patronage by rail was greater than the total commuting by car.

Investment in Wellington is now occurring on catch up maintenance, facility renewal, rolling stock upgrading and track improvements. Some further improvements are planned[25] but much more investment will be needed to achieve substantial increases in peak train frequencies and proposals to do this are only at a preliminary stage of development.

[21] Ortuzar, 12.5.2, 2006
[22] Nash, 2004
[23] MoT, 2011
[24] Wellington CBD Cordon Survey, AM peak inbound rail passenger growth, 3.4% p.a. over the period 2003-2019,
[25] GWRC, 2022

4. SIMPLIFIED PATHING MODEL

4.1 Need for Simplified Models

Simplified techniques to estimate rail corridor capacity are needed to:

i) Identify the capacity implications of variations in train frequencies and train type mixes.

ii) Quantify effects, in terms of service proximity, conflicts and delay.

iii) Supplement the capabilities of detailed rail capacity modelling, and

iv) Represent capacity restraint for rail links in strategic transport modelling.

Simplified rail capacity techniques are used within consultancies and rail organisations, but are not generally commercially available, at least not to my knowledge. Professionals within the rail sector often use freehand rail path sketching or spreadsheet modelling for initial planning purposes, prior to commissioning testing on detailed models, such as OpenTrack.

Rail professionals may also hold the required knowledge of rail capacity in 'mental models' or use OpenTrack (perhaps partially) in some way for initial capacity assessments, but these are very experienced individuals with specialised rail knowledge.

Such assessment techniques are unlikely to be used by strategic transport planners or modellers. The simplified pathing model described in this paper demonstrates a quantified technique for initial planning scenario comparison, including testing alternative rail service mixes, timings, stopping patterns and speeds.

Assuming train headways can be estimated for any given corridor section, and for any particular train service mix, potential capacity limitations can be identified and the likely scale of effects then estimated.

The pathing model is intended to identify locations where infrastructure improvements may be needed, where train service scheduling changes could be considered and to assist in specifying capacity requirements.

It is important to note that the use and interpretation of simplified pathing models will require close liaison with rail professionals to confirm assumptions and identify capacity limitations.

4.2 Model Application

Application of the model will usually be to test or scope specific objectives in the context of identified constraints.

In its present form, the pathing model is intended to be illustrative but capable of assessing scenarios where rail corridor capacity may act as a constraint to the introduction of additional services. The primary reasons for developing the model are to:

i) Determine the broad workability or otherwise of future train service scenarios in strategic terms, identify conflicts, service proximity and recovery period need.,

ii) Provide quantified delay estimates for comparison, optimisation and appraisal purposes,

iii) Identify (broadly) where capacity improvements are needed by (say) shortening block sections / upgrading signalling systems, providing passing / overtaking loops, adding rail lines on whole sections, making changes to service patterns by varying service frequencies, timings, stopping patterns or running shuttle services.

iv) Make a version of the model available on request to transport planners, modellers, academics, students to allow the results in this paper to be replicated, for education, training and further testing purposes.

The simplified pathing model is intended to allow, for any given scenario, potential train-throughput to be compared with capacity estimates for a section of line, quantify the magnitude of potential delays identified and estimate the degree of under or over capacity available.

A simplified pathing model can also be used to represent and compare theoretical alternative future scenarios where proposed train throughput may exceed capacity. These are not necessarily realistic scenarios but can be useful for scoping purposes, to identify where and when capacity improvements may be needed and to compare the scale of effects and improvements potentially required, in each case.

4.3 Study Corridor

Train-throughput capacity has been considered with specific reference to the Wairarapa / Hutt Valley rail corridor, maximum hourly train-throughput between Masterton and Wellington. The study corridor was selected for its interesting mix of short, medium and long-distance passenger rail services.

Figure 2 Study Corridor Location Plan

In order to facilitate rapid quantified assessment, a simplified (time-distance) pathing model was developed to represent existing conditions in the corridor and to test alternative future scenarios. In this way, different combinations of service types and frequencies can be compared in performance terms.

The pathing model can also be used to identify locations where capacity enhancements are required to support future proposals to vary stopping patterns and frequencies.

The pathing model is intended to be used for strategic concept assessment and development and is not suitable for any detailed purpose. Detailed analysis should always be undertaken using OpenTrack or similar rail simulation models.

Some outputs from an OpenTrack model have been compared with the simplified pathing model results for initial calibration purposes.

Establishing the current capacity of the rail corridor and the effects of alternative scenarios (varying service stopping patterns and frequencies) is intended to improve understanding, assist interpretation and optimise the potential of rail to support mode change targets and emissions reduction initiatives.

4.4 Model Specification

A train pathing model representing the rail corridor between Masterton and Wellington was constructed in Excel with supporting code in Visual Basic (VB). This was to test how effective a simple representation of southbound[26] train pathing is in assessing train throughput capacity. This could be expanded, be adapted to represent other corridors or made generic as needed. The current version is for demonstration, training and educational purposes only.

The worked examples used in the results presented in this paper, relate to the existing service pattern (base case scenario) and an illustrative future scenario (Option 1) a demonstration service specification with no connection to any real-world proposal.

The VB Code takes the user settings for the service pathing required (total number of hours, frequency in the hour, exact departure times) reads the individual service type definitions and generates a series of individual operating service timings. The individual service operating timings are aggregated into a single schedule and sorted into destination arrival time order. The sorted accumulated schedule is then scanned for headway and overtaking at every stop and final destination, using user defined headway proximity settings, highlighting applied to individual cells and counts of occurrences made.

The headway proximity counts identify less than desirable spacings between successive services and aggregates these occurrences.

