MSc in Railway Systems Engineering and Integration

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An Analysis of Single Track High Speed Rail Operation

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Executive Summary

High speed rail is a consequence of the need for safe, fast, reliable and environmentally friendly mode of transport. Increasing competition from other modes of transport and the high capital cost of high speed rail all efforts should be focused on reducing the costs to be more compatible. Adding a track to the system involves adding additional subsystems such as signals, power supply etc., thus the price is generally in the region of 60-70% additional costs. Similarly, removing a track reduces the costs, which is why single track operation might be a great alternative to double track. However, as far as the Author is aware of there is no single track high speed rail operation operative anywhere in the world. The demand for single track system might be limited due to the operational constraints involved, such as less capacity, frequency and flexibility, but the potential cost savings in infrastructure costs can outweigh these constraints.

The timetable, rolling stock performance and capacity are key elements in the planning and design phase of a single track. To get a better understanding of the relationship between the elements they are carefully analysed in this report. However, as it involves a high number of calculations the Author has invested a great deal of effort in creating a train performance calculator. This tool has been used greatly by the Author during the project and new features were added as they were needed.

One of the key finding was that the differences in speed have little effect on the ratio of double track required, as illustrated below

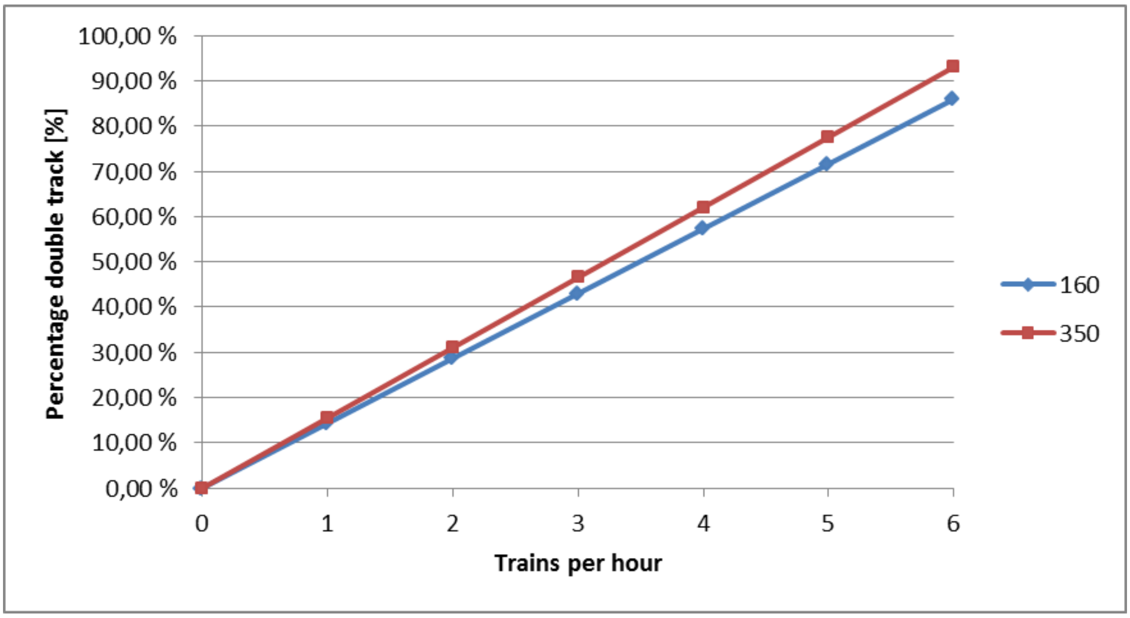

Figure 1 – Double track ratio based on TPH, with 3 min BT (Author)

Other key findings can be summed up as:

- Single track high speed rail operation is realisable based if the following conditions are met:
    - Timetable assuming regular interval
    - High level of reliability and punctuality
    - Completely segregated operations
    - Homogenous rolling stock
    - Limited frequency – somewhere in the region of 1 to 4 train per hour per direction dependent on the buffer time
- Increasing the number of trains per hour significantly increases the ration of double track required
- Capacity of a double track is significantly higher than for single track. With 3 min buffer time the capacity is about 5 times higher.
- The loss of running time due to speed restrictions on the diverging track in passing loop can potentially be very high based on the speed difference.
- Higher performance trains can save running times if the speed varies greatly of a line
- Stations can be one of the biggest bottlenecks on the line if not design adequately.
- Having an alternate stopping pattern allows for high frequent and low frequent stations on the same line.

The Author recommends that the train performance calculator should be further developed to include train following each other in conveys and a relative cost factor. It should also be evaluated against a simulator to verify the result in this report.

The train performance calculator and a detailed description of the functions are available online on the webpage of the Author until another suitable method of hosting will be been solved: http://www.sampawar.com/msc/

The train performance calculator is considered a part of the delivery of this report.

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Glossary of Terms / List of Abbreviations

Term	Explanation / Meaning / Definition
ADT	Acceleration Distance Reduced (speed, for loop calculations)
AS	Approach Section
ATC	Automatic Train Control
BS	Block Section
BD	Braking Distance
BDR	Braking Distance Reduced (speed, for loop calculations)
BT	Buffer Time
CO_2	Carbon Dioxide
DOT	Department of Transportation’s
EMU	Electrical Multiple Unit
ERTMS	European Rail Traffic Management System
EU	European Union
FRA	Federal Railroad Administration
HD	Headway
HS	Headway Section
HSR	High Speed Rail
HST	High Speed Train
UIC	Internationale des Chemins de fer (International Union of Railways)
RSP	Rolling Stock Performance

Term	Explanation / Meaning / Definition
RF	Route Formation
RR	Route Release
STS	Single Track Section
TE	Tractive Effort
TGV	Train à Grande Vitesse
TL	Train Length
TPC	Train Performance Calculator
TPH	Trains Per Hour
TS	Turnout Section (Distance)
VD	Visual Distance

Notation – Variable and Constants

Symbol	Unit	Explanation / Meaning / Definition
$a(v)$	m/s^2	Acceleration related to velocity
f_ρ		Rotating mass factor
F_G	kN	Gradient resistance force
F_{max}	kN	Maximum starting force
$F_R(v)$	kN	Total resistance force
$F_{Tr}(v)$	kN	Tractive effort force
g	m/s^2	Acceleration due to gravity
m	t	Mass of train
P	kW	Power of all motors
r_0	kN	Mass-related coefficient of mechanical resistance
r_1	$kN\,s/m$	Viscous mass-related coefficient of mechanical resistance
r_2	$kN\,s^2/m^2$	Coefficient of aerodynamic resistance
s	m	Distance travelled

Symbol	Unit	Explanation / Meaning / Definition
t	s	Time elapsed
v	$m/_s$	Velocity
v'	$m/_s$	Initial velocity
v''	$m/_s$	Exit velocity
v_{max}	$m/_s$	Maximum velocity
α	%	Grade

1 Introduction

1.1 Brief

Transport systems can be appreciated as the backbone of modern societies and involves car, bus, ship, air and rail services to mention some of the most common systems. The range of railway types can be tailored to fit different systems designed for capacity, frequency and distance demands, e.g. trams, metros, local, regional, intercity, etc. In this report, the Author will focus on High Speed Rail (HSR), a rapid mode for travelling between two cities with distances ranging 100 – 800 km apart.

HSR offers passengers a safe, fast and comfortable mode of transport. Adding the benefit of city-centre to city-centre stops, it becomes one of the most preferable methods of travelling today. The low level of friction between the rail and the wheel also allows HSR to market itself with the benefit of being environmentally friendly, with low emission rates of carbon dioxide (CO_2) per passenger kilometre. Naturally, HSR has been appraised by many as the transport system of the 21st century

Controversially, HSR systems are very expensive to construct and to operate, not to mention the maintenance and repair required over time. With immense competition from road and air transport there is a need to design the HSR system as cost-effectively as conceivable, though not compromising the future capacity demand. Single track rail might just be the solution to reduce the capital cost and deliver the level of quality demanded.

However, as single track railway systems are much more interdependent than double track it requires careful planning of the passing loops, based on the infrastructure, the rolling stock performance and the timetable.

HSR on single track does not exist at the moment anywhere in the world and the demand for such a system is limited due to its operational and capacity constraints. The closest comparable system is the Botniabanan in Sweden, however it is not considered to be a true HSR system as its maximum operating speed is only 200 km/h.

1.2 Scope

In this report the Author intends to investigate the concept of HSR on single track infrastructure. To analyse HSR on single track important aspects of this report include rolling stock performance, capacity calculations, crossing loop design and the relationship between capacity and required infrastructure. Also, in the report the Author will review some of the general principles of planning, designing and operating HSR on single track. Definition, history and technological aspects of HSR will also be examined in this report.

Even though cost is one of the main driver for considering HSR on single track, the costs analysis itself are outside of the scope. However, where it is found appropriate by the Author some references to relative costs assumptions will be made. It is not intended to deliver a specific design solution for a particular network as each system is unique and must be treated in that sense. This report is rather aimed to inspire for continuous work on understanding HSR on single track.

1.3 Methodology

The Author has based this report on information and literature reviews found in research papers, journals, books and on the world wide web (internet). Also, directives, legislations and standards have been used as a resource for this paper. There is not assigned a literature review section; however reviews have been done through the text in the report. The Author has done a great deal of analytical research and calculations. All calculations are presented with formulas, either in the report itself or in the appendixes. Where there is insufficient information available to the Author, reasonable assumptions have been qualitatively chosen for the calculations. Some simplifications are made to the calculations where needed. In addition to the report the Author has developed a calculator in Excel. Most of the calculations found in this report are created in this calculator. This calculator can be used to calculate, control and to evaluate different scenarios than the Author has used in this report and is a part of the report. The information found in this report is based on entirely theoretical assumptions and values which are viewed as general.

1.4 Assignment structure

The report is divided into 7 sections. Besides the normal introduction, the Author will present the reader to some background information on HSR, featuring some early history and technological developments in the second section. Also, the components and the complexity of railways will be examined in this section. In the third section the focus will be directed towards rolling stock performance characteristics, how it is calculated and how it affects the operations and why it has a great influence on single track railways. The fourth section has been devoted to capacity by investigating the definitions and the theoretical capacity of both double track and single track. In the fifth section the Author will bring the attention to the main feature of single track railways, the passing loops. The design, placement and length calculations will be analysed. The sixth section have been dedicated to one of the key findings in this report, the effect of double track ration on a single track railway by increasing the capacity and speed. Other associated issues related to single track operations have been briefly investigated in the seventh section. Finally, the conclusions can be found in section 8, before the references and appendixes.

2 Background

2.1 Definition of HSR

The term “high speed” is a vague term as it can have different meanings in different places, but also as its definition can change over time, e.g. due to advancement of railway technology. At the moment, the definition of HSR which is recognised in several places around the world is set by the European Union (EU) Directive 96/84/EC and supported by the Union Internationale des Chemins de fer (UIC), also known as International Union of Railways. Principally, the EU Directive defines HSR as where the infrastructure and rolling stock allows for services of 250km/h or more. An extract of the Directive is given underneath.

> ”
>
> **1. Infrastructure**
> ***a) The infrastructure of the trans-European High Speed system shall be that on the trans-European transport network identified in Article 129C of the Treaty:***
>
> - *those built specially for High Speed travel,*
> - *those specially upgraded for High Speed travel. They may include connecting lines, in particular junctions of new lines upgraded for High Speed with town centre stations located on them, on which speeds must take account of local conditions.*
>
> ***(b) High-speed lines shall comprise:***
>
> - *specially built high-speed lines equipped for speeds generally equal to or greater than 250 km/h,*
> - *specially upgraded high-speed lines equipped for speeds of the order of 200 km/h,*
> - *specially upgraded high-speed lines which have special features as a result of topographical, relief or town-planning constraints, on which the speed must be adapted to each case.*
>
> ***2. Rolling stock***
> *The High Speed advanced-technology trains shall be designed in such a way as to guarantee safe, uninterrupted travel:*
>
> - *at a speed of at least 250 km/h on lines specially built for High Speed, while enabling speeds of over 300 km/h to be reached in appropriate circumstances,*
> - *at a speed of the order of 200 km/h on existing lines which have been or are specially upgraded,*
> - *at the highest possible speed on other lines.*
>
> ***3. Compatibility of infrastructure and rolling stock***
> *High Speed train services presuppose excellent compatibility between the characteristics of the infrastructure and those of the rolling stock. Performance levels, safety, quality of service and cost depend upon that compatibility.*
>
> ”

Figure 2 - Definition of High Speed Rail (The Council Of The European Union, 1996)

As mentioned above, this definition is only affective in the EU, even though it is recognised in other places as well. For example, the U.S. Department of Transportation’s (DoT) Federal

Railroad Administration (FRA) has defined high speed rail into three different categories in their latest strategy and vision for HSR in America (Federal Railroad Administration, 2009).

- Express High Speed Rail – top speed of 150 mph (ca 240 km/h), distances of 200 – 600 miles (ca 320 – 970 km) completely grade separated.
- Regional High Speed Rail – top speed of 110 – 150 mph (ca 180 – 240 km/h), distances of 100 – 500 miles (ca 100 – 800 km) and grade separated.
- Emerging High Speed Rail – top speed of 90 – 110 mph (150 – 180 km/h), distances of 100 – 500 miles (ca 100 – 800 km) on primarily shared track (upgraded).

Another common term is the “Very High Speed Rail” which is quite often used, also within the EU. This term is often used for systems operating with speeds higher than 250km/h, e.g. 300km/h and upwards as high as 500km/h.

Despite the different definitions of HSR, this report recognise HSR as rail systems with infrastructure and rolling stock capable of operating services at speeds of 250km/h and above.

2.2 Operations of High Speed Rail Systems

The infrastructure directly affects the operation of HSR systems and it gives the limitations of how the system can be utilised. Around the globe there are several different approaches on how the operations of HSR are done. The strategy for choosing the appropriate solution for any given HSR system is not straight forward and relies on the circumstances of the locations where it will be built. Some places may be heavily urbanised, thus the space required for constructing a new HSR line may be impossible to find without drastic measures which again will cost a huge amount of money. How the existing network is built, the costs of upgrading versus the cost of building new, the demand, the travel times will all affect the different methods for choosing the infrastructure for a HSR. Also, the total distance of HSR lines and the distances between intermediate stations will have an influence in this matter. The author has identified different methods of operations of HSR around the globe. The matrix below shows how the different operation types are set up based on the infrastructure and type of rolling stock that will be a part of it.

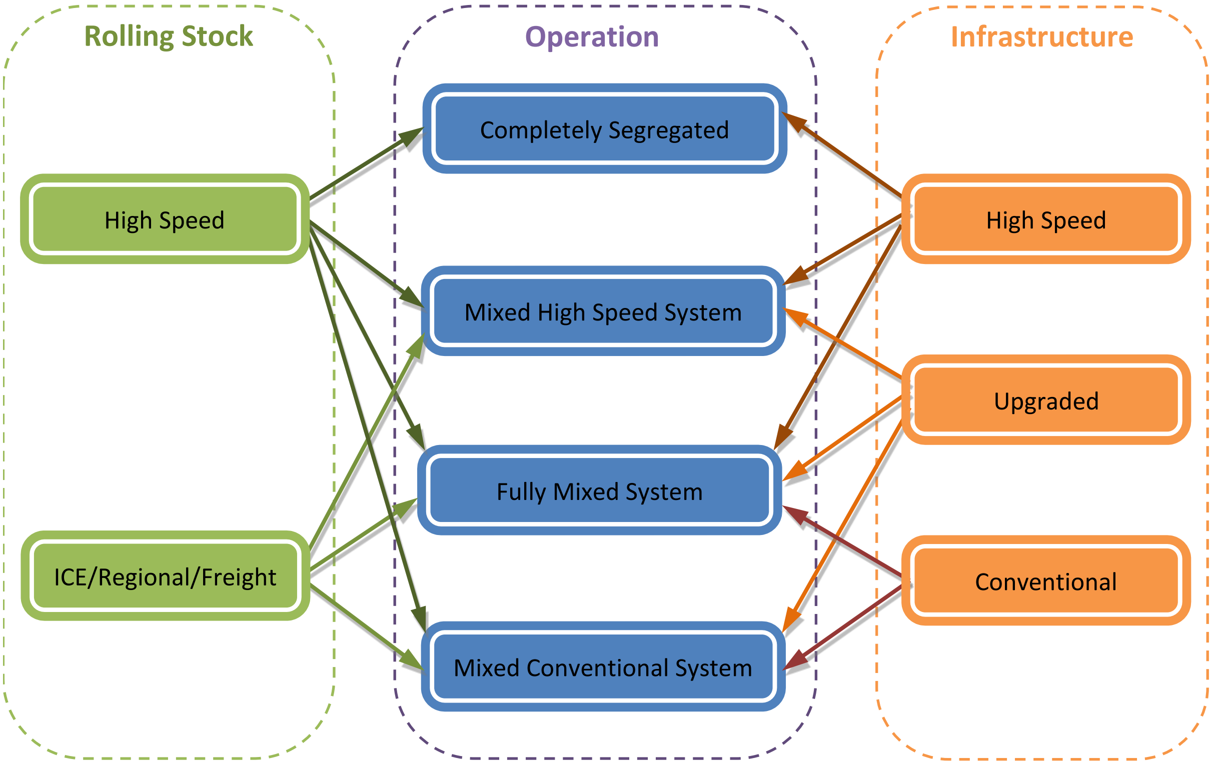

Figure 3 – Types of high speed train operations (Author)

2.2.1 Completely segregated

Completely segregated HSR systems are the most preferable in terms of capacity and are used in places where there are very high traffic demands. A system entirely dedicated to HSR services is characterized by infrastructure which is specifically design for HSR operations only and does not allow for any other train services to enter the infrastructure. It does not allow the HSR to enter upgraded or conventional tracks either. The advantages are especially the homogeneousness properties of rolling stock and the lack of influences from external operations which leads to high capacity, reliability and punctuality of the services provided. A good example is the Japanese Shinkansen system with its nearly 50 years of service still has not had any fatal accidents. The Tokyo Naikada station is one mos, and the high capacity between the Shinkansen line of Tokyo and Osaka which operates with up to 400 000 passenger per day (UIC Paris, 2010). The introduction of other HSR systems such as the magnetic levitated system MAGLEV are also relevant to this category even though it operates on a different type of propulsion and track structure.