With the exception of the 1,500 lines of VB code, developing a simplified pathing Excel model based on publicly available timetables is not an overly complex task. The base case scenario also has the advantage of being (effectively) self-validating, as by definition, the public timetable is a realistic reflection of existing operational conditions and travel times.

The model represents rail movements between Masterton and Wellington stations, a distance of 90 km, with 7 intermediate stations between Masterton and Upper Hutt, and 4 key intermediate stations included in the model between Upper Hutt and Wellington (selected to represent the 15 closely spaced actual stations) plus a nominal Wellington rail freight destination.

[26] For the worked examples in this paper, contra-peak train movements do not materially affect capacity.

The line is single track between Masterton and Upper Hutt (including a 9 km single track tunnel), double track from Upper Hutt to Distant Junction (south of Petone, where the Kāpiti Line joins) and triple track (with a central bi-directional line) between Distant Junction and Wellington Rail Station (WRS).

Five rail movement types are represented in the model, locomotive hauled carriages for the Masterton to Wellington express passenger service, Upper Hutt semi-express electric multiple units (EMUs), Taita all-stop EMUs, Melling all-stop EMUs and Freight trains.

Figure 3 Southbound EMU at Taita Station

Being in Microsoft Excel, the model is highly accessible and designed to be easily adjustable by users. The model can be used to experiment with, and assess the effects of, alternative train timings and frequencies. The model may be described as data-poor but facility-rich, with the ability to rapidly test different service planning scenarios.

The model is also able to quantify the approximate effects of alternative scenarios in terms of proxy delays, even for theoretical future over-capacity scenarios. This is not necessarily realistic but (with interpretation) allows broad, order of magnitude, comparisons to be made between alternative scenarios and to assist in identifying the scale of future infrastructure needs, for any given service mix.

Outputs from the model are intended be used for scenario development and optimisation purposes, but these operations require a degree of judgement. The model can be used to test different service scenarios under set conditions. User understanding of capacity related factors, issues and effects improves through experience of operating the model.

The model is pre-loaded with train movement types, stations, section distances and travel time data for the corridor, taken from timetables, other published data (such as average freight speeds) and differentiated by movement type.

The main inputs required for the model are, the number of trains by service type, train timings, and corridor section distances. The model can be varied to cover up to a 6-hour period. Service timings and frequencies are used to generate approximate scenario timetables, wherever possible using evenly spaced clock face timings, although there is an ability to vary these inputs (to avoid conflicts) and to optimise timings where necessary.

Results are available in graphical format to assist interpretation, optimisation and to visually identify the approximate locations where capacity improvements or other changes need to be considered.

The results from any given scenario can also be viewed in tabular form to quantify the extent of close running, and (potentially) conflicting services, especially where faster services are following slower services.

The pathing model is not intended to replace the need for more detailed modelling but rather to supplement available techniques and to provide a rapid assessment tool to review and compare strategic rail service planning scenarios.

4.5 Model Form

User specified inputs are listed below:

Worksheet 1

- Run title.
- Number of hours modelled (whole numbers between 1 and 6).
- Choice of specific hours modelled within period.
- Frequency by service type (express, semi-express, all-stop, freight) in whole numbers per hour).
- Departure times (where evenly spaced services are indicated as operating in that hour).
- Timings in each hour (whole minutes) where services are not evenly spaced.
- Minimum, moderate and desirable service headway separation (whole minutes past each hour, currently set at 1, 2 and 3 minutes respectively).

Worksheet 2

- List each potential overtaking event and specify time saving/delay in each case (minutes). This is taken to be the average of the maximum and minimum delay potentially experienced by a faster train encountering an adjacent slower train, where overtaking events are forecast to occur in generated timetables. See also overall 'Indicative Delay Assessment' as discussed in 4.12.

Worksheet 3

- List timings by each service type (in seconds).

4.6 Model Operational Commands

Once set up, the model is operated by 4 commands:

- *Create Timetable*, creates a timetable representing the service timing inputs. This is a generic representation of a timetable and does not attempt to replicate an actual detailed timetable.
- *View Generated Sorted Timetable*, sorts the generated timetable by arrival time in Wellington.
- *View Generated Timetable Separations*, allows the approximate separation between services to be viewed in colour coded tabular format.

- *View Generate Graphic*, provides a time-distance train pathing graph to identify service conflicts.

The current four command procedure has been developed for testing and development purposes, to allow the user to see the outcome of preceding steps before continuing. This makes any subsequent additions and enhancements easier apply and test.

The outputs of the model take the form of

Worksheet 1	Summary table of proxy delays, relating to immediately adjacent service. This assumes a 3-minute separation is desirable for operational / reliability purposes and lesser separations are likely to incur delays. If additional trains are affected manual interpretation is needed and if overtaking is possible indicated delays will be reduced.
Worksheet 4	Generic timetable, generated from input data.
Worksheet 5	Pathing graphic, visually identifying conflicts, indicating potential overtaking needs and blockages.
Worksheet 6	Sorted generic timetable, by WRS arrival time, colour coded to assist visual appreciation / identification of close running tabulation / quantification and delay implications, link back to Worksheet 1.

4.7 Base Case Scenario

The base case used in this instance is a simplified representation of current operations in terms of train types, frequencies and timings, although in reality, the actual timetable has a number of subtleties and variations on train timings and travel times. The purpose of modelling the base case is to compare model performance with existing, known conditions.

In the base case, the following morning peak train frequencies (per hour) have been tested:

- 2 x Masterton to Wellington express services,
- 3 x Upper Hutt semi-express electric multiple units (EMU)
- 3 x Taita all-stop EMUs
- 3 x Melling all-stop EMUs
- 1 x early Freight train.