2.2.2 Mixed High Speed System

Another method to utilise the infrastructure more efficiently, if there are capacity available, is to introduce other services than HSR to the HSR infrastructure, partly or fully. By doing so the total capacity of the line would be reduced quite dramatically as will be described in the capacity sections. However, if it is assumed that the introduced services exploit the spare capacity this could lead to improved local and intercity services. Moreover, construction costs may be reduced. This method relates to the French system where in some situations the TGV also runs on re-electrified tracks of conventional lines

2.2.3 Mixed Conventional System

The opposite approach is to allow both high-speed and conventional services to operate on the provided existing infrastructure, of which maximum flexibility may be achieved. This model is for instance used in Germany with the ICE trains and in on the Rome-Florence line in Italy. However, such comprehensive/broad use of the infrastructure may lead to greater maintenance costs.

2.2.4 Fully Mixed System

The last method is to introduce HSR to conventional infrastructure. This may be done in areas where it is not justifiable to build new infrastructure, such as in urban areas. This can however only be done in small sections.

(Campos and Rus, 2009)

3 Rolling Stock Performance

In this section the author will discuss the fundamental principles of rolling stock performance (RSP). There will also be a comparison of High Speed (HS) rolling stock and a series of calculations will be performed to provide necessary input to be used throughout this report.

3.1 The Importance of RSP

RSP can provide timetable planners with necessary information such as acceleration characteristics, maximum speed and deceleration distances. These, among other important inputs such as demand and infrastructure details, can help planners to estimate running times and generate timetables. However, the process is slightly different when designing for a single track. The main difference lies in the fact that RSP feeds the infrastructure designer with important input on the placement of crossing loops, which will be discussed in section 5. The reason for this is that unlike double track operations, single track operations rely on optimum placement of crossing loops to save infrastructure cost and running times.

Double track operation can be expressed as a system with infinite number of possible meeting points, as trains can pass each other at any place at any time. However, single track operation is restrained to a defined range of meetings points given by the infrastructure as sections of double track, also known as passing loops.

A simplified overview of the overall process from demand to a product of HSR can be presented as in the illustration below:

Figure 4 – Overview of process from demand to operation (Author)

Consider a flat tunnel-free line between two stations, A and B, where trains are allowed to operate at maximum train speed throughout the journey in both directions. This will give a meeting point at the middle of the section with equal starting time at both ends. This hypothesis is valid for all different types of rolling stock provided that the meeting trains have identical RSP.

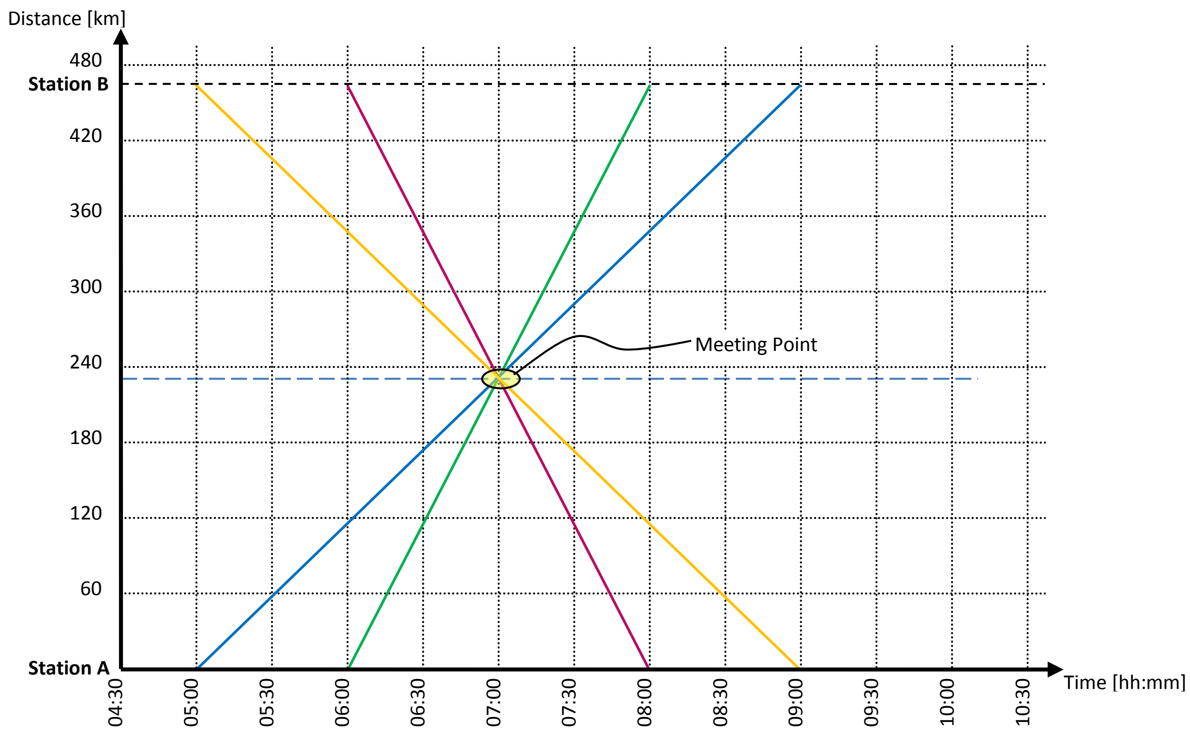

Figure 5 – Equal speed increase in both directions require the same middle meeting point (Author)

The figure above illustrates two dissimilar rolling stock classes, one fast running and one slow running. The figure validates the hypothesis of evenly positioned meeting points regardless of speed. However, in a real situation the probability to have such perfect conditions are very low as naturally the infrastructure is not uniform throughout the line. The infrastructure consists of different gradients, curves, tunnels and other infrastructure elements which can have a large impact on the performance of a train. Furthermore, the infrastructure is commonly locked to pre-specified meeting points due to station positioning etc. In view of these factors it is evident that trains with different RSP will have different meeting points given the same infrastructure.

As single track operations are much more inherently connected to the infrastructure than double track, there are some important differences in the structure of the planning and design phase. For double track it is important to know the demand to create a draft timetable. This will then give input to the infrastructure design, such as track layout, station layout, signalling systems etc. After the draft infrastructure concept design is done, infrastructure information can then be fed back to the timetable design. This iteration process will continue until a good design is accomplished. The influence of RSP does not necessary need to be very detailed as double track operation is more flexible to adapt to different rolling stock. However, some requirements for RSP can be defined as a result of infrastructure constraints and timetable demands.

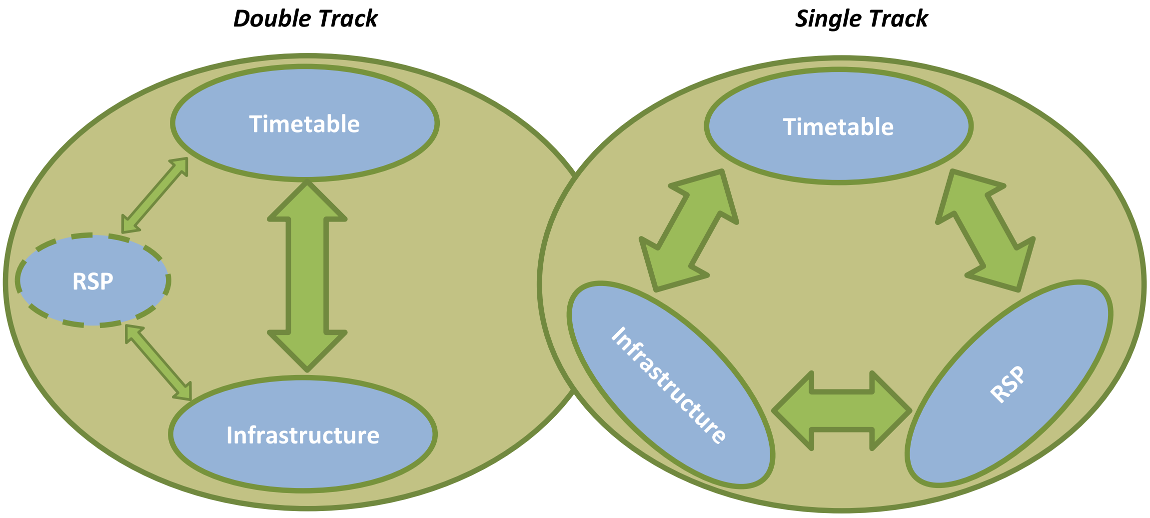

Figure 6 – Detailed viewed of the iteration process in the planning & design phase (Author)

For a single track the same process of iteration between the timetable and the infrastructure is required, with the demand as the central input. As seen above, the RSP is much more important during the planning and design phase for single track than for double track. Slight changes in the RSP can alter the position of the train over time. This can lead towards two outcomes depending on the performance. With lower RSP it is likely that either of the trains will reach the meeting point later than the first approaching train. This will lead towards poor infrastructure utilisation and lower capacity, as trains must wait at the crossing loops for the oncoming train.

Trains with higher RSP cannot exceed the design speed and the opportunity to exploit the additional performance is limited to recovering lost time with by faster acceleration and higher speeds up slopes as the meeting point is fixed. In single track operations the running speed will also influence the length of the passing loops which will be discussed in section 5. Thus, the RSP is of important value to planning and design phase and therefore it must be included in the iteration process at a level closer to timetable and infrastructure design.

3.2 Tractive Effort

Tractive Effort (TE) is the force produced by the torque of the traction motor, which is used for accelerating a train. The amount of forces that can be transferred to the rail from the wheel can only be transmitted through a small contact area, also known as the contact patch. The transmission of TE forces as a vertical force to the rail are limited by the available adhesion and the load transferred to the rail in the contact patch. The contact patch is only about 50mm^2 in area (Dweyer-Joyce et al., 2009), and it is illustrated as a tiny red zone in the figure below.

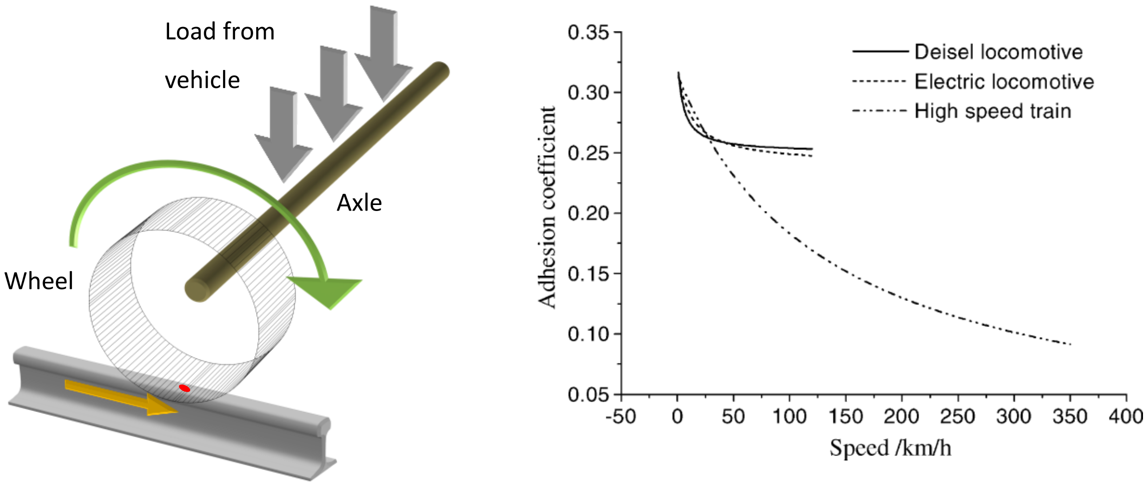

Figure 7 – Contact patch (Author) and level of adhesion coefficient (Weihua et al., 2002)

The following equation is a proposed method to estimate the level of adhesion available for HSR (Weihua et al., 2002).

$$\mu = 0.24 + \frac{8}{100 + 8v} \qquad \textit{Equation 1}$$

A typical TE curve is illustrated in Figure 8, with the speed on the x-axis and the force on the y-axis. There are three regions of the TE forces.

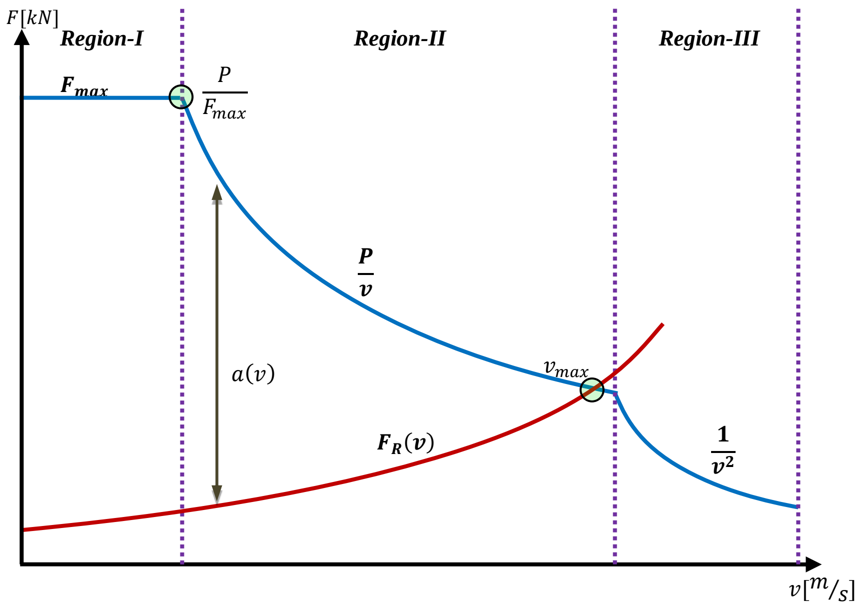

Figure 8 – Typical tractive effort and resistance graph (Author) (Hillmansen, Schmid and Schmid, 2011)

The first region is limited by two factors; the first is the motoring limit and the second is the adhesion limit. Since TE is related to the power divided by speed, at low speeds the engine would in theory produce extreme values of TE, overloading the motor which eventually would breakdown. The adhesion limit will only allow a certain amount of force to be transferred between the wheel and the rail before it starts to slip (accelerating) or slide (braking).

In the second region the motor is running with maximum power and the force available is therefore limited to the general formula of mechanical power:

$$P = Fv$$ *Equation 2*

$$F = \frac{P}{v}$$ *Equation 3*

In the third region, the motor approaches its maximum limitations and the current and the flux is reduced at a greater rate to avoid motor excitation (Hillmansen, Schmid and Schmid, 2011). To simplify further calculations done in this report the author has assumed that the given rolling stock will reach its maximum speed within region two, thus region three will be left out of the calculations.

In Figure 8 the train resistance is also plotted as it has a major impact on the performance of the rolling stock, which is the sum of all forces opposed to the driving movement (Steimel, 2008). The total resistance force consists of two types of resistance, inherent and incidental.

$$F_{R(Davis)}(v) = A + Bv + Cv^2$$ *Equation 4*

The inherent resistance consist of mechanical rolling resistance and aerodynamic resistance (Kutz, 2003), which associates to the coefficients of the Davis Equation A, B and C. These coefficients are normally experimentally measured by a series of run-down tests in perfect wind still open-air conditions. These coefficients are not valid in other conditions, e.g. tunnels, high winds etc. There are methods for estimating these coefficients based on calculation using fundamental laws of physics, however such approximation are not necessary suitable for train performance calculations as there are many complex factors which can lead to inaccurate data (Rochard and Schmid, 2000). In this report the coefficients A, B and C are renamed to resistance factor r_0, r_1 and r_2 respectively.

$$F_{R(Davis)}(v) = r_0 + r_1 v + r_2 v^2$$ *Equation 5*

At lower speeds the mass is the dominant factor of resistance, which in the Davis Equation is represented by coefficients r_0 and r_1. Coefficient r_2 represents the aerodynamics resistance and is related to the square of the speed. At higher speeds the aerodynamic resistance becomes the dominant factor (Rochard and Schmid, 2000), and thus there is a desire to reduce this factor for HST by improving the aerodynamic design.

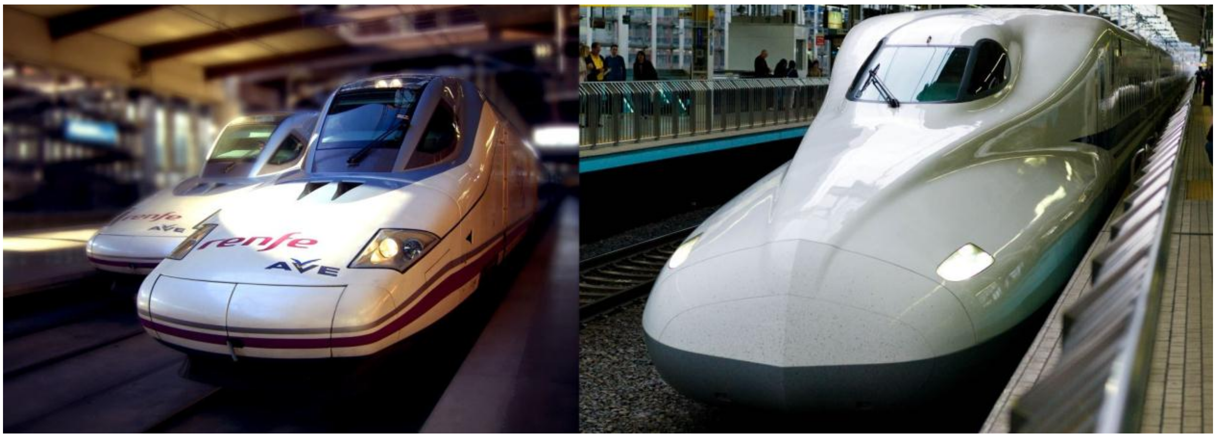

Figure 9 – Aerodynamic nose of Bombardier S-102 (Ortega, 2007) and Hitachi N700 (Ito, 2008)

The incidental resistance is a result of resistance due to grade, curvature, wind and vehicle dynamics (Kutz, 2003). The resistance due to horizontal curvature with radius higher than 700m is relatively low (Hansen and Pachl, 2008) and therefore they are assumed by the author not to be relevant for HSR calculations where all speeds require curvatures with radius far above this level. In this report, the author has left the incidental resistance forces out of the calculations as they will vary along a given infrastructure, with the exception of the gradient resistance which is present in some calculations where mentioned.

3.3 Formulas of motion

The resultant force of TE minus F_R is the force available for acceleration. This force divided by the total mass of the train gives the acceleration rates. From the TE figure it becomes apparent that the acceleration is not constant, making the basic formulae for motion invalid as they assume constant acceleration. This can however be resolved by solving a series of differential equations (Hansen and Pachl, 2008). For the two regions of tactive effort the author has identified four differential equations that must be solved in order to calculate the distance and the time consumed for accelerating.

The limitations for the regions are defined below:

Region 1

$$F_{Tr}(v) = F_{max}\,, \quad 0 \leq v \leq \frac{P}{F_{max}}$$ *Equation 6*

Region 2

$$F_{Tr}(v) = \frac{P}{v}\,, \quad \frac{P}{F_{max}} < v \leq \frac{P}{v_{max}}$$ *Equation 7*

The total resistance F_R is:

$$F_R(v) = r_0 + r_1 * v + r_2 * v^2 + F_G$$ *Equation 8*

Where the gradient force F_R is:

$$F_G = m * g * \frac{\alpha}{100}$$ *Equation 9*

Acceleration is equal to TE minus F_R divided by the mass and a rotating mass factor:

$$a(v) = \frac{F_{Tr}(v) - F_R(v)}{f_\rho * m}$$ *Equation 10*

Solving variable acceleration related to variable speed is done best by solving it as differential equation:

$$F_{Tr}(v) - F_R(v) = f_\rho * m \frac{dv}{dt}$$ *Equation 11*

Where the result of time and distance can be presented by:

$$t = \frac{v'' - v'}{a(v)}$$ *Equation 12*

$$s = \frac{v^{2''} - v^{2'}}{2a(v)}$$ *Equation 13*

The following operations merge the equations above to a differential equations solved by integration. First the expression for calculating time elapsed is defined.

$$t = \int_{v'}^{v''} m * f_\rho \frac{dv}{F_{Tr}(v) - F_R(v)}$$ *Equation 14*

Then the different variables are inserted in the general expression. This equation is only valid for the first region, where there is constant traction.

$$For \quad 0 \leq v \leq \frac{P}{F_{max}}$$ *Equation 15*

$$t = \int_{v'}^{v''} m * f_\rho \frac{dv}{F_{max} - (r_0 + r_1 * v + r_2 * v^2 + F_G)}$$ *Equation 16*

$$t = \int_{v'}^{v''} \frac{m * f_\rho}{F_{max} - (r_0 + r_1 * v + r_2 * v^2 + F_G)} dv$$ *Equation 17*

The next step is to do the same for region two, where traction is not constant.

$$For \quad \frac{P}{F_{max}} < v \leq \frac{P}{v_{max}}$$ *Equation 18*

$$t = \int_{v'}^{v''} m * f_\rho \frac{dv}{\frac{P}{v} - (r_0 + r_1 * v + r_2 * v^2 + F_G)}$$ *Equation 19*

$$t = \int_{v'}^{v''} \frac{m * f_\rho * v}{P - \left((r_0 + F_G) * v + r_1 * v^2 + r_2 * v^3\right)} dv$$ *Equation 20*

Likewise, to calculate the distance travelled the expression is developed as shown below. What differentiates this expression from the expression of the time is the additional variable factor of speed (v).

$$s = \int_{v'}^{v''} v * m * f_\rho \frac{dv}{F_{Tr}(v) - F_R(v)}$$ *Equation 21*

The different variables are inserted in the general expression. This equation is only valid for the first region, where there is constant traction.

$$For \quad 0 \leq v \leq \frac{P}{F_{max}}$$ *Equation 22*

$$s = \int_{v'}^{v''} v * m * f_\rho \frac{dv}{F_{max} - (r_0 + r_1 * v + r_2 * v^2 + F_G)}$$ *Equation 23*

$$s = \int_{v'}^{v''} \frac{m * f_\rho * v}{F_{max} - (r_0 + r_1 * v + r_2 * v^2 + F_G)} dv$$ *Equation 24*

The next step is to do the same for region two, where traction is not constant.

$$For \quad \frac{P}{F_{max}} < v \leq \frac{P}{v_{max}}$$ *Equation 25*

$$s = \int_{v'}^{v''} v * m * f_\rho \frac{dv}{\frac{P}{v} - (r_0 + r_1 * v + r_2 * v^2 + F_G)}$$ *Equation 26*

$$s = \int_{v'}^{v''} \frac{m * f_\rho * v^2}{P - \left((r_0 + F_G) * v + r_1 * v^2 + r_2 * v^3\right)} dv$$ *Equation 27*

The author did not succeed in analytically solving these differential equations as they are fairly complex. The main issue remained in solving the integration of cubic equations where the author identified a high degree of potential mistyping/miscalculation in the process of solving the root values. Cubic equations can be solved by using Mathematica software, which has built-in functions to solve cubic equations (Weisstein, 2011) but however, the author did not use this software.

Because of this problem, two approaches have been used in order to solve the equations. The first method uses a tool developed by the developers of Mathematica, Wolfram Research. The tool named "WolframAlpha" is available online for free of charge for both commercial and personal usage. It uses intelligent algorithms to compute queries in to a relevant answer. These queries can range from mathematical to natural language fact-based questions (Wikipedia, 2011). However, only a single enquire can be calculated at each time.

The second approach is the Train Performance Calculator (TPC) developed by the Author in Microsoft Excel. This calculator uses the principle of the rectangle method to approximate the solution of the differential integration. The step length of the rectangles has been chosen to be 0.1 m/s which is validated later in this section against WolframAlpha, and provides results that are above 99 % equal to WolframAlpha. In addition, the author has added several additional functions in the calculator so that all calculations in the following section will be connected to the TPC and thereby the performance of the rolling stock can be investigated. This will be described where the calculations are made.

The TPC and a detailed description of the TPC and its functions are available online on the webpage of the Author until another suitable method of hosting will be been solved: http://www.sampawar.com/msc/

3.4 High Speed Rolling Stock

There is a need to define some important performance characteristics of HSR that will form the base for the calculations in the rest of this report. Modern HS train sets usually consist of distributed traction motors along the train. These are known as Electrical Multiple Units (EMU) and have many benefits compared to conventional locomotive hauled trains. The main benefit is the level of adhesion that can be achieved as there are more axles to distribute the traction forces to. A locomotive hauled train requires high axle loads to maximise the adhesion output of the few motored axles, but as an EMU can distribute its weight along the train the maximum axle loads can be reduced quite significantly. This also reduces the infrastructure deterioration rate. Furthermore, EMU offers the advantage of higher seating capacity as the traction equipment is situated underneath the floor of the cars and the space in the locomotive cars can be used for seating (Sato, Masakatsu and Takafumi, 2010). The figure below illustrates the principle difference between a locomotive powered train and an EMU.

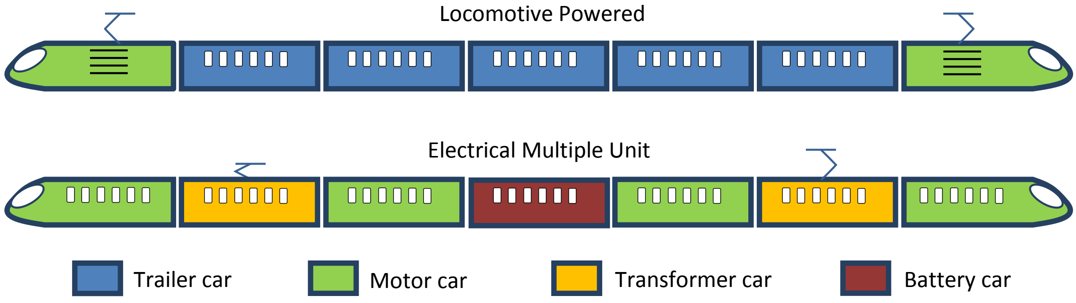

Figure 10 – Principle difference between locomotive powered train and EMU (Author)

Generally, modern EMUs are provided with about 50 % powered axles. There is however a trade-off between the number of traction motors, the total weight, axle loads and adhesion levels on an EMU. A study reveals that moderate distribution is the optimal formation (Ito and Heumann, 1997).

Modern rolling stock today offers great power outputs, high starting TE and low mass. These elements combined together leads to high performance rolling stock, yet there are quite significant differences in the mixture of performance characteristics. The following two tables summarises the train performance characteristic for modern HST. To have an equivalent base for evaluation all train s under consideration are produced after year 2000 and are approximately 200m long. The first table consist of HST from Europe and USA. The second table consist of HSTs from Asia.

Table 1 – Key performance characteristics of modern HSR – Europe and Spain

Country		**France**	**Germany**	**Italy**		**Spain**	**USA**
Operator		SNCF	DB AG	NTV	Trenitalia	Renfe	Amtrak
Class		TGV Duplex	ICE3 403	AGV11	ETR1000	AVE S 102/112	Acela
Year		2009	2000	2011	2013	2005/2010	2000
Max V	*km/h*	320	330	360	360	330	241
Max oper. V	*km/h*	320	300	300	300	300	241
Length	*m*	200	200	200	200	200	203
Empty Weight	*tonne*	380	409	416	-	322	-
Full load	*tonne*	-	-	-	500	347	566
Voltage	*kV*	25	25	25	25	25	25
Power	*kW*	9280	8000	8640	9800	8000	9200
Starting TE	*kN*	-	300	272	370	200	225
Powered axles		-	-	12/24	-	8/21	-
Max axle load	*tonne*	17	16	-	17	17	23
Acceleration	*m/s^2*	-	-	-	0,7	-	-
Deceleration	*m/s^2*	-	-	-	-	-	-
Source		***6***	***6***	***4,5,6***	***6***	***2,3,6,***	***6***

Table 2– Key performance characteristics of modern HSR – Asia

Country		**China**			**Japan**		**Korea**
Operator		China Railways			Shinkansen		KTX
Class		CRH3C	CRH380A	CRH380D	500-7000	N700-8000	KTX-II
Year		2008	2010	2010	2008	2011	2010
Max V	*km/h*	350	380	380	285	300	330
Max oper. V	*km/h*	300	350	350	285	300	300
Length	*m*	200	200	215	204	204,7	201
Empty Weight	*tonne*	447	-	462	344	356	434
Full load	*tonne*	-	-	-	-	-	-
Voltage	*kV*	25	25	25	25	25	25
Power	*kW*	8800	9600	10000	8800	9760	8800
Starting TE	*kN*	300	-	-	-	-	210
Powered axles		16/32	-	-	-	28?	-
Max axle load	*tonne*	17	15	17	-	11	-
Acceleration	*m/s²*	0,46	-	0,48	-	0,72	0,45
Deceleration	*m/s²*	-	-	-	-	-	-
Source		***1,6***	***6***	***6,7,8***	*6*	***6***	***6***

Sources: 1 (Siemens, 2009), 2 (Werske, 2011), 3 (Bombardier, 2006), 4 (Alstom, 2009), 5 (SNCF, 2006), 6 (UIC, 2011), 7 (Bombardier, 2010), 8 (Bombardier, 2010)

Based on data above the author has chosen a set of values considered to be representative of a modern HST, hereinafter known as EMU1. Newer rolling stock performance is likely to evolve with even higher performance motors, lower mass and more efficient aerodynamic design in the future. In accordance with the time it takes to plan and construct a HSL it is expected that rolling stock will have different performance characteristics. Therefore, a second generic EMU has been chosen to simulate a potential future HST, hereinafter known as EMU2. In EMU2 it is assumed that the motors have reduced mass and are fitted to at least 75% of the axles, increasing the total power effect and the starting tractive effort. Also, the total mass of the train is reduced by about 10% and the train has better aerodynamic performance.

The table underneath summarises the two generic EMU's which will be used in the calculations throughout this report. It must be emphasised that these values have been qualitatively chosen and that they do not represent any specific train in operation today. They are used in the calculations done in this report, alternative values can be chosen in the TPC provided.

Table 3 –Performance Characteristics of EMU1 and EMU2

Performance Characteristics			EMU1	EMU2
Rotating Mass Factor	f_p		1,06	1,06
Maximum Starting Force	F_{max}	*kN*	300	400
Total Mass of Train	m	*tonne*	445	400
Power of all Motors	P	*kW*	9000	12000
Mechanical Resistance	r_0	*kN*	4	4
Viscous Mechanical Resistance	r_1	*kN s/m*	0,060	0,055
Aerodynamic Resistance	r_2	*kN s²/m²*	0,0075	0,0065
Maximum Speed	V_{max}	*m/s*	101,80	121,00
Maximum Acceleration	a_{max}	*m/s²*	0,66	0,99
Average Deceleration	a_b	*m/s²*	0,70	0,70
Train Length	S_{TL}	*m*	200	200

In the table above the resistance force for the values r_0, r_1 and r_2 in the Davis Equation has been qualitatively chosen to fit a modern and future high speed EMU. The assumption is based on information found in TE graphs available from rolling stock manufactures Siemens (Siemens, 2009) and (Alstom Transport, 2006) data made available by Parsons Brinckerhoff (2008) and methods described in Rochard and Schmid (2000). The mechincal resistance is assumed to be 10N per mass tonne of the train.

However, as this data can only be provided by the rolling stock manufacturer originally and it is not usually easily available for public, the values cannot be validated. Nonetheless, the values for resistance force provided in the performance characteristics table seem reasonable as compared to the values in the table below:

Table 4 – Resistance factors for Bombardier S-102 and Hitachi N700 (Parsons Brinckerhoff, 2008)

		S-102	N700
r_0	*kN*	2,24521	5,85419
r_1	*kN s/m*	0,02678	0,06105
r_2	*kN s²/m²*	0,00055	0,00055

The author came across one document published by Jernbaneverket (2011) which contained resistance force values for several HST types, however they are provided in an uncommon format as seen in the table underneath. Based on the denomination of the number the values are provided per mass tonne of the respective trains. This is probably a more appropriate method for managing the coefficient r_0 and r_1 as they are related to the mass which increases with the number of passengers. However, for coefficient r_2 the Author questions the use of mass to calculate the aerodynamic performance.

Table 5 - HST coefficient values of resistance found in report (Jernbaneverket, 2011)

		ICE 3	ICE T	TGV	Talgo	Talgo	SJ X2	AGV
f_p		1,0422	1,0800	1,0429	1,0400	1,0400	1,0790	1,0500
m	*tonne*	448	399	427	312	322	365	410
r_0	*N / kN*	0,7799	0,8804	0,6600	0,9311	0,9133	0,6493	1,6266
r_1	*kN h/kN km*	7,92E-06	9,48E-	1,29E-	7,84E-06	1,10E-05	5,82E-	2,64E-06
r_2	*N h²/kN km²*	1,11E-04	1,30E-	1,34E-	1,76E-04	1,58E-04	1,61E-	1,15E-04

A transformation of the values to the format used in this report is done by the following equations:

$$r_{0,transformed} = \frac{100 r_0 m}{10000} \qquad \text{Equation 28}$$

$$r_{1,transformed} = \frac{60^2 r_1 m}{1000} \qquad \text{Equation 29}$$

$$r_{2,transformed} = \frac{60^4 r_2 m}{1000^2} \qquad \text{Equation 30}$$

Table 6 - Transformed HST coefficient values of resistance found in report (Author)

		ICE 3	ICE T	TGV	Talgo	Talgo	SJ X2	AGV
r_0	*kN*	3,4940	3,5128	2,8182	2,9050	2,9408	2,3699	6,6691
r_1	*kN s/m*	0,01277	0,01362	0,01978	0,00881	0,01273	0,00765	0,00390
r_2	*kN s²/m²*	0,00064	0,00067	0,00074	0,00071	0,00066	0,00080	0,00061

3.5 Performance

The performance characteristics values are used to generate the TE graphs for EMU1 and EMU2. The graph also includes resistance at different gradients. From the graph it is clear that gradients do affect the performance of rolling stock quite severely, hence the need for strict alignment parameters in railway track design. From the figure below it can be observed that the maximum speed at 4% incline is about 45 m/s (160 km/h) if the train were to run with maximum power output.

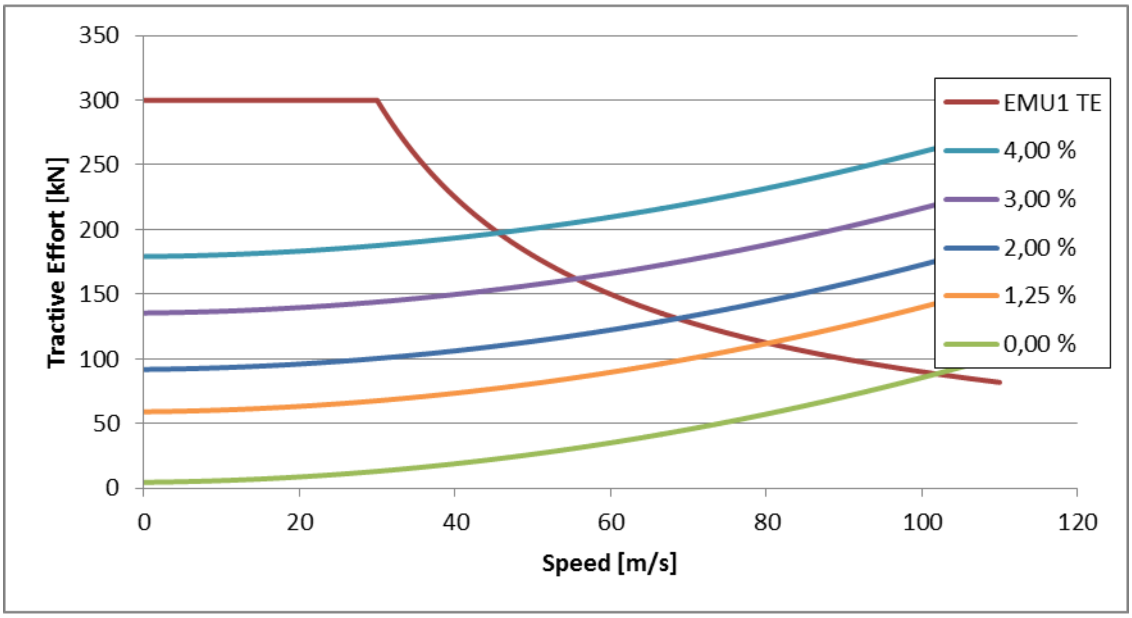

Figure 11 – Tractive effort and resistance curves for EMU1 (Author)

The TE graph for EMU2 indicates characteristics similar to EMU1. However, as the starting TE and the power output are higher there are greater tractive forces available for acceleration, which causes EMU2 to be capable of running at higher speeds on gradients. Looking at the same 4 % , the maximum speed for EMU2 is slightly above 60 m/s, approximately 220 km/h. This is a nearly a 40 % increase in speed as compared to EMU1.