Outputs from the base scenario modelling are illustrated below:

Figure 4: Train Path Diagram: Base Scenario (8 tph at Taita)

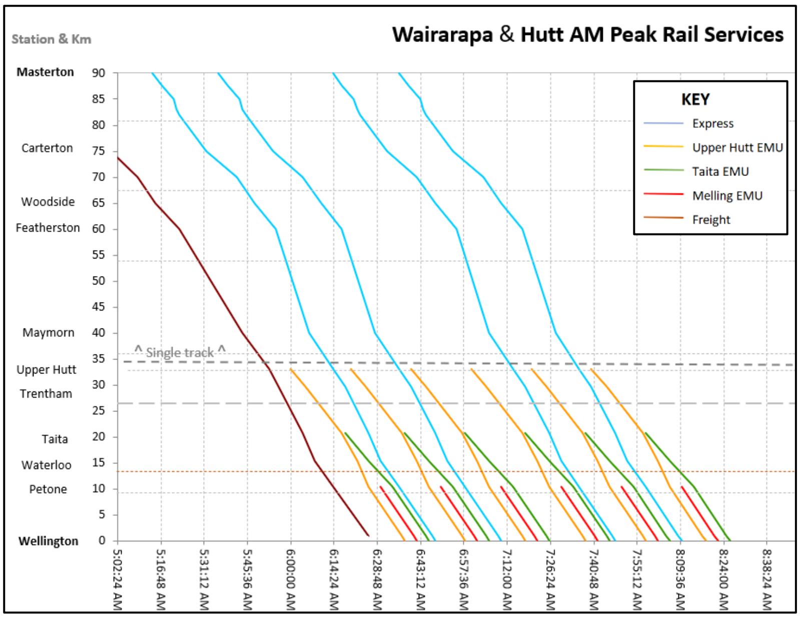


Figure 4 shows that services can operate independently, in separated time-distance paths without any clear conflicts.

Table 1 provides quantified confirmation of service separation and the proximity of services, with green highlighting representing a desirable separation of at least 3 minutes, amber indicating a service proximity of 2 minutes, red 1 minute and purple no separation where overtaking is required.

Table 1: Base Scenario Service Proximity (8 tph at Taita)

Run Label	90	87.7	85	83	82	75	70	65	60	40	33	29.7	20.7	15.5	10.5	1	0	km
Base	Masterton Station	Renall St Station	Solway Station	Waingawa	Waingawa	Carterton Station	Matarawa Station	Woodside Station	Featherston Station	Maymorn Station	Upper Hutt Station	Trentham Station	Taita Station	Waterloo Station	Petone Station	Wellington Freight	Wellington Station	Arrival Separation Wellington
Type																		
Freight	4:15:00	4:19:00	4:23:00	4:25:00	4:51:00	5:00:00	5:09:00	5:15:00	5:23:00	5:44:00	5:53:00	5:56:00	6:04:00	6:08:00	6:14:00	6:26:00		
Upper Hutt											6:00:00	6:05:00	6:17:00	6:22:00	6:26:00	6:37:00	6:38:00	06:38:00
Melling															6:30:00	6:41:00	6:42:00	00:04:00
Taita													6:18:00	6:26:00	6:34:00	6:45:00	6:46:00	00:04:00
Long-Distance	5:14:00 am	5:17:00	5:21:00	5:22:00	5:23:00	5:32:00	5:42:00	5:48:00	5:55:00	6:06:00	6:14:00	6:18:00	6:26:00	6:30:00	6:36:00	6:47:00	6:48:00	00:02:00
Upper Hutt											6:20:00 am	6:25:00	6:37:00	6:42:00	6:46:00	6:57:00	6:58:00	00:10:00
Melling															6:50:00 am	7:01:00	7:02:00	00:04:00
Taita													6:38:00 am	6:46:00	6:54:00	7:05:00	7:06:00	00:04:00
Long-Distance	5:36:00 am	5:39:00	5:43:00	5:44:00	5:45:00	5:54:00	6:04:00	6:10:00	6:17:00	6:28:00	6:36:00	6:40:00	6:48:00	6:52:00	6:58:00	7:09:00	7:10:00	00:04:00
Upper Hutt											6:40:00 am	6:45:00	6:57:00	7:02:00	7:06:00	7:17:00	7:18:00	00:08:00
Melling															7:10:00 am	7:21:00	7:22:00	00:04:00
Taita													6:58:00 am	7:06:00	7:14:00	7:25:00	7:26:00	00:04:00
Upper Hutt											7:00:00 am	7:05:00	7:17:00	7:22:00	7:26:00	7:37:00	7:38:00	00:12:00
Melling															7:30:00 am	7:41:00	7:42:00	00:04:00
Taita													7:18:00 am	7:26:00	7:34:00	7:45:00	7:46:00	00:04:00
Long-Distance	6:14:00 am	6:17:00	6:21:00	6:22:00	6:23:00	6:32:00	6:42:00	6:48:00	6:55:00	7:06:00	7:14:00	7:18:00	7:26:00	7:30:00	7:36:00	7:47:00	7:48:00	00:02:00
Upper Hutt											7:20:00 am	7:25:00	7:37:00	7:42:00	7:46:00	7:57:00	7:58:00	00:10:00
Melling															7:50:00 am	8:01:00	8:02:00	00:04:00
Taita													7:38:00 am	7:46:00	7:54:00	8:05:00	8:06:00	00:04:00
Long-Distance	6:36:00 am	6:39:00	6:43:00	6:44:00	6:45:00	6:54:00	7:04:00	7:10:00	7:17:00	7:28:00	7:36:00	7:40:00	7:48:00	7:52:00	7:58:00	8:09:00	8:10:00	00:04:00
Upper Hutt											7:40:00 am	7:45:00	7:57:00	8:02:00	8:06:00	8:17:00	8:18:00	00:08:00
Melling															8:10:00 am	8:21:00	8:22:00	00:04:00
Taita													7:58:00 am	8:06:00	8:14:00	8:25:00	8:26:00	00:04:00

Key
Desirable
Moderate
Minimum
Overtaking

Figure 4 and Table 1 indicate the base case operates relatively well, with an operational margin allowing some timing flexibility during busy periods.

There are known reliability issues with the Wairarapa loco-hauled express services, but these are not understood to be specifically due to timetabling or to over-capacity issues, rather the unreliability appears more connected to the condition of track and lineside equipment. These issues are currently being addressed through the catchup maintenance and renewals investment programme.

4.8 Future Test Scenario

The future scenario Option 1 includes increased frequencies for certain services, although these are not based on any specific proposal. The purpose of modelling future theoretical scenarios is to answer the question, what would the scale of effects be, if a particular combination of service types and frequencies was to be operated?

A future scenario, using the following morning peak train frequencies (per hour) was tested:

- 2 x Masterton to Wellington express services,
- 6 x Upper Hutt semi-express electric multiple units (EMU)
- 6 x Taita all-stop EMUs
- 3 x Melling all-stop EMUs
- 1 x early Freight train.

The only differences between this future scenario and the base case, are the doubling of the Upper Hutt and Taita hourly frequencies from 3 to 6 tph in each case. Outputs from the future scenario modelling are illustrated below:

Figure 5: Train Path Diagram: Future Scenario Option 1 (14 tph at Taita)

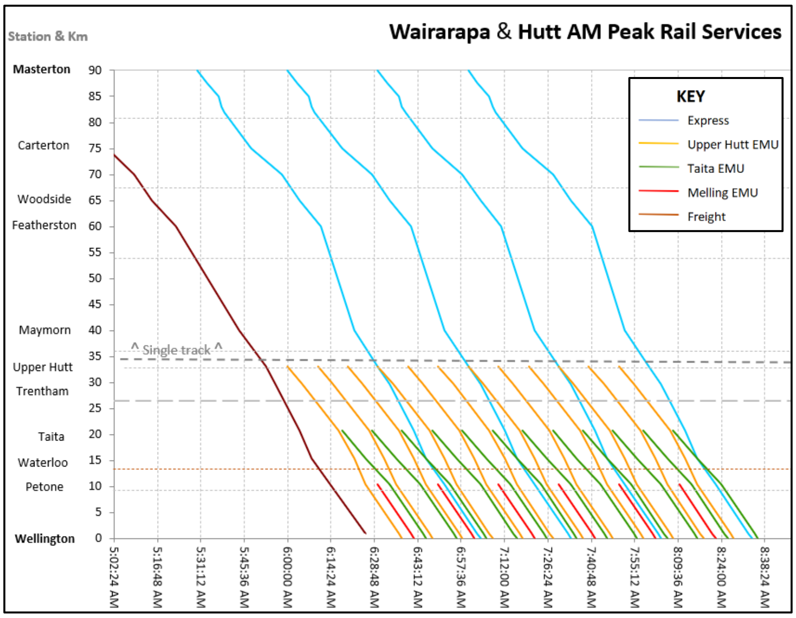


Figure 5 and Table 2 indicate (theoretical) conflicts between trains at locations where delays may occur and where overtaking opportunities or other measures would be needed.

Table 2: Future Scenario Option 1 Service Proximity (14 tph at Taita)

Run Label	90	87.7	85	83	82	75	70	65	60	40	33	29.7	20.7	15.5	10.5	1	0	km
Future Scenario	Masterton Station	Renall St Station	Solway Station	Waingawa	Waingawa	Carterton Station	Matarawa Station	Woodside Station	Featherston Station	Maymorn Station	Upper Hutt Station	Trentham Station	Taita Station	Waterloo Station	Petone Station	Wellington Freight	Wellington Station	Arrival Separation Wellington
Type																		
Freight	4:15:00	4:19:00	4:23:00	4:25:00	4:51:00	5:00:00	5:09:00	5:15:00	5:23:00	5:44:00	5:53:00	5:56:00	6:04:00	6:08:00	6:14:00	6:26:00		
Upper Hutt											6:00:00	6:05:00	6:17:00	6:22:00	6:26:00	6:37:00	6:38:00	06:38:00
Melling															6:30:00	6:41:00	6:42:00	00:04:00
Taita													6:18:00	6:26:00	6:34:00	6:45:00	6:46:00	00:04:00
Upper Hutt											6:10:00 am	6:15:00	6:27:00	6:32:00	6:36:00	6:47:00	6:48:00	00:02:00
Taita													6:28:00 am	6:36:00	6:44:00	6:55:00	6:56:00	00:08:00
Upper Hutt											6:20:00 am	6:25:00	6:37:00	6:42:00	6:46:00	6:57:00	6:58:00	00:02:00
Melling															6:50:00 am	7:01:00	7:02:00	00:04:00
Long-Distance	5:30:00	5:33:00	5:37:00	5:38:00	5:39:00	5:48:00	5:58:00	6:04:00	6:11:00	6:22:00	6:30:00	6:34:00	6:42:00	6:46:00	6:52:00	7:03:00	7:04:00	00:02:00
Taita													6:38:00 am	6:46:00	6:54:00	7:05:00	7:06:00	00:02:00
Upper Hutt											6:30:00 am	6:35:00	6:47:00	6:52:00	6:56:00	7:07:00	7:08:00	00:02:00
Taita													6:48:00 am	6:56:00	7:04:00	7:15:00	7:16:00	00:08:00
Upper Hutt											6:40:00 am	6:45:00	6:57:00	7:02:00	7:06:00	7:17:00	7:18:00	00:02:00
Melling															7:10:00 am	7:21:00	7:22:00	00:04:00
Taita													6:58:00 am	7:06:00	7:14:00	7:25:00	7:26:00	00:04:00
Upper Hutt											6:50:00 am	6:55:00	7:07:00	7:12:00	7:16:00	7:27:00	7:28:00	00:02:00
Long-Distance	6:00:00 am	6:03:00	6:07:00	6:08:00	6:09:00	6:18:00	6:28:00	6:34:00	6:41:00	6:52:00	7:00:00	7:04:00	7:12:00	7:16:00	7:22:00	7:33:00	7:34:00	00:06:00
Taita													7:08:00 am	7:16:00	7:24:00	7:35:00	7:36:00	00:02:00
Upper Hutt											7:00:00 am	7:05:00	7:17:00	7:22:00	7:26:00	7:37:00	7:38:00	00:02:00
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Taita													7:38:00 am	7:46:00	7:54:00	8:05:00	8:06:00	00:02:00
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Melling															8:10:00 am	8:21:00	8:22:00	00:04:00
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Upper Hutt											7:50:00 am	7:55:00	8:07:00	8:12:00	8:16:00	8:27:00	8:28:00	00:02:00
Long-Distance	7:00:00 am	7:03:00	7:07:00	7:08:00	7:09:00	7:18:00	7:28:00	7:34:00	7:41:00	7:52:00	8:00:00	8:04:00	8:12:00	8:16:00	8:22:00	8:33:00	8:34:00	00:06:00
Taita													8:08:00 am	8:16:00	8:24:00	8:35:00	8:36:00	00:02:00