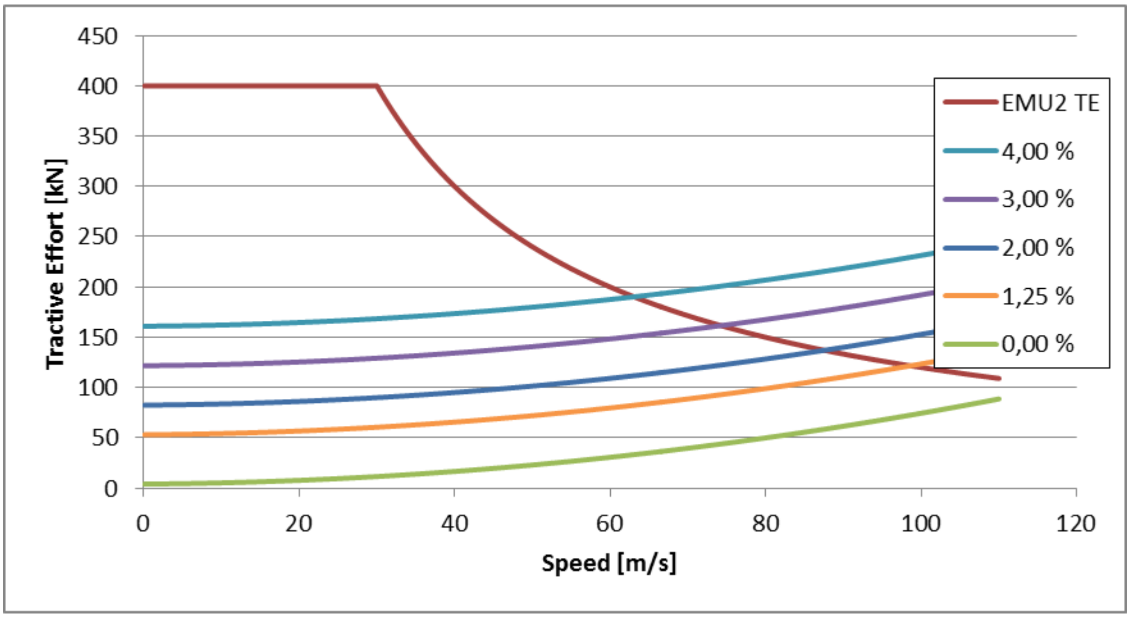

Figure 12 – Tractive effort and resistance curves for EMU2 (Author)

The following figure presents the traction power needed to accelerate at a maximum rate and the power required in maintaining a constant speed.

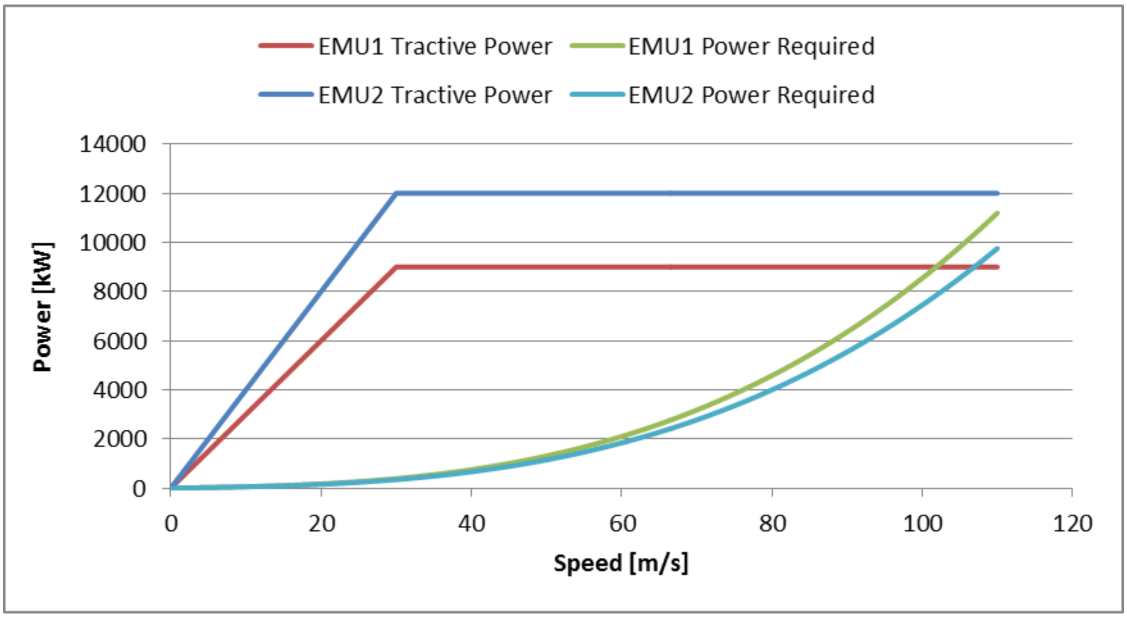

Figure 13 – Power required for maximum acceleration and for maintaining line speed (Author)

For maximum acceleration in the first region the power output linearly rises towards maximum until it reaches the second region. The second region is characterised by constant maximum power output. Maintaining line speed consumes relatively small amounts of power at low speeds, but at higher speeds this power consumption increases considerably which can be observed in the figure above.

3.6 Calculations

The difference between the EMU's in acceleration performance will be assessed in this section by calculating the time elapsed and distance travelled to reach selected speeds. To verify the accuracy of the TPC, this calculation is done with the WolframAlpha tool and then compared towards the results found in the TPC. With the WolframAlpha tool the calculation must be done in minimum two steps for both time and distance due to the change in TE regions.

The calculation has been divided into 4 speed ranges. The first speed range that is assessed is 0-30 m/s (0-108 km/h) as 30 m/s is the intersection point between the two first TE regions. From 30 m/s the calculation is separated into 30-69.4 m/s (108-250 km/h), 69.4-83.3 m/s (250-300 km/h) and 83.3-97.2 m/s (300-350 km/h).

In the following table the calculations performed with WolframAlpha and the TPC are presented for EMU1 running at grade.

Table 7 – Speed calculations for EMU1 (Author)

Range	EMU 1	Wolfram	TPC
0-108km/h	$t = \int_{0}^{30} \frac{445 * 1.06}{300 - \left((4.45 + 0) + 0.06 * x + 0.0075 * x^2\right)} dx$	*48s*	*49s*
108-250km/h	$t = \int_{30}^{69.4} \frac{445 * 1.06 * x}{9000 - \left((4.45 + 0) * x + 0.06 * x^2 + 0.0075 * x^3\right)} dx$	*127s*	*127s*
250-300km/h	$t = \int_{69.4}^{83.3} \frac{445 * 1.06 * x}{9000 - \left((4.45 + 0) * x + 0.06 * x^2 + 0.0075 * x^3\right)} dx$	*103s*	*109s*
300-350km/h	$t = \int_{83.3}^{92.7} \frac{445 * 1.06 * x}{9000 - \left((4.45 + 0) * x + 0.06 * x^2 + 0.0075 * x^3\right)} dx$	*264s*	*256s*
0-108km/h	$s = \int_{0}^{30} \frac{445 * 1.06 * x}{300 - \left((4.45 + 0) + 0.06 * x + 0.0075 * x^2\right)} dx$	*730m*	*735m*
108-250km/h	$s = \int_{30}^{69.4} \frac{445 * 1.06 * x^2}{9000 - \left((4.45 + 0) * x + 0.06 * x^2 + 0.0075 * x^3\right)} dx$	*6791m*	*6812m*
250-300km/h	$s = \int_{69.4}^{83.3} \frac{445 * 1.06 * x^2}{9000 - \left((4.45 + 0) * x + 0.06 * x^2 + 0.0075 * x^3\right)} dx$	*7975m*	*8393m*
300-350km/h	$s = \int_{83.3}^{97.2} \frac{445 * 1.06 * x^2}{9000 - \left((4.45 + 0) * x + 0.06 * x^2 + 0.0075 * x^3\right)} dx$	*24254m*	*23851m*

Comparison of the TPC is measured against the results from WolframAlpha for EMU1:

Table 8 – Comparison of results for EMU1 (Author)

	Time			**Distance**		
Range	Wolfram	TPC		Wolfram	TPC	
0-250km/h	*175s*	*176s*	***99.43%***	*7520m*	*7542m*	***99.71%***
0-300km/h	*279s*	*279s*	***99.96%***	*15495m*	*15467m*	***99.82%***
0-350km/h	*543s*	*546s*	***99.45%***	*39749m*	*40065m*	***99.21%***

In the following table the calculations performed with WolframAlpha and the TPC are presented for EMU2 running at grade.

Table 9 – Speed calculations for EMU2 (Author)

Range	EMU 2	Wolfram	TPC
0-108km/h	$t = \int_0^{45} \frac{400 * 1.06}{400 - ((4+0) + 0.055 * x + 0.0065 * x^2)} dx$	*32s*	*33s*
108-250km/h	$t = \int_{45}^{69.4} \frac{400 * 1.06 * x}{12000 - ((4+0) * x + 0.055 * x^2 + 0.0065 * x^3)} dx$	*79s*	*79s*
250-300km/h	$t = \int_{69.4}^{83.3} \frac{400 * 1.06 * x}{12000 - ((4+0) * x + 0.055 * x^2 + 0.0065 * x^3)} dx$	*54s*	*56s*
300-350km/h	$t = \int_{83.3}^{97.2} \frac{400 * 1.06 * x}{12000 - ((4+0) * x + 0.055 * x^2 + 0.0065 * x^3)} dx$	*85s*	*82s*
0-108km/h	$s = \int_0^{45} \frac{400 * 1.06 * x}{400 - ((4+0) + 0.055 * x + 0.0065 * x^2)} dx$	*487m*	*490m*
108-250km/h	$s = \int_{45}^{69.4} \frac{400 * 1.06 * x^2}{12000 - ((4+0) * x + 0.055 * x^2 + 0.0065 * x^3)} dx$	*4188m*	*4200m*
250-300km/h	$s = \int_{69.4}^{83.3} \frac{400 * 1.06 * x^2}{12000 - ((4+0) * x + 0.055 * x^2 + 0.0065 * x^3)} dx$	*4118m*	*4312m*
300-350km/h	$s = \int_{83.3}^{97.2} \frac{400 * 1.06 * x^2}{12000 - ((4+0) * x + 0.055 * x^2 + 0.0065 * x^3)} dx$	*7706m*	*7544m*

The accuracy of the TPC is measured against the results from WolframAlpha for EMU2:

Table 10 – Comparison of results for EMU2 (Author)

	Time			Distance		
Range	Wolfram	TPC	**Acc.**	Wolfram	TPC	**Acc.**
0-250km/h	*111s*	*112*	***99.28%***	*4675m*	*4687*	***99.74%***
0-300km/h	*165s*	*165s*	***99.93%***	*8793m*	*8780m*	***99.85%***
0-350km/h	*250s*	*251s*	***99.60%***	*16499m*	*16560m*	***99.63%***

The results above suggest that the speed step used for the approximation in the TPC provides accurate enough results to be used in this report.

From the following table we can see how much time it takes in total for the trains to reach operating speed. This variation is related to the speed and is higher with distance than with speed. This is related to the fact that the EMU1 spends more time at higher velocity trying to reach its maximum speed and the distance travelled at higher speed is therefore added up. The table indicates that the benefits of EMUs with higher power are superior at higher speeds compared to a lower powered EMUs for reaching top speed quicker.

Table 11 – Comparison of time and distance used for EMU1 vs. EMU2 to reach given speeds (Author)

	Time			Distance		
Range	EMU1	EMU2	**EMU1 Difference**	EMU1	EMU2	**EMU1 Difference**
0-250km/h	*175s*	*111s*	***+64s (+57%)***	*7520m*	*4675m*	***+2845m (+61%)***
0-300km/h	*279s*	*165s*	***+114s (+69%)***	*15495m*	*8793m*	***+6702m (+76%)***
0-350km/h	*543s*	*250s*	***+293s (+117%)***	*39749m*	*16499m*	***+23249m (+141%)***

However, the table above does not present the real time difference of the two trains. The real time difference can only be found when comparing the trains at total equal distanced travelled. The difference is presented in the table below:

Table 12 – Comparison of time elapsed for EMU1 vs. EMU2 to reach same distance and speed (Author)

	Distance Remaining	Time		
Range		Time to travel	Total Travel Time	**EMU1 Difference**
0-250km/h	*2845m*	*41s*	*152s*	***+23s (+15%)***
0-300km/h	*6702m*	*80s*	*245s*	***+33s (+14%)***
0-350km/h	*23249m*	*239s*	*489s*	***+54s (+11%)***

The difference between the EMUs in the speed range investigated is in the range of 10-15 %. This effect is not very noticeable if the line speed is kept constant, however if the line speed varies greatly and there are many station stops the difference will be accumulated and it will have a greater influence on the running times.

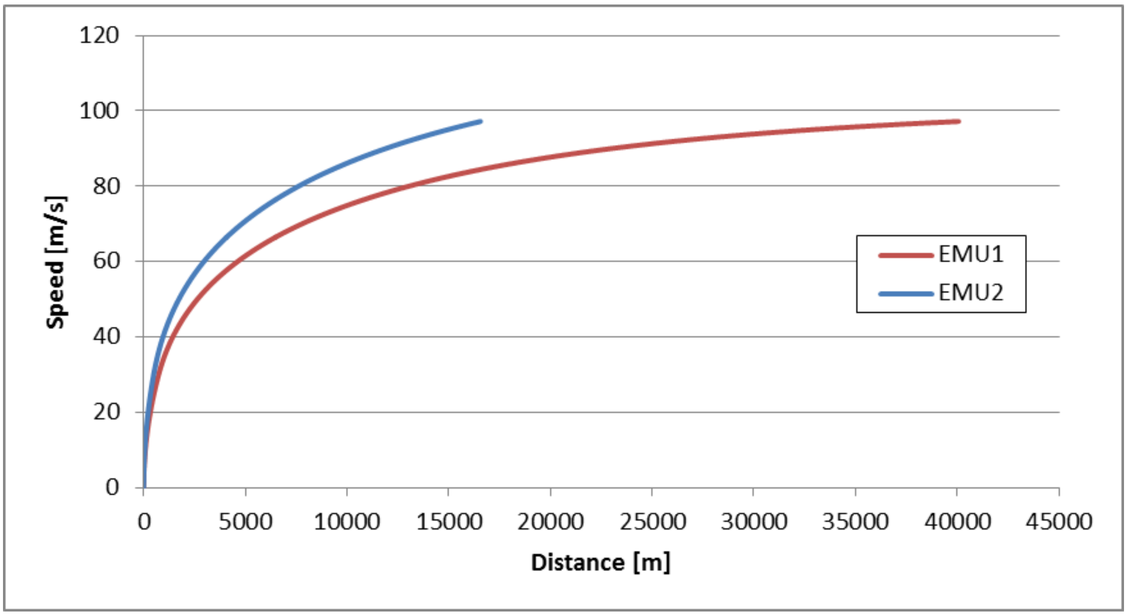

Figure 14 – Speed distance graph up to 97m/s (350km/h) (Author)

Figure 14 illustrates the distance EMU1 and EMU2 requires to reach a speed.

4 Capacity

4.1 Concept of Capacity

Capacity is a term which is defined in regards to the context it is being applied to. It is a common term and it is widely understood by the general public as a measure for the ability to or potentially receive, contain, perform, function, yield or withstand over a given time period (Dictonary.com, 2011). Within the railway context the word capacity can have several meanings depending on what is being measured, e.g. trains, passengers, goods, etc. A good definition of capacity in rail terms by Krueger is formulated as followed:

"Capacity is a measure of the ability to move a specific amount of traffic over a defined rail line with a given set of resources under a specific service plan" (Krueger, 1999).

This definition is valid for a number of performance criteria, e.g. numbers of passenger per day, passenger-kilometre, numbers of trains in peak hour, tonne-kilometre, station capacity etc. In this report the term trains per hour (TPH) will be used to measure the difference in capacity between double track and single track. TPH measures the number of trains that can pass through a section during one hour in one direction.

Some performance criteria's (Hansen, 2010):

- Number of trains, passengers and load per time period,
- Amount of passenger-kilometre and ton kilometre per time period,
- Operating and circulating speed of trains,
- Headways and buffer times,
- Scheduled waiting times,
- Time and effort for modification and updating (reschedule).

In the International Union of Railways (UIC) leaflet 406 the following definition of capacity is presented;

"Capacity as such does not exist. Railway infrastructure capacity depends on the way it is utilised. The basic parameters underpinning capacity are the infrastructure characteristics themselves and these include the signalling system, the transport schedule and the imposed punctuality level." (International Union of Railways, 2004)

It is important to recognise that capacity is in many cases a theoretical term which equivalent to the highest achievable capacity, not necessarily how the system performs in real situations. Theoretical capacity can be based on perfect conditions with homogenous rolling stock with equal performance and no perturbation in the service. However, theoretical capacity does not exist in the sense that it is not achievable for practical reasons.

The practical capacity is a more realistic approach to determine the capacity that can be achieved on a daily basis. It takes account of the actual mixed fleet of trains, signalling, and infrastructure to mention some elements (Abril et al., 2008). Furthermore, Buffer Time (BT), crossing delays (for single track), maintenance time, unusable capacity and lost capacity must be included in the calculations in order to add reliability into the system (International Union of Railways, 2004). The practical capacity can in some cases be substantially lower than the theoretical capacity, however in most circumstances it will be in the region of 60-75% of maximum achievable capacity (Abril et al., 2008). However, capacity can also be defined as how fast the system can recover from disruption by defining the level of reliability.

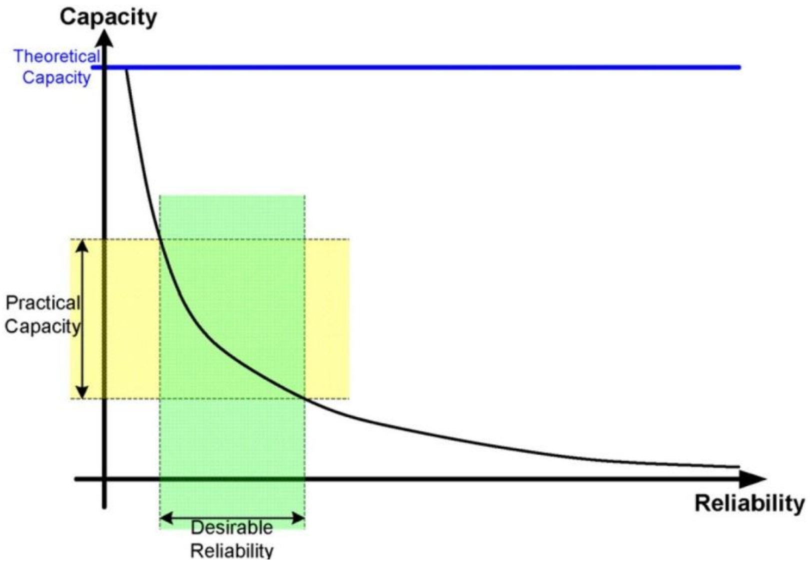

Figure 15 – Practical capacity involves the desirable reliability level (Abril et al., 2008)

The UIC leaflet 406 has made guidelines values for how much practical capacity can be achieved in the table underneath based on the current practise of European infrastructure managers. In the leaflet there is a distinction between what can be expected of capacity during the peak hour and throughout the whole day (International Union of Railways, 2004).