Key
Desirable
Moderate
Minimum
Overtaking

In reality, with current infrastructure, the frequencies specified in the future scenario would be unable to operate within a single hour, as the Masterton express services and inner semi-express and all-stop services from Taita would, in combination, exceed the currently available capacity.

The modelling can be used to provide an initial overall indication of potential problems and service proximity issues for scenario comparison and optimisation purposes (as shown below

Table 3: Service Proximity Summary Option 1 (14 tph at Taita)

Proximity category	Proximity Incidents	Desirable Time (mins)	Desirable Margin (mins)
Minimum separation	8	2	16
Moderate separation	51	1	51
Target separation (desirable)	95	0	0
Overtaking required	4	4.1	16.4
Total	158	Total	83.4

To quantify overall potential delay, additional analysis is needed as described below (see 4.12 Indicative Delay Assessment).

Potential improvements in response to identified issues are not restricted to providing overtaking facilities but could include possible combinations of other measures, such as:

i) New infrastructure: Additional lines, more passing loops, shorter block sections, improved signalling.

ii) Planning: Higher capacity/longer trains and platforms, varying the mix of services, adjustment of stopping patterns, introducing slower / more homogeneous service patterns, increased service interchange and introducing shuttle services.

Each potential measure has a potential effect on patronage demand forecasting (not addressed directly in this paper) and would incur costs and benefits also requiring consideration, prior to selecting a preferred option.

For example, slowing express services or forcing interchange would incur time penalties and potentially suppress demand in outer area markets. If longer distance rail services were negatively impacted, this could have a disproportionate effect (on longer road-based trip lengths) on efforts to reduce traffic VKT and associated road traffic emissions.

4.9 OpenTrack Comparison

Information held within the OpenTrack model is very useful for testing and comparison purposes. As a reality check, capacity estimates from the simplified pathing model were compared with OpenTrack parameters, for southbound movements at Taita, as shown below:

Table 4 Model Headways and Estimated Capacity

Model Parameters: Hutt Valley Line Southbound at Taita				
		Design Capacity	Operational Capacity	Maximum Capacity
	AM Weekday Peak	All Trains Pass Signals at Green	All Trains Pass Signals at Yellow	All Trains Brake for Signals
OPENTRACK Service mix 50:50 All-stop: Express Services	Ave. Headway (seconds)	383s	348s	300s
	Train throughput	9.4 tph	10.4 tph	12.0 tph
Pathing Model Service mix 50:50 All-stop: Express Services	Ave. Headway (seconds)	-	-	300s
	Train throughput	-	-	12.0 tph

The results indicate that at Taita (the start of the busiest corridor section) the simplified pathing model produces the same capacity (12 tph) as the OpenTrack estimate based on all trains needing to brake for signals, the maximum capacity of the corridor at that point.

The average headway is the combination of long headways for fast services following slow services (497s in OpenTrack, 540s in the pathing model) and short headways for slow trains following other services (103s in OpenTrack, 60s in the pathing model). The mix of services, considered with combined with infrastructure and operational constraints, determines the average headway.

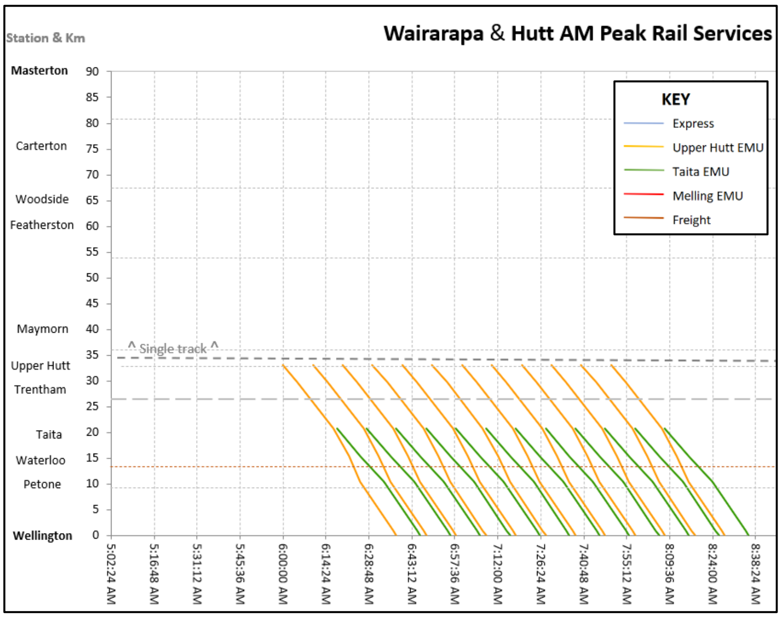
OpenTrack provides a more nuanced capacity range at Taita, depending on assumptions regarding train progressions through signals, of between 9 and 12 tph. This range represents the 25%[27] recommended minimum spare capacity for mixed lines up to full 100% compression.