Type of line	Peak hour	Daily period	Comment
Dedicated suburban passenger traffic	85%	70%	The possibility to cancel some services allows for high levels of capacity utilisation.
Dedicated high-speed line	75%	60%	
Mixed-traffic lines	75%	60%	Can be higher when number of trains is low (smaller than 5 per hour) with strong heterogeneity.

Figure 16 – Achievable practical capacity values (International Union of Railways, 2004)

Introducing mixed traffic to the timetable can be very capacity consuming. The capacity can be assumed to be inversely proportional to the speed differences between two or more types of rolling stock operating on a particular section. The following figure illustrates how one slow train path consumes several HST paths, and likewise how one HST path consumes several slow train paths.

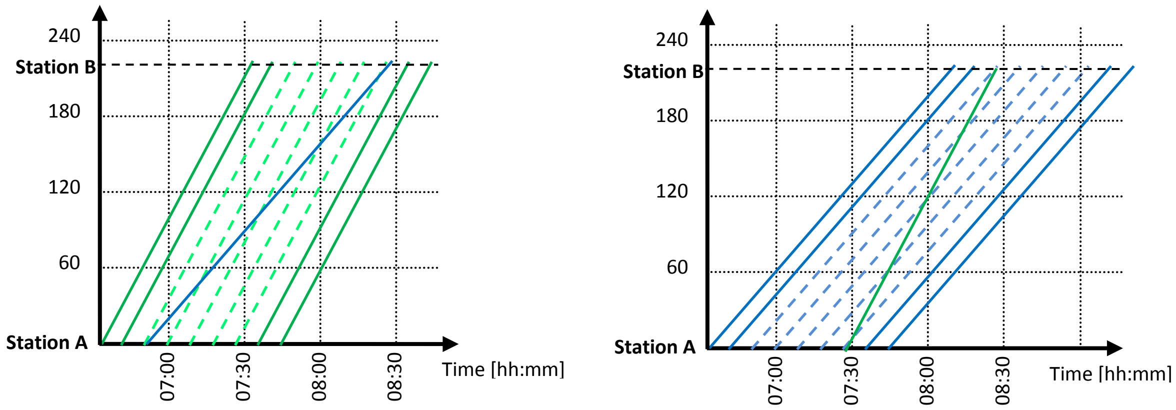

Figure 17 – Mixed traffic eliminates train paths and reduces capacity (Author)

4.2 Braking

Unlike road traffic where vehicles are separated by relative braking distance and are able to bypass hindrances by quick evasive reaction by the drivers, trains are fixed to their paths and are unable to avoid obstruction on the rail line which can lead to catastrophic outcomes. Rail operations must rely on the principle of safe train separation which requires any train to be able to stop in front of any signal at danger (red aspect). Train separation in one direction is based on the headway distance (s_{HD}) between two running trains. The main element influencing the minimum headway distance is the braking distance (s_{BD}) from full line speed and the type of signalling system. (Hansen and Pachl, 2008) [Add Second Source]

The braking distance is based on the general laws of motion and it is assumed by the Author to be a constant deceleration rate (a_b) to simplify calculations:

$$v^2 = v_i^2 + 2a_b s_{BD} \qquad \textit{Equation 31}$$

$$s_{BD} = \frac{v^2 - v_i^2}{2a_b}, v_i = 0 \qquad \textit{Equation 32}$$

$$s_{BD} = \frac{v^2}{2a_b} \qquad \textit{Equation 33}$$

The braking rate varies for different rolling stock and systems used. At greater speeds, as the kinetic energy dissipated is very high, it is common for a HST to use several types of braking systems simultaneously in order to maintain high deceleration rates throughout the braking procedure. With tread, wheel disc, disc and track braking the energy is transformed to heat by the use of friction. With regenerative, rheostatic and eddy current braking the energy can be transformed to either heat or electricity (Kang, 2007). However, track brakes and eddy current brakes are not applied through the wheel/rail interface but directly to the rail and can therefore enhance braking performance beyond the wheel/rail adhesion limit (Wang and Chiueh, 1998) (Emery, 2009).

At very high speeds, the headway between rains is mainly determined by the braking performance of the train (Emery, 2009).

The following figure illustrates the braking distance required to stop from different speeds with three different braking deceleration rates.

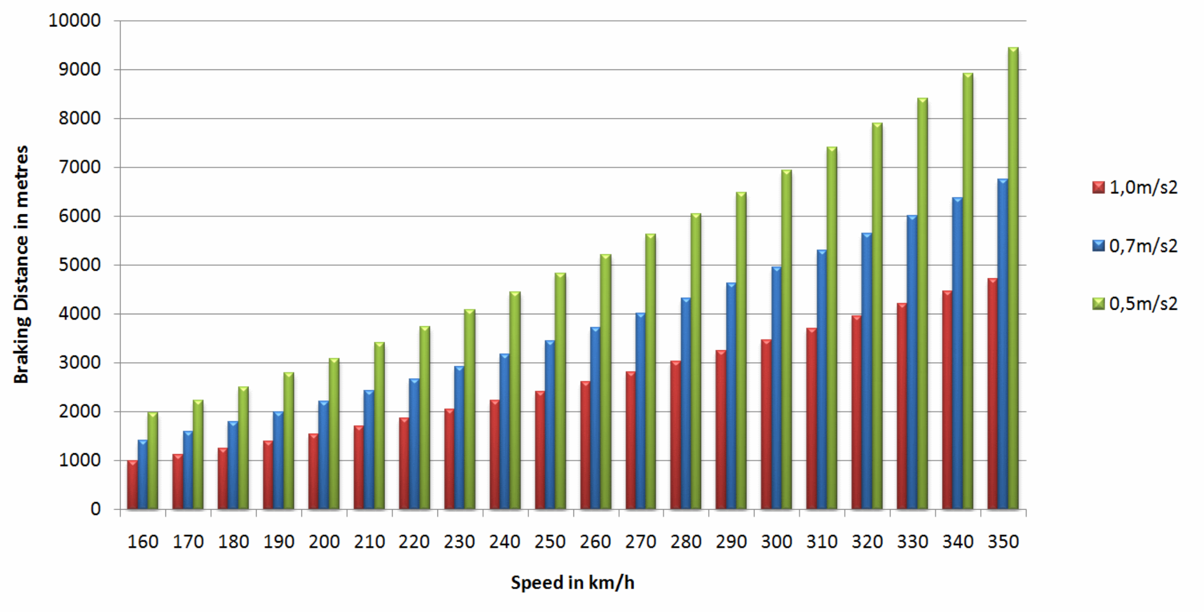

Figure 18 – Full braking distance with constant deceleration rates (Author)

4.3 Train Separation

The signalling systems for railways are usually block based. The principle of block system signalling is based on several fixed blocks along the track. The Author has based this section on the concept of occupation time figure presented by the UIC leaflet 406 (International

Union of Railways, 2004).

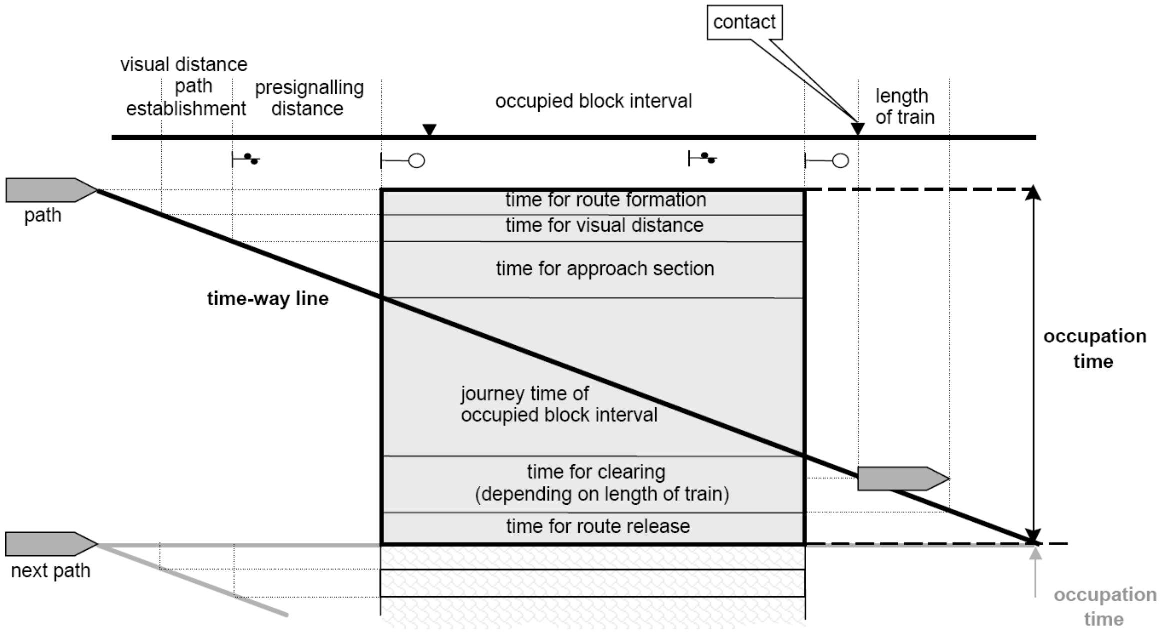

Figure 19 – Elementary occupation time (schematic) (International Union of Railways, 2004)

Before a train approaches a block section, the block section is required to be cleared of any obstructing train or train paths. The train path must then be set and locked. This includes the setting the turnouts in correct position and setting the signal to the right aspect. This is known as route formation (RF) and is measured in time (t_{RI}), and it is dependent on the infrastructure elements and the type of signalling system. Next the driver must be able to see the signal aspect clearly from a particular distance known as the visual distance (VD). The VD is based on the drivers sighting and reacting times with a safety margin and is also measured in time (t_{VD}). The approach section (AS) which follows the VD is basically the first block section (BS) before the train reaches a signal indicating caution, usually a double yellow aspect in the UK. A signal at caution requires the train driver to start reducing speed as there is a signal at danger ahead.

The length of Block Section (BS) is dependent on the signalling type, the operating speed and the Braking Distance (BD) and is usually a fixed length (s_{BS}). After the BS an Overlap Section (OL) is required to ensure safety in case a train overruns the signal at danger due to poor braking performance or late reaction time. The length of an OL (s_{OL}) can vary according to the speed, signalling type and topography, but is usually defined by a fixed length which varies depending on the networks or the country. When the entire length of the train (s_{TL}) has passed the OL the route is ready to be released for new train paths. The route release (RR) is measured in time (t_{RR}).

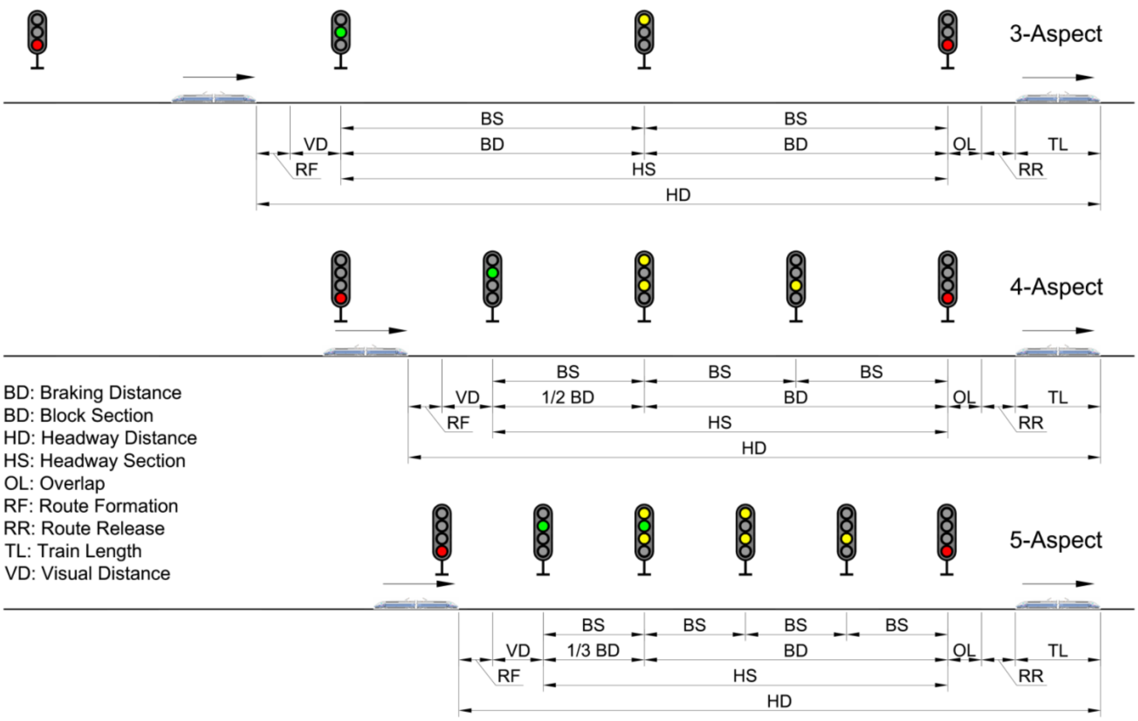

Figure 20 – Principle of headway distance with 3, 4 and 5 aspect signalling (Author)

4.4 Double Track Headway

The components BS and BD together form a theoretical minimum HD, identified as headway section (s_{HS}) in this report. Increasing the number of aspects in a system reduces the total HD. However, the HS can never be shorter than the BD as the BD is the distance required to stop is a signal if at danger. Therefore:

$$s_{HS} \geq s_{BD} \qquad \textit{Equation 34}$$

With 3 aspect signalling the BS is equal to the BD and with 4 aspect signalling the BS is equal to half the length of BD. The relation between the BD and the BS with *n* number of aspects must therefore be:

$$s_{BD} = (n-2)s_{BS} \qquad \textit{Equation 35}$$

$$s_{BS}(n) = \frac{s_{BD}}{n-2}, \begin{cases} 3 \leq n < \infty \\ n \in \mathbb{Z} \\ s_{BD} < 0 \end{cases} \qquad \textit{Equation 36}$$

The HS, as stated in Equation 34, is never shorter than the BD. It also includes the additional BS before the BD. The equation for HS is therefore equal to the equation for BS added to the length of one BD.

$$s_{HS}(n) = \frac{s_{BD}}{n-2} + s_{BD} \quad \textit{Equation 37}$$

$$s_{HS}(n) = \left(\frac{1}{n-2} + 1\right) s_{BD} \quad \textit{Equation 38}$$

$$s_{HS}(n) = \left(\frac{1 \cdot 1 + (n-2) \cdot 1}{(n-2) \cdot 1}\right) s_{BD} \quad \textit{Equation 39}$$

$$s_{HS}(n) = \frac{n-1}{n-2} s_{BD} \,, \begin{cases} 3 \leq n < \infty \\ n \in \mathbb{Z} \\ s_{BD} < 0 \end{cases} \quad \textit{Equation 40}$$

This can be used to calculate the HS for any number of aspects in the signalling system:

$$s_{HS}(3) = \frac{3-1}{3-2} s_{BD} = \frac{2}{1} s_{BD} = 2 s_{BD} \quad \textit{Equation 41}$$

$$s_{HS}(4) = \frac{4-1}{4-2} s_{BD} = \frac{3}{2} s_{BD} = 1.5 s_{BD} \quad \textit{Equation 42}$$

$$s_{HS}(5) = \frac{5-1}{5-2} s_{BD} = \frac{4}{3} s_{BD} = 1.333 s_{BD} \quad \textit{Equation 43}$$

The principle of moving block is equal to infinite number of aspects:

$$\lim_{n\to\infty} s_{HS}(n) = \lim_{n\to\infty} \left(\frac{n-1}{n-2} s_{BD}\right) = s_{BD} \quad \textit{Equation 44}$$

As can be seen in the Equation 41 and Equation 42 above the effect of increasing the number of aspect from 3 to 4 corresponds to reducing the HS by 25%, but increasing from 3 to infinite number of aspects only gives a 50% reduction. However, this does not include the other elements of the HD calculations and thus the maximum reduction in HD by increasing the number of aspects to an infinite number can be a maximum of 50%. To achieve higher capacity the additional elements of HD must be reduced.

Based on Figure 16 and the assumptions made in this section the following formula for determining the minimum HD becomes:

$$s_{HD_{min}} = (t_{RF} + t_{VD} + t_{RR}) \cdot v + s_{HS} + s_{OL} + s_{TL} \quad \textit{Equation 45}$$

$$s_{HD_{min}}(n) = (t_{RF} + t_{VD} + t_{RR}) \cdot v + \left(\frac{n-1}{n-2}\right) s_{BD} + s_{OL} + s_{TL}$$ *Equation 46*

$$s_{HD_{min}}(n) = (t_{RF} + t_{VD} + t_{RR}) \cdot v + \left(\frac{n-1}{n-2}\right) \cdot \left(\frac{v^2}{2a_b}\right) + s_{OL} + s_{TL}$$ *Equation 47*

4.5 Single Track Headway

Calculating the operation of single track can be much more difficult than for double track (Landex, 2006) as the operation is more inherently dependent on trains meeting at fixed position at defined times. The operation of alternating bidirectional traffic on a single track does not require the single track section (STS) to be divided into several BS to increase capacity. This is because when a train occupies the STS, the train from the opposite direction is not allowed to enter the STS before the first train has exited the STS and released it. Also, this can mean that less signalling infrastructure investments is required. However, it does not allow for two succeeding trains, also known as convey operation, to use the STS at the same time using the principle of double track minimum HD. The decision of having additional signals within the STS must be taken based on the required level of traffic.