4.10 Alternative Service Mixes

If only semi-express and all-stop services are operated, as indicated above in Table 4, the maximum throughput capacity at Taita of 12 tph would be fully used with a 50:50 mix of 6 Upper Hutt semi-express trains and 6 Taita all-stop trains, (headway progression 1 min, 9 min, average 5 min) pathing example shown below:

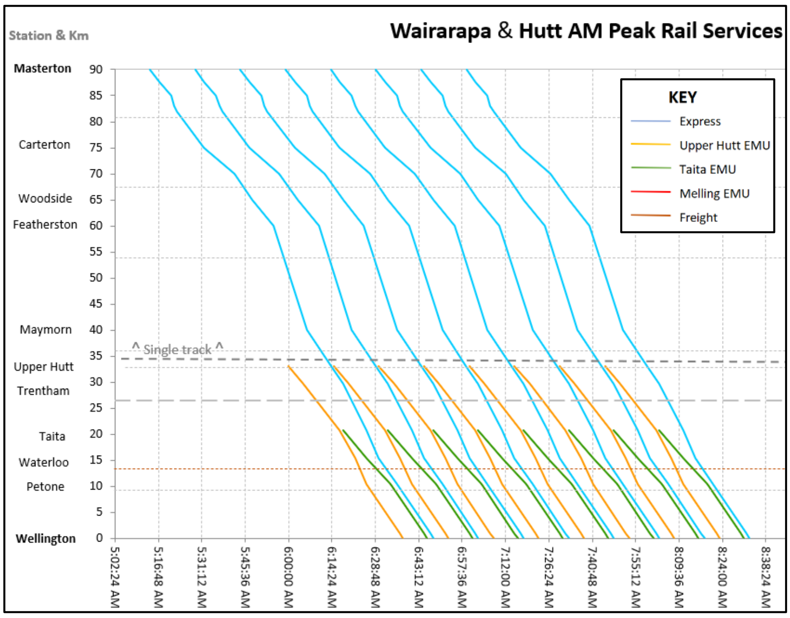
[27] UIC, T1, 2013

Figure 6 Train Path Diagram: Semi-Express and All-Stop Service Mix (12 tph)



The maximum train throughput capacity of 12 tph at Taita could also be fully used with equal numbers of express, semi-express and all-stop services, (headway progression 1 min, 8 min, 6 min, average 5 min) as shown below:

Figure 7 Train Path Diagram: Express, Semi-Express, All-Stop Service Mix (12 tph)



4.11 Illustrative Ratio of Flow to Capacity Analysis

An illustrative approach to corridor analysis for the future service mix for the worked example (Option 1) in in this paper, using the ratio of flow to capacity ratio, measured in terms of hourly train throughput.

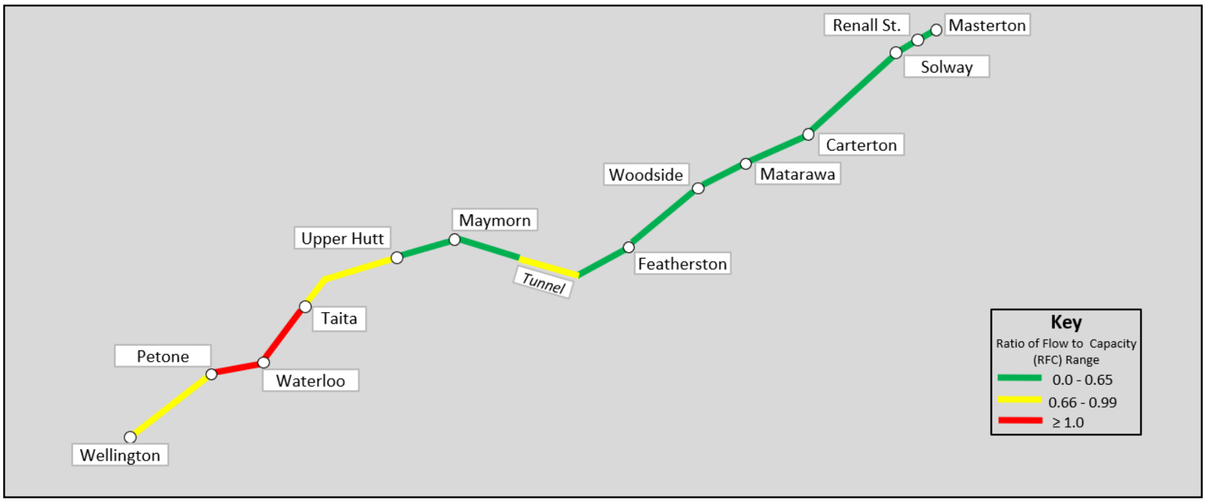
To assess levels of service, and for reliability reasons, the adoption of a range of operational, design and maximum capacities can be applied to reflect levels of service.

The scale used in this paper for assessment purposes assumes a train throughput capacity range of between 8 tph (design capacity with one spare path for operational purposes) and 12 tph (maximum capacity). This range represents the 33%[28] recommended spare capacity for mixed line LOS up to full 100% compression.