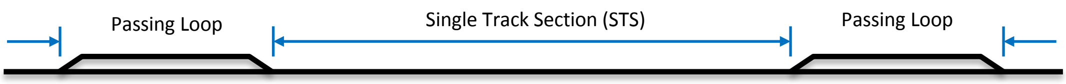

Figure 21 – A single track section (Author)

In this report, for the calculations done on single track the Author assumes that alternate trains will run in the opposite direction and that all trains enter and exit the STS at full line speed. It is also assumed that only one train can occupy each track in the passing loop at any given time. Similar to double track operation, the occupation time of the HS is a required element in the calculation. The STS is effectively one large BS being occupied by a train, the BD is the second BS. Hence, the HS must be equivalent to the STS and the BD added together.

$$s_{HS} = s_{BD} + s_{STS}$$ Equation 48

The RF, VD, OL, TL and RR are same as the double track obligatory elements for HD calculations. Furthermore, the length of the turnout section must also be added as well as an additional OL at the first loop. However, as the RF involves movement of points, this operation will demand some additional time to be set. Suppose that all trains will enter and exit the STS at line speed in a perfect sequence we get the following formula:

$$s_{HD_{min}} = (t_{RF} + t_{VD} + t_{RR}) \cdot v + 2(s_{TS} + s_{OL}) + s_{HS} + s_{TL}$$ *Equation 49*

$$s_{HD_{min}} = (t_{RF} + t_{VD} + t_{RR}) \cdot v + 2(s_{TS} + s_{OL}) + \left(\frac{v^2}{2a_b}\right) + s_{STS} + s_{TL}$$ *Equation 50*

4.6 Capacity Calculations

This section will demonstrate how the different signalling systems and the running speed of a train will affect the capacity of a double and a single track railway line. The line is assumed to be operated by identical rolling stock to simplify calculations. As this report does not investigate a defined network but the general principles, it is sensible to limit the capacity calculation to what can be achieved on a section of line within a given time period.

The general formula for capacity in train per time interval (C_{TPI}) can be found by dividing the sum of the time interval (t_I) in seconds multiplied with the speed (v) on the headway distance (s_{HD}). (Abril et al., 2008)

$$C_{TPI} = \frac{t_I \cdot v}{s_{HD}}$$ *Equation 51*

The HD should not necessary be the minimum value for the capacity calculations as the block sections can be larger for many reasons, e.g. additional safety parameters, rolling stock with different braking characteristics etc. The main element though is the BT between trains. The BT accounts for trains running at different speeds, acceleration, deceleration, dwell times at stations, time for perturbation, etc. Adding additional tracks at stations can improve the BT significantly. The same can be achieved by Automatic Train Operation (ATO).

Therefore, the formula for TPH is for double track operation is:

$$C_{TPH}(n) = \frac{3600 \cdot v}{(t_{RF} + t_{VD} + t_{RR} + t_{BT}) \cdot v + \left(\frac{n-1}{n-2}\right) \cdot \left(\frac{v^2}{2a_b}\right) + s_{OL} + s_{TL}}, C_{TPH}(n) \in \mathbb{Z}$$ *Equation 52*

Different signalling systems have different timings for the separate elements. The author has used values given in the table below based on reasonable assumptions. These values can easily be altered in the TPC for custom tuning.

Table 13 – Signalling system element values (Author)

		Aspect	ERTMS L2	ERTMS L3	ATO
Route Formation	[s]	5	6	6	5
Visual Distance	[s]	8	5	5	1
Route Release	[s]	3	3	3	3
Overlap Length	[m]	200	50	50	20

Plotting the Equation 52 with zero BT provides the following figure:

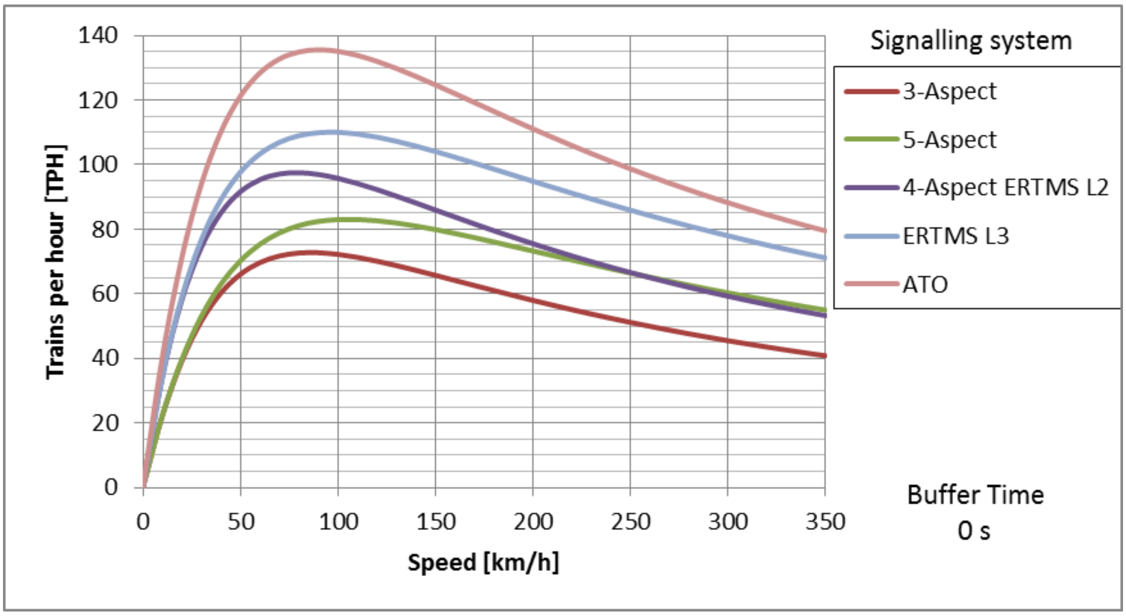

Figure 22 – Theoretical capacity double track, no buffer time (Author)

The values presented in this figure are not practicable values as the BT is not included. From the figure it becomes clear that the maximum capacity is achieved within the region of 60-100 km/h (16-28 m/s), which is the normal operating speed for high capacity metros. Increasing the speed above this region leads to lower capacity on all types of signalling systems. It also becomes evident that the capacity difference between the different signalling systems decreases with the increase in line speed. This is a consequence of the BD being related to the square of the speed which will be a more dominant element at high speeds.

The BT will differ from system to system, however assuming a 3 min (180 s) BT on a main line railway presents the following figure:

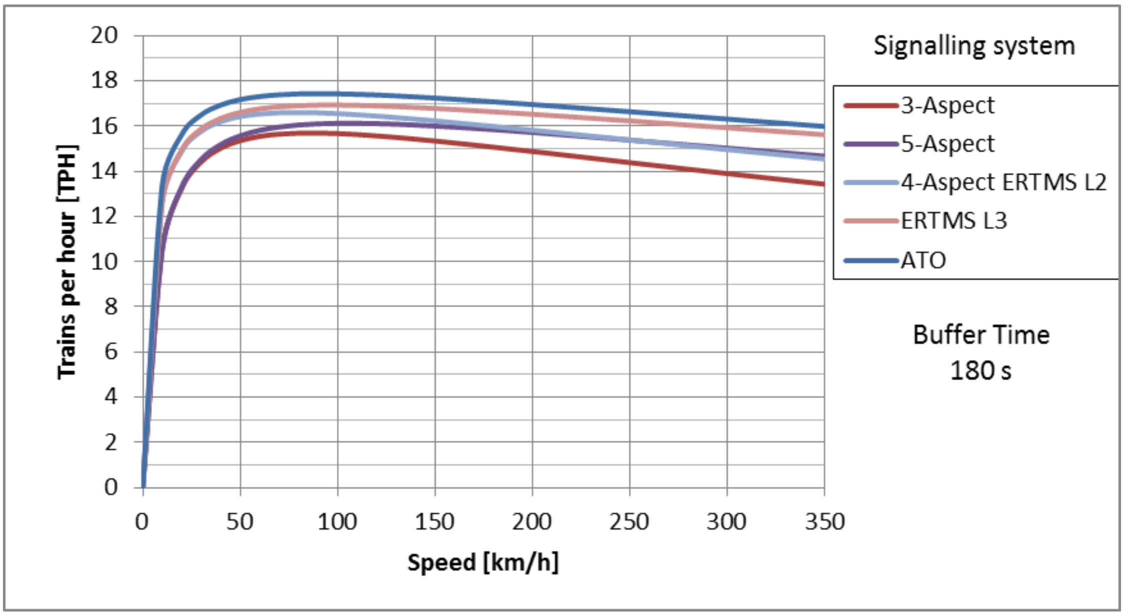

Figure 23 – Theoretical capacity double track, 3 min buffer time (Author)

It is clear that the BT consumes a considerable portion of capacity. Nevertheless, it is a necessary element required to maintain reliability in the system. The differences in capacity between the signalling systems are significantly less when the BT is introduced.

Single track follows the same principle as double track in regards of BT. However, as the HD endorses traffic in both directions the formula for capacity must be divided by a two in order to find the TPH for one direction. Therefore, the formula for TPH for single track operation is:

$$C_{TPH}(n) = \frac{1800 \cdot v}{(t_{RF} + t_{VD} + t_{RR} + t_{BT}) \cdot v + 2(s_{TS} + s_{OL}) + \left(\frac{v^2}{2a_b}\right) + s_{STS} + s_{TL}} \qquad \textit{Equation 53}$$

$$C_{TPH}(n) \in \mathbb{Z}$$

Assuming perfect crossing with no BT and the values of aspect signalling with a RR of 10s provides the following curve is obtained:

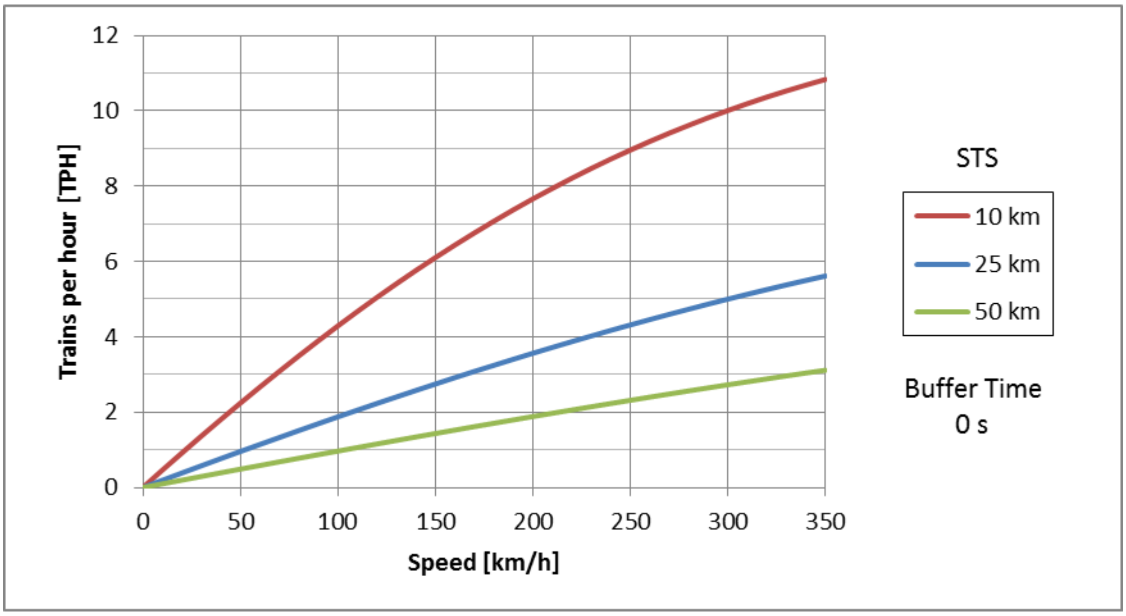

Figure 24 – Theoretical capacity single track, no buffer time (Author)

The figure clearly demonstrates that capacity increases with speed on single track. This makes sense as a train would use less time to travel through the STS at higher speeds, which is in line with the results of similar studies (Abril et al., 2008). The graph has a near linear increase initially, however as speed increases the BD increases exponentially and the graph flattens out (in the speed range investigated).

However, allocating a 3 min BT reduces the capacity to approximately half:

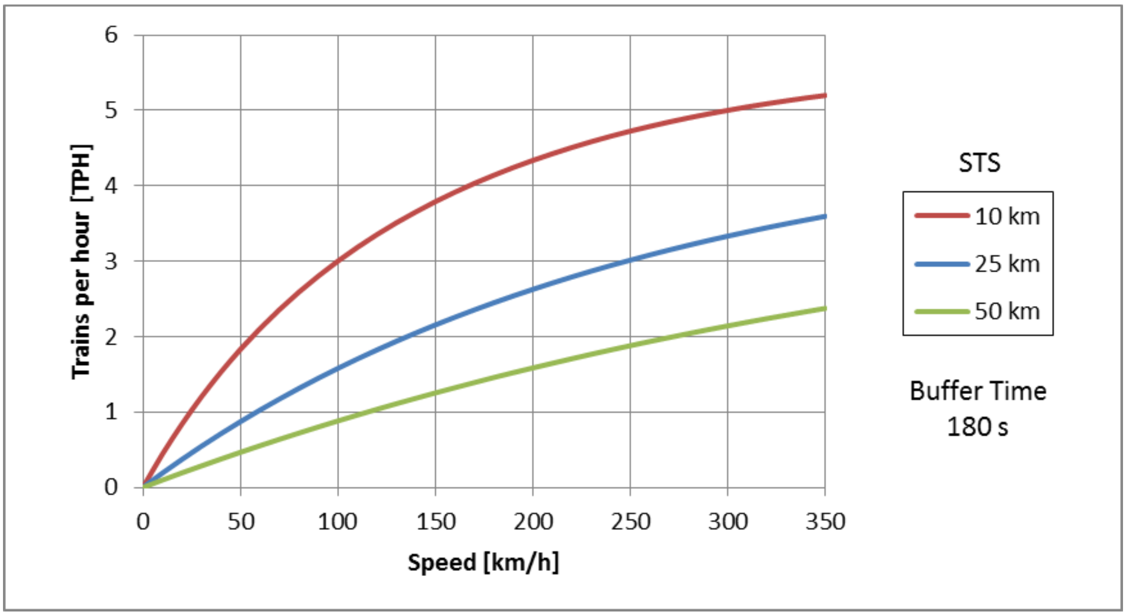

Figure 25 – Theoretical capacity single track, 3 min buffer time (Author)

From the figure it is quite clear that it is difficult to achieve high capacities on single track lines. With trains running at minimum 300km/h through a 50km STS, it is possible to achieve a 2 TPH in each direction.

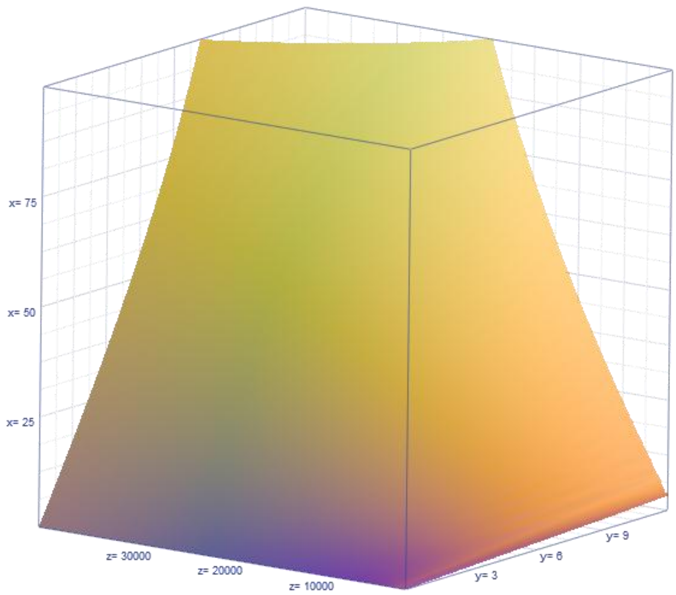

Figure 26 - Theoretical capacity with variable speed and STS, no BT, both directions (Author)

A 3D plot of Equation 53 illustrates the achievable capacity with variable speeds and STS. The x-axis represents the running speed, the y-axis represents the number of trains and the z-axis represents the length of the STS.

4.7 Evaluation of Capacity

Calculations based on the methods presented in UIC leaflet 406 are only representative for the section of the network they are calculated for and with the parameters assumed (Landex, 2009), and this is also the case for this report. To calculate and simulate whole networks advanced software tools are needed such as RailSys (Rail Management Consultants, 2011) and OpenTrack (OpenTrack Railway Technology, 2011) which can handle several variables in a more sensible approach. A fundamental principle is that the overall capacity of a line between two points cannot exceed the capacity of the section with the lowest capacity, also known as the bottleneck.