By comparing required throughput with available capacity, ratios of flow to capacity (RFC) can be derived for individual corridor sections. For example, the required throughput in Option 1 is 14 tph at Taita, which is 2 tph or 17% over the existing maximum throughput capacity of 12 tph.

For the potential service mix represented in the future Option 1, a simple green, amber, red, LOS illustration for the corridor,[29] with RFC thresholds at 66% and 100% is shown below:

Figure 8 Ratio of Flow to Capacity: Rail Corridor Illustration



The diagram above illustrates potential future southbound AM weekday peak conditions and provides an outline visual summary of capacity constraints for initial planning and communication purposes.

4.12 Indicative Delay Assessment

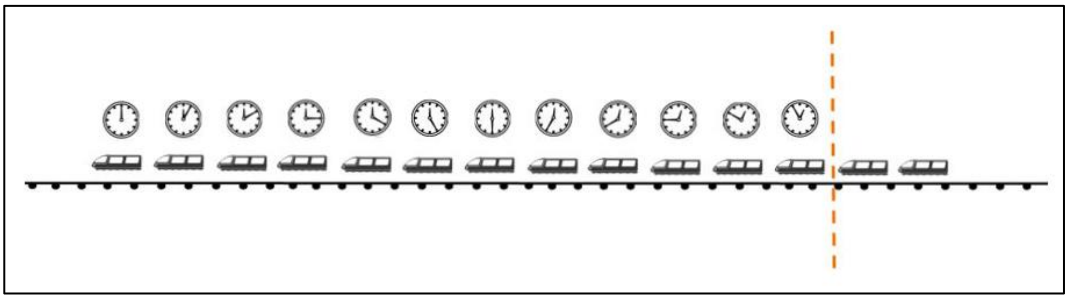
An indicative approach to the assessment of maximum theoretical overall delay for any given mix of service types and frequencies is suggested below:

If for example, there is an intention to operate (say) 14 tph but capacity is estimated to be between 8 and 12 tph, then (based on maximum capacity of 12 tph), a minimum of 2 trains would be displaced to the next hour.

The concept of calculating delays when capacity is exceeded is standard in road capacity modelling, where transfers of vehicles and traffic queues to later time periods are routinely undertaken.

[28] UIC, T2, 2013
[29] UIC, App C.3, 2013

Figure 9 Capacity 12 tph, Demand 14 tph



In this case, the first displaced train is assumed to be delayed by 5 min, being the average time required per train to travel this section. The second displaced train is delayed by a further 5 min. Further considerations are needed for potential delaying effects of displaced trains on trains in the following time-period.

Alternative approaches could be adopted to estimate delays, (say) using design or operational capacities instead of maximum capacity. Also, rather than applying average train delays, the headway progression for individual displaced trains could be taken from the pathing model for calculation purposes. For example, the headway progression at Taita, for the pathing example shown above in Figure 7, is 1, 8 and 6 mins.

This type of analysis can be used to indicate the scale of delay for scenarios where proposed throughput exceeds the available capacity.

4.13 Further Model Development

The pathing model has limitations with potential to be addressed through further development, including:

- Further interrogation and testing using OpenTrack to calibrate results from the simplified pathing model.
- Better representation of delays between individual successive trains. estimates.
- Inclusion of successive train proximity events, rather than (as at present) adjacent service interaction only.
- Automated linkage of model commands.
- Representation of other corridors (rail path models for Palmerston North to Wellington and WRS approach are at an earlier stage of development).
- Creation of generic pathing model version, adaptable to any rail corridor.
- Potential to extend the user's ability to refine scheduling by individual hour.
- Ability to change an individual leg timing of an individual service in the accumulated schedule.
- Evaluation functions could be added to help users better understand capacity limitations, such as the overall workability of a particular timetable.
- Model conversion to a non-proprietary spreadsheet for alternative operating systems (Windows, Mac, Linux).

5. FINDINGS

5.1 Overview

This paper rehearses general rail capacity concepts for the benefit of strategic transport planners and modellers, rather than for rail sector experts with a detailed knowledge of rail operations or specialised rail models.

Transport planners are trained in road capacity concepts and could benefit from better understandings of rail capacity assessment techniques.

The paper draws comparisons between road and rail assessments and attempts to derive and describe rail capacities in ways meaningful to strategic transport planners and strategic modellers.

There is an extensive and well researched literature on the topic of rail capacity analysis, but equivalent material describing simplified rail assessment techniques is much more limited and as a result, reliance is often placed on in-house techniques by rail professionals and on subjective judgements by strategic planners, for preliminary assessment purposes.

Historically, post WW2 investment in rail has tended to be one of 'managed decline' or at best marginal incrementalism, limiting the need for major scenario options testing.

In NZ the ambition to substantially increase passenger rail frequencies has only occurred relatively recently. In the last two decades, there have been substantial investments in rail in Auckland, including Britomart, electrification and the City Rail Link. There is interest also (currently) in substantially increasing passenger service levels in Wellington and in further developing of inter-regional passenger rail services in other areas.

5.2 Conclusions

This paper argues that simplified capacity modelling has a useful role in the preliminary assessment of rail investment scenarios and improving the effectiveness of strategic transport planning, modelling, programming and preliminary economic appraisal.

Capacity concepts are central to all transport planning. Transport planners understand road capacity analysis and the shortcomings in strategic road capacity are widely known. In contrast, rail capacity analysis is very hard to penetrate, exists only at the detailed level and is only undertaken by rail sector specialists.

Without simplified rail capacity modelling, detailed operational rail models are unlikely to supply the information required for the preliminary strategic assessment of alternative rail planning scenarios

Simplified techniques to assess rail capacity do exist but are currently based on individualised techniques used by rail experts. No simplified rail pathing model is currently commercially available for use by strategic transport planners or modellers.

The pathing model and the worked examples provided in this paper are illustrative, but with potential for further development and extension to cover other factors (such as terminal or station capacity) when required.

The pathing in the simplified model is approximate and strategic in nature and is not intended to compete with other models such as OpenTrack, which remains the industry standard in NZ, recommended to be used for all detailed analysis.

The paper suggests ways of defining different train throughput levels to represent design capacity, operational capacity and maximum capacity. Relationships between capacity and delays, travel-times and reliability are also discussed.

A basic comparison between headways derived from an OpenTrack model and a simplified pathing model, for maximum capacity estimation purposes, yielded identical results.

An approach using a ratio of flow to capacity (RFC) technique to derive approximate levels of service (LOS) criteria for rail corridors, is suggested in the paper.

The risk of omitting rail line capacity from strategic modelling is rail capacity enhancement needs on rail corridors may not be identified by strategic modellers, whose current focus is on demand-based forecasting.

If the required capacity enhancements are not included in in forward rail infrastructure programmes, then planned rail patronage growth, associated mode change and emissions reductions will not be achieved.

The work so far indicates that the concept of simplified modelling for rail corridors is workable and potentially useful for strategic analysis and in representing rail link capacity in strategic multi-modal models.

References

ATAPG, (2016) Australian Transport Assessment and Planning, Guidelines, T1 Travel Demand Modelling.

Austroads, (2020) *Guide to Traffic Management Part 3: Transport Studies and Analysis Methods*.

Briso-Rodríguez C, García-Loygorri J M, Zhang L, (2021) *Transmission-Based Signalling Systems.*

Brett A, (2021) *Can't Get There from Here: New Zealand Passenger Rail since 1920.*

Bruton M J, (2020) *Introduction to Transportation Plann*ing, 1993.

DfT (UK), (2007) *Rail passenger demand forecasting research: Uni-mode and multi-mode rail demand.*

Dicembre A, Ricci S, (2011) *Railway traffic on high density urban corridors: Capacity, signalling and timetable*, Journal of Rail Transport Planning & Management.

Douglas N, (2006) *North West Rail Link, Economic Appraisal.*

GWRC, (2022) *Future Rail, Building a better rail network for the Lower North Island.*

Hensher D A, Button K J, (2008) *Handbook of Transport Modelling*, Second Edition, Vol 1.

Hobbs F D, (1974) *Traffic Planning and Engineering.*

KiwiRail, (2012) *Whole of Network Economic Model Report.*

KiwiRail, (2010) *Overview and Turnaround Plan.*

MoT, (April 2021) *The New Zealand Rail Plan.*

MoT, (February 2021) *The Value of Rail in New Zealand*.

MoT, Treasury, NZTA, (2011) *Auckland City Centre Rail Link Business Case Review*.

Nash A, Huerlimann D, (2004) *Railroad simulation using OpenTrack.*

NZTA, (2016) *The Value of Rail in New Zealand.*

Ortuzar, J.D. and Willumsen LG, (2006) *Modelling Transport, Third Edition*.

TAIC (Transport Accident Investigation Commission), (2016) *Signal passed at danger leading to near collision, Wellington Railway Station*, Final Report.

TRB (Transportation Research Board), (2013) *Transit Capacity and Quality of Service Manual.*

UIC (International Union of Railways), (2013) *Code 406, Capacity Edition No 2.*

UNIFE (Union des Industries Ferroviaires Européennes), (accessed August 2021) *ERTMS Increasing Infrastructure Capacity, Factsheet 10*.

Bibliography

Abril M, Barber F, Ingolotti L, Salido M A, Tormos P, Lova A, (2007) *An Assessment of Railway Capacity,* Technical University of Valencia.

ATAPG (Australian Transport Assessment and Planning, Guidelines), (2021) *M1 Public Transport.*

Douglas N, (2009) *Modelling Passenger Loads & the Impact of Changes to the CityRail Timetable*, Report for the Independent Transport Safety and Reliability Regulator NSW.

Douglas N, (2012) *Modelling Train & Passenger Capacity. Final Report for Transport for NSW.*

Jensen L W, Landex A, Nielsen O A, Kroon L G, Schmidt M, (2017) *Strategic assessment of capacity consumption in railway networks: Framework and model*, Transportation Research, Volume 74.

KiwiRail, (2020) *Wellington Metro Rail Network Capacity Consumption Operating RS1 to UIC 406.*

Lindfeldt A, (2015) *Railway capacity analysis, Methods for simulation and evaluation of timetables, delays and infrastructure*, Doctoral Thesis.

TRL, (2017) *Options for Capacity Measures/Metrics*, Project Report.

Tzieropoulos P, Buri J D, (2009) *Increasing line capacity with constant infrastructure*, Swiss Transport Research Conference.

Waka Kotahi, (2019) *Transport Model Development Guidelines.*

Wardrop A, (accessed, August 2021) *What Line Capacity Can ETCS Deliver to Australian Suburban Railways?* Sydney, Australia.

Warg J, (2012) *Effects of increased traffic volume and speed heterogeneity on the capacity of a railway with dense mixed traffic.*

Wignall D, Furnish P, (2009) *Making the Most of Models, Using Models to Develop More Effective Transport Policies and Strategies,* VTPI.

Wignall D, (2017) *Economic Re-evaluation of New Zealand Transport Investments*, ATRF.

Xiaobing D, Zhang S, Liu Z, Hu H, Xu X, Xuet W, (2016) *The Analysis and Calculation Method of Urban Rail Transit Carrying Capacity Based on Express-Slow Mode,*

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