It must not be forgotten that single track operations are highly interdependent systems:

"A single line cannot be considered as a fully independent part of the whole network due to crossing and overlapping lines, which can be true bottlenecks. As a consequence, the capacity of a line cannot be defined without considering what happens on the interfering lines." (Abril et al., 2008)

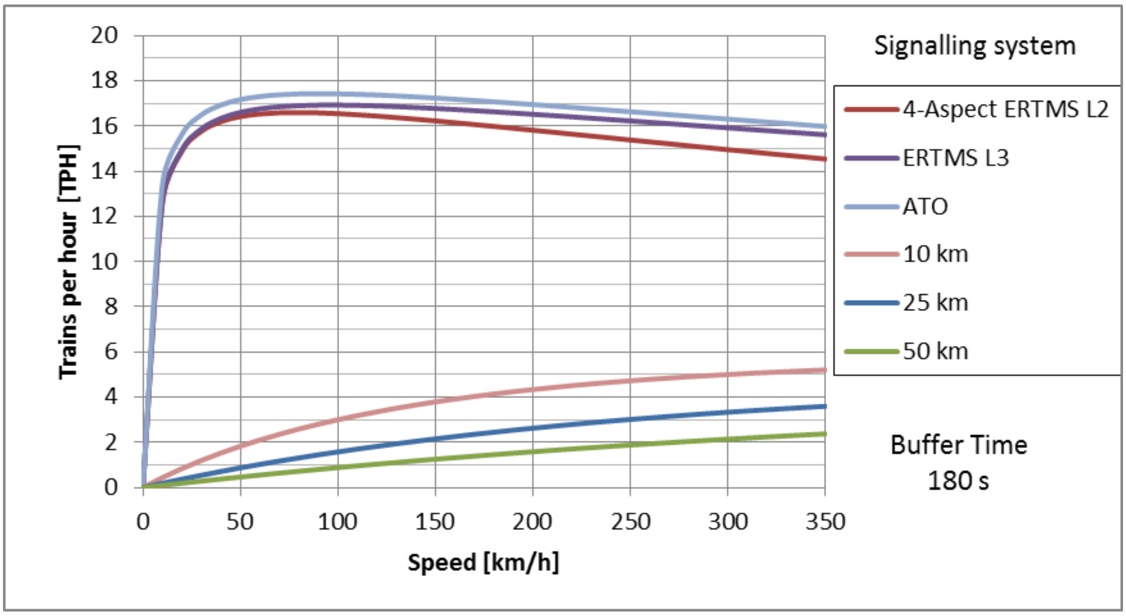

Figure 27 – Theoretical capacity of double and single track, 3 min buffer time (Author)

A graphical timetable presents alternative approach for evaluating the capacity compared to the figure above. Below are two figures representing the capacities for double track and single for a given section of a railway network. The following graphical timetable assumes constant speed and flow of trains:

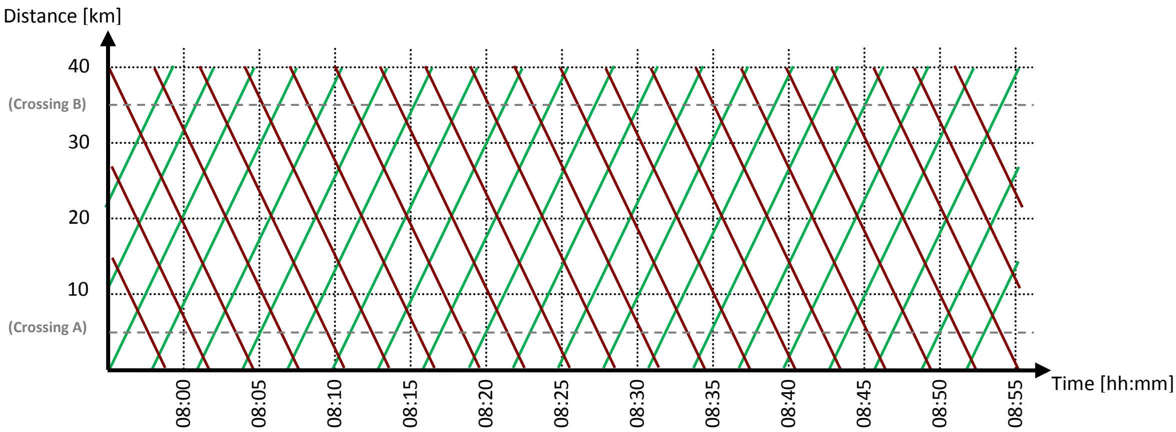

Figure 28 - Graphical timetable double track, 3 min between trains (Author)

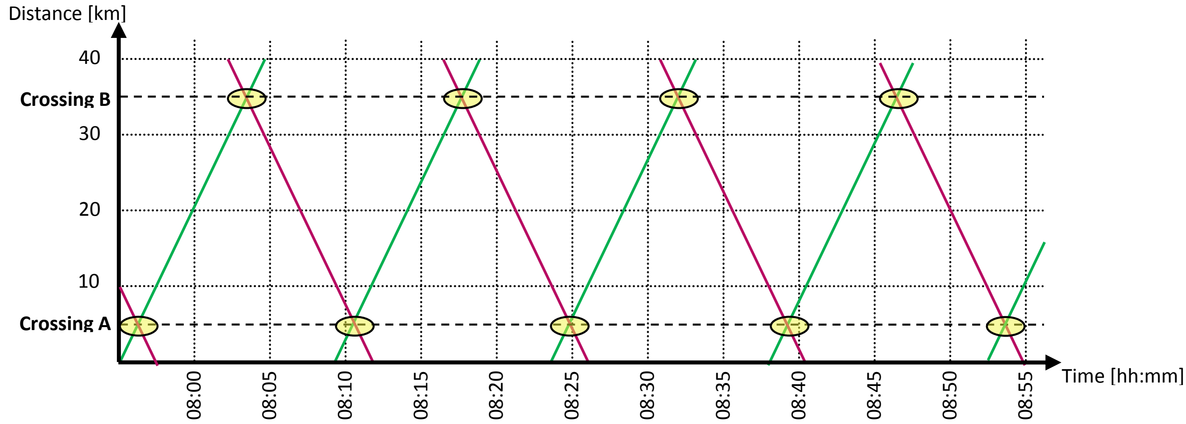

Figure 29 – Graphical timetable single track, 25km between meeting point (Author)

The difference in capacity between double track and single track is fairly substantial as can be perceived from the graphical timetables. Double track railways are suitable for high frequency operations, while single track is suitable for low frequency operations.

Another important aspect of capacity calculation is in relation to the number of passenger journeys. To find the capacity in number of passengers per interval (PPI), the number of trains per interval can simply be multiplied with the average number of available seats on the train.

$$C_{PPI} = C_{TPI} \cdot x_{seats} \qquad \textit{Equation 54}$$

In systems where TPH is the limiting factor of capacity, increasing the train length or providing a second floor are powerful and simple methods to increase the passenger capacity in a cost effective way for systems that will be newly constructed. For systems already in operation, this is related to how easily the existing infrastructure can be modified to adapt to the changes.

5 Passing Loops

Passing loops, also known as crossing loops, meetings points and sidings, are short sections of an additional track adjacent to the main line. The passing loops are connected at both ends to the main line with turnouts where two trains travelling in opposite directions can pass each other, or it can also be used for trains travelling in the same direction to overtake each other. The latter practice is more commonly used where there is mixed traffic with different stopping pattern, for example an HST overtaking a freight train.

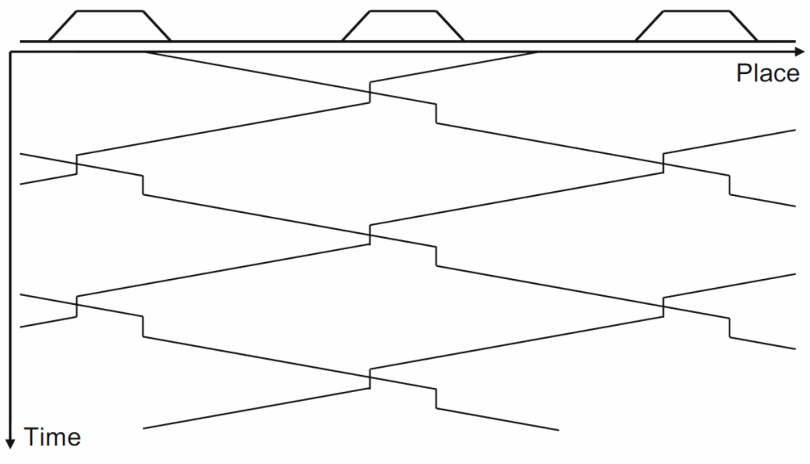

Figure 30 - Typical timetable pattern for a single track line (Landex, 2009)

Single track rail operations rely on the use of passing loops to allow trains operate in both directions at the same time. The passing loops are usually placed to where two conflicting routes intersect in the timetable as illustrated in Figure 30.

5.1 Passing loops design

There are two types of passing loops designs investigated in this report, which are named after their mathematical quadrilaterals shapes; trapezoid and rhomboid. The difference in design remains in which direction the turnout is connected and this difference can impact on the running times for the trains.

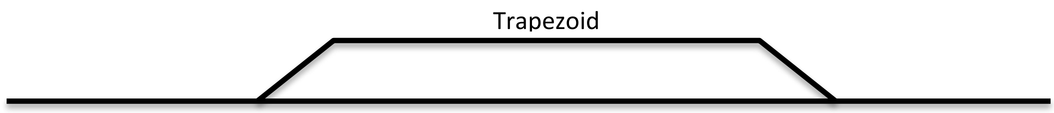

Figure 31 - Trapezoid shaped passing loop (Author)

In the trapezoid shaped loops the diverging track forms the passing loop. This design is very commonly used and requires only one train to decelerate to diverge while the second train can proceed at full line speed. This design is preferable in station design which we will discuss in the next section. The disadvantage is that the diverging train loses valuable running time. If the trapezoid loop is long enough the train on the diverging track can accelerate to full line speed and then decelerate again before passing the second turnout back to the mainline or. In both cases the time loss of the diverging train is high, but in the latter option there is an increase in energy consumption due to acceleration.

Figure 32 - Rhomboid shaped passing loop (Author)

The rhomboid shaped loop can be debated to be either both tracks diverging or none diverging. Nevertheless, trains from both directions are required to decelerate while passing the turnout. The advantage of this design is that the trains will only be speed restricted for a short period before they are able to resume to full line speed again, thus saving time. The disadvantage of this design is that if there is only one train approaching the loop it would still have to decelerate and accelerate for the turnout, loosing precious running time.

5.2 Passing loop types

Passing loops can serve several types of functions, e.g. overtaking, crossings, station stop etc., and therefore it must be designed accordingly to its function. The main difference lies in the shape and the length of the passing loops, however it also affects the interlocking system (Lindfeldt, 2011). Three types of passing loops will be described in this report, however other types of passing loops exists which are not covered in this report.

Scheduled passing loops with passenger stop

Stations with more than one track do effectively functions as passing loops. Strategic timetabling by placing the passing loops to the location of stations can be very beneficial as the trains would need to reduce the speed for stopping at the station, thus there is no additional running time lost due to the passing loop. However this coordination between loops and stations location is not always practically achievable as stations are usually required to be situated at urban locations. The opposite approach is to place the stations where the timetable designed meeting point is. This can potentially stimulate for future growth in the area where the station is located. The length of the loop does not require any BT as this can be included into the dwell time at the station, thus the loop length can be relatively short. The length of the loop should be so that the trains have one BD from each approaching direction plus the length of the station in between the BD's. The stopping pattern determines the shape, which will be discussed in the next section. The trapezoid shaped loop can be advantageous in this type of loop as it allows for a non-stopping train to pass the station area while another train has stopped at the station. Since the diverging speed will be low there is not a need for high standard turnouts, thus limiting the additional infrastructure costs.

Scheduled passing loops without passenger stop

This type of loop is also known as “flying meet” as it is designed so that two train running in opposing direction can pass each other without stopping (Petersen and Taylor, 1987). The speed through the loop is dependent on the characteristic of the turnout. This is a preferred approach as it does not influence the running times nearly as much as a full stop would do. Controversially, as trains are running at higher speeds the length of the flying meets becomes significantly longer than those at stations, increasing the infrastructure investments. The main factor influencing the length of the loop is the BT which is needed to add reliability in to the system as it is not realistic that the trains will cross at perfect timings (Harrod, 2009).

The turnouts are required to be of very high standard as they must accommodate for diverging trains running at high speeds. Both the trapezoid and the rhomboid designs can be used for this type of loop, however as one of the trains in a trapezoid design can run at maximum speed throughout the loop this design would require a longer loop length than a rhomboid loop would with the same HD and BT. This type of loop should be built were there are scheduled crossings in the timetable without requiring stops.

Secondary passing loops

These loops are used for unscheduled crossings of trains as a result of delays to scheduled services, by adding none-timetabled services or by maintenance rolling stock. It could also be used for scheduled lower priority services such as freight trains. The length of the secondary crossing loop must be minimum the length of the longest train running on the network plus twice the OL. The turnouts should be of high standard for trains running straight through them, but it does not necessary need to be able to operate high speeds on the diverging track.

5.3 Passing loop placement

The optimum placement of loops lies in careful planning and assessment of the timetable, infrastructure and the RSP as discussed in section 3.1, to accurately predict the position of a train at any given time. With this information available the loops can be positioned, however, the theory of loop placements can be derived without the need for such detailed infrastructure information. Based on the assumption of a simple line with only two stations and constant train speeds, irrespective of gradients, tunnels etc. the principles of loop placement originates.

First of all there is a need to define the symbols used in the following figures in this section:

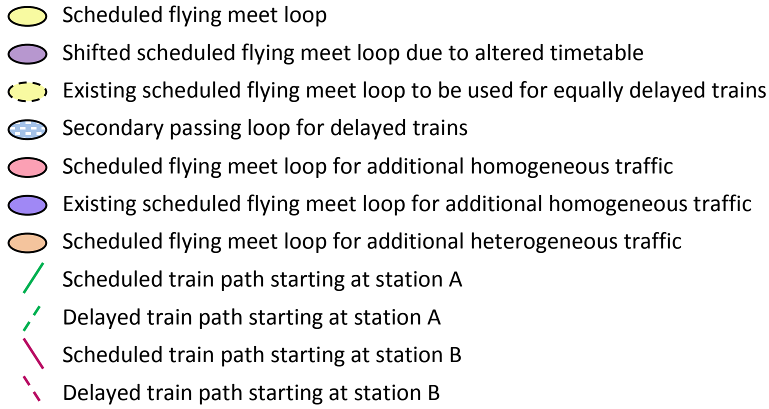

Figure 33 - Definition of symbols used in the following figures (Author)

All figures consist of the same scenario of a long single track line with two end stations, “A” and “B”, and no intermediate stations. Train runs through the line, including loops at constant speed to simplify the graphs and the calculations. In Figure 34 there is an hourly service departing from both ends which requires 4 passing loops evenly spaced. The loops form a cyclical pattern in the timetable as the trains are homogeneous with fixed intervals (Harrod, 2009). The HD measured in time divided by 2 gives the time between each loop (Petersen and Taylor, 1987).

The equation for calculating the minimum number of loops is (Petersen and Taylor, 1987):

$$Minimum\ number\ of\ loops = \frac{2 \cdot (total\ travelling\ time)}{HD_{Time}} \qquad \textit{Equation 55}$$

The great importance of creating a high-quality timetable while designing the infrastructure of single track operations becomes evident in Figure 35. If the scheduled departure time would need to be changed unevenly from both ends it will cause all of the loop placements to be repositioned which would be very expensive in terms of new infrastructure investments. Another drawback is that the initial loops that were built will be poorly utilised. This illustrates the great importance of designing a single track network after the timetable and not the opposite approach (Petersen and Taylor, 1987).

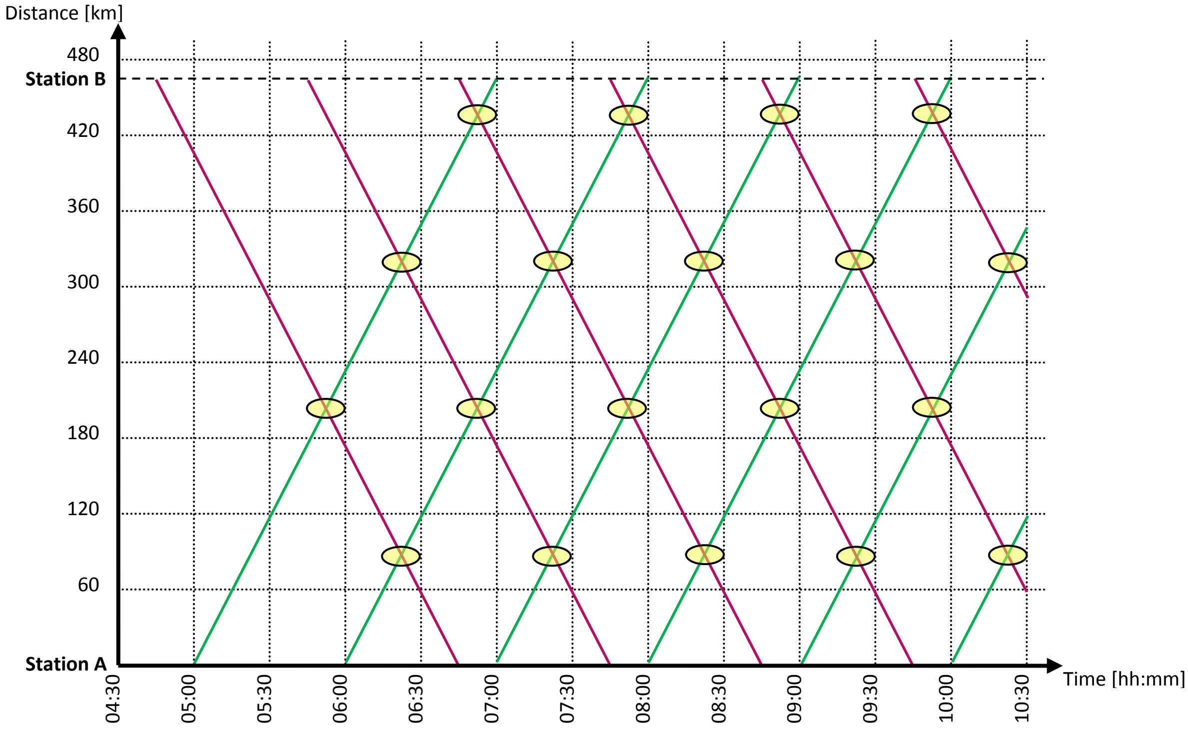

Figure 34 – Scheduled placement of passing loops based on the timetable (Author)

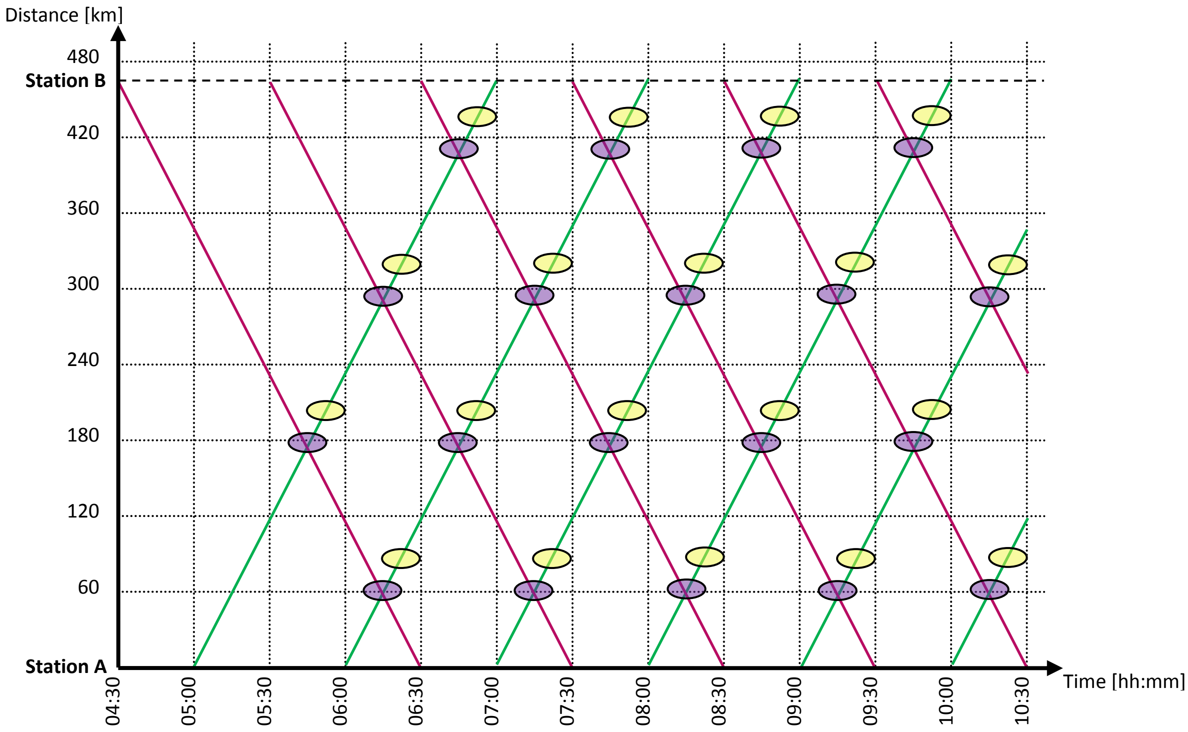

Figure 35 – The effect of changing the timetable to loop placements (Author)

5.4 Secondary Delays

Naturally delays do occur in a transport system for many different reasons which of many delays potentially could have been prevented with more efficient management, but many are also force major and cannot be avoided. However, if a train is delayed due to whatever reason the meeting point to the oncoming train will be changed from the scheduled meeting point. Although, as the meeting point is fixed the delay would cause a knock-on delay to the train which is running on time as it is required to wait at the passing loop for the late running train.

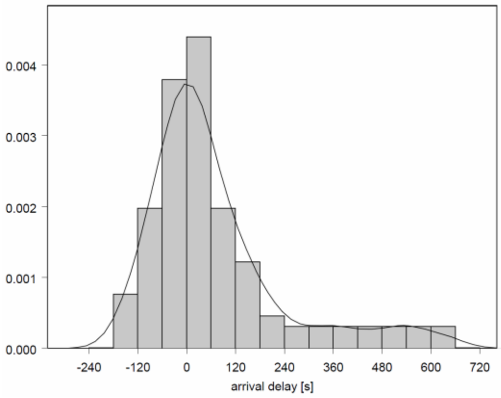

Figure 36 - Estimate of the arrival delay of IC 1500 Heerlen-Den Haag, Eindhoven (Goverde et al., 2001)

The function of the BT, as used in the HD calculations is to add reliability in to the system by assuming that trains will run late. The delay distribution can vary greatly between systems, e.g. in Japan the average delay is less than one minute and the timetable is measured in seconds while in Europe it is common to measure in minutes. Applying this level of punctuality to Europe can be hard due to institutional, organisational and cultural differences (Goverde et al., 2001).

Secondary loops must be placed on both sides of the scheduled loop as illustrated in Figure 38 to capture the trains coming from both directions which are more delayed than the BT. As previously discussed the length of a secondary loop is relatively short, thus it requires the late running and diverging train to have a complete stop. However, this will increase the delay further, which is why the next meeting must be positioned further from the scheduled loop. Nevertheless, the secondary loop on each side is not equally distanced from the scheduled either as the accumulated delay will be different in each direction. A major drawback of this concept is that it increases the delay, however it also gives the operator the opportunity to predict its path much more efficiently. The concept asymmetrical loop placement is illustrated in Figure 37 and Figure 39.

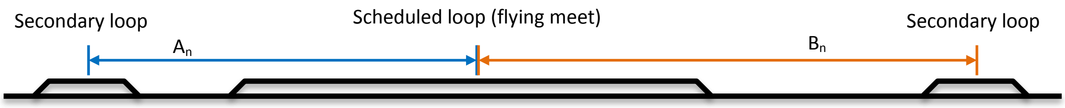

Figure 37 - The distance from the flying meet to the secondary loop increases with the number of stops (Author)

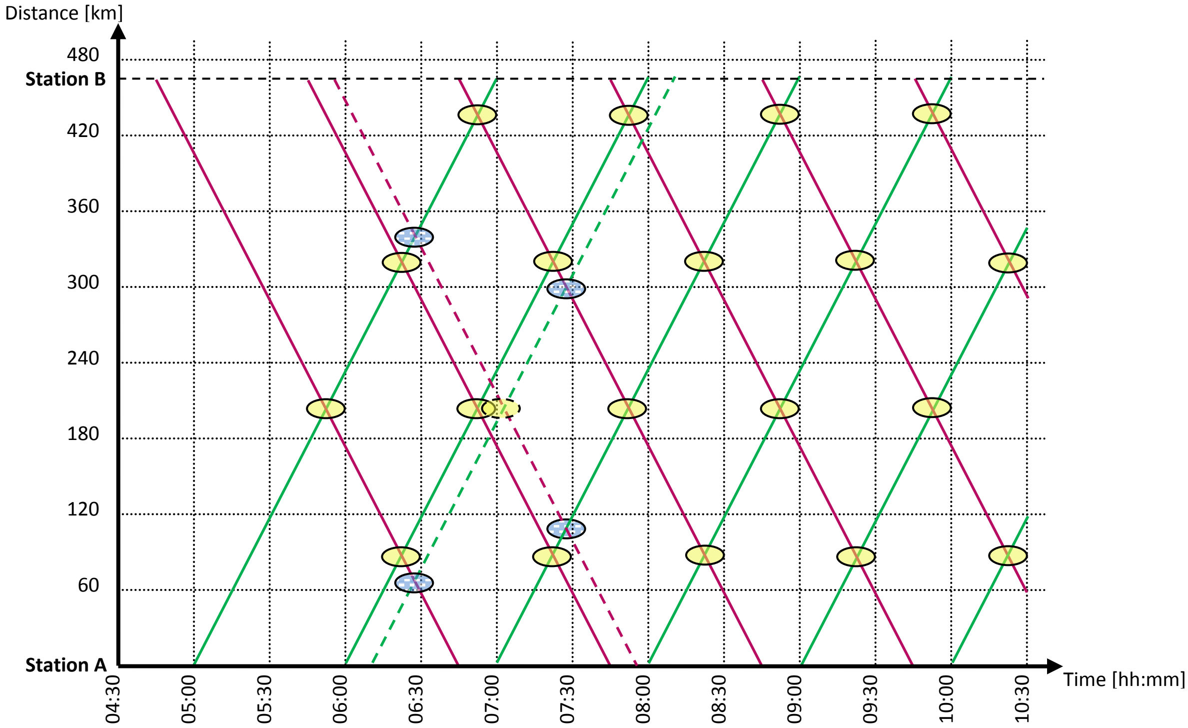

Figure 38 – Delayed trains releases a need for secondary loops on both sides of the flying meet (Author)

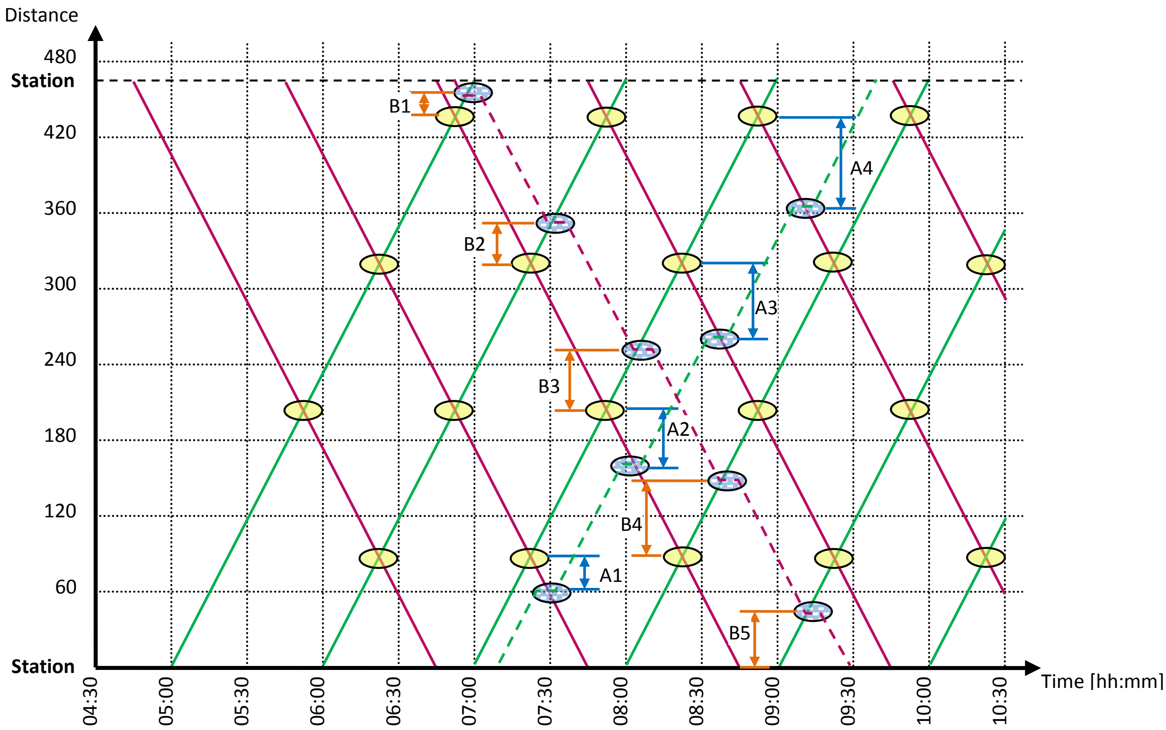

Figure 39 – The distance from the flying meet to the secondary loop increases with the number of stops (Author)

5.5 Additional services

Adding train paths to the timetable requires additional loops. For freight trains these loops can be of the same standard as the secondary loop, requiring the freight train to stop and wait for the passenger service to pass. For additional passenger service where the running times are of much higher importance the loop must have the same high standard as in flying meets.

Adding homogeneous train paths to the service is a reasonably uncomplicated procedure in the planning process as the number of required loops can be found by using the same equation as found in Equation 55. In Figure 40 it assumed the same scenario as previously with an added peak hour service, resulting in a total of 2 TPH per direction with evenly spaced intervals of 30min. The number of required scheduled loops and secondary loops are doubled to meet this additional service.

Adding heterogeneous train paths requires a different approach to estimate the number of loops required and the positions of these. As trains are running at different operating speeds and the HD varies these elements becomes important factors in the equation. The easiest method of estimating the number of loops is by doing a graphical timetable as shown in Figure 41. It is clear that the number of required loops must be more than doubled compared to not introducing the service. The loops are also in this scenario required to be of flying meet standard to avoid loss of running time. However, as can be observed in the figure the total loop length due to the number of flying meet, potentially exceeding the total track length, thus becoming a double track railway.

The costs of adding additional service to the timetable is undeniably very high as it require additional infrastructure investments. As discussed in the capacity section longer trains are a more cost effectively way to increase capacity than increasing the number of trains. Naturally the stations and the infrastructure must be able to handle the longer trains. Another option is to allow multiple trains run subsequently after each other, also known as convey operation (Landex, Kaas and Hansen, 2006). This would require fine-tuning of the passing loops lengths and it would require additional block section and to deal with the succeeding trains.

The drawback of not introducing additional service can be, especially in peak hours that customers who seek flexibility may to search for alternative modes of transport.

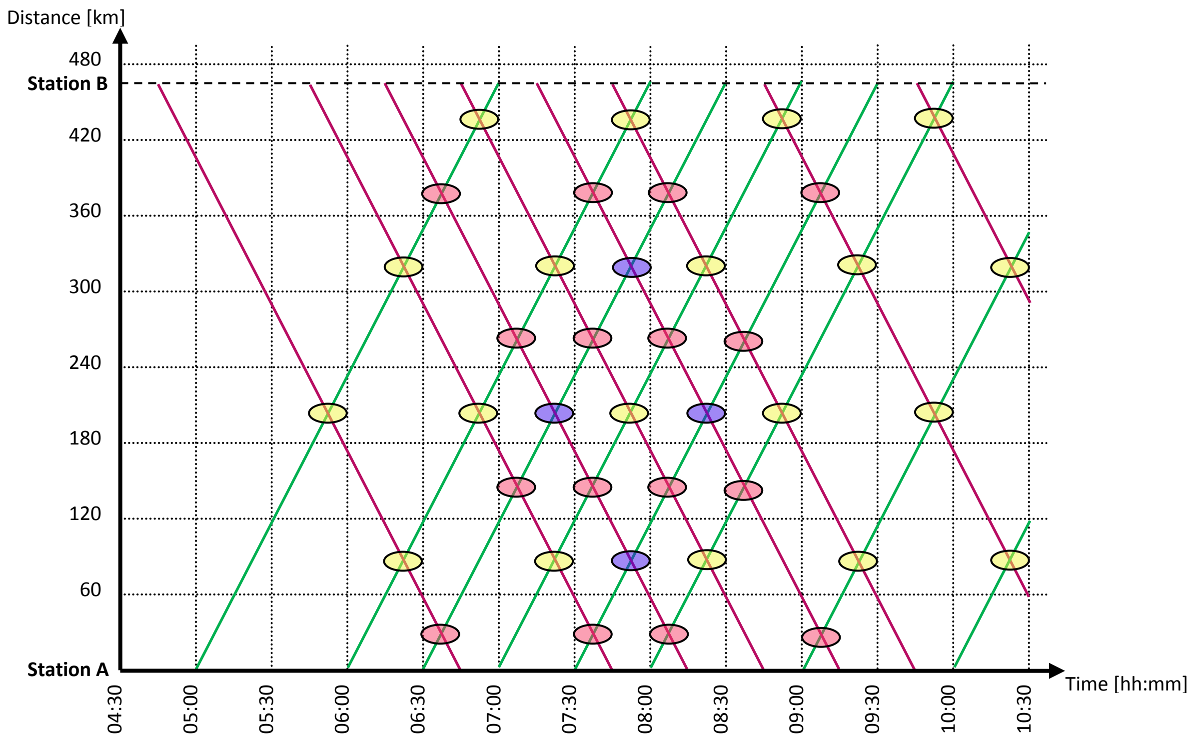

Figure 40 - Introducing additional 1TPH homogeneous peak hour service (Author)

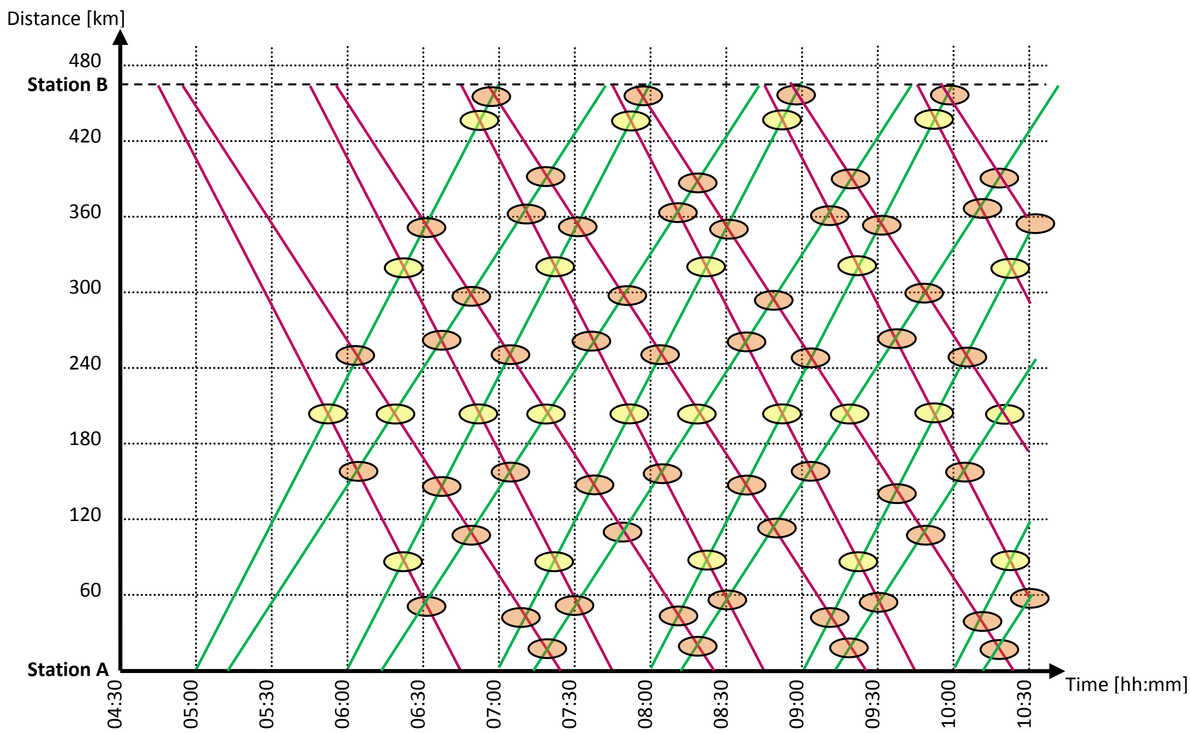

Figure 41 – Introducing additional 1TPH heterogeneous service (Author)

5.6 Flying meets

In both trapezoid and rhomboid shaped loops the fastest running train will determine the minimum required flying meet length and to calculate the minimum flying loop length the principles from the UIC leaflet 406 and the assumptions made in section 4.3 are used. Assuming that the train would need to clear the TS and connected elements before the opposing train can have a green aspect to enter the TS section in the opposite direction provides the following principle arrangement of elements:

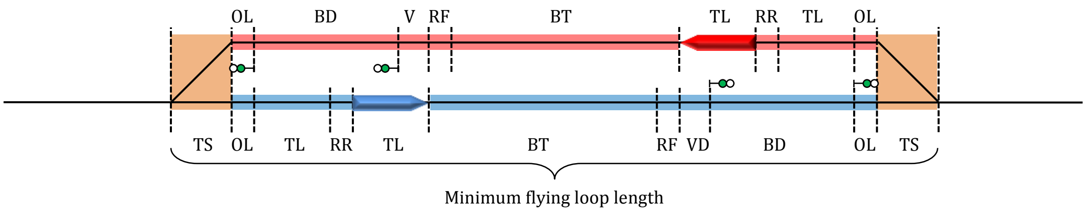

Figure 42 – Principle arrangement of elements influencing minimum flying loop length (Author)

Assuming constant speed the following equations are derived to calculate the minimum length of a flying meet ($s_{L,FM}$) with the trapezoid shape:

$$s_{L,FM} = s_{BD} + 2(s_{TS} + s_{TL} + s_{OL}) + v(t_{RF} + t_{VD} + t_{RR} + t_{BT}) \quad \textit{Equation 56}$$

$$s_{L,FM} = \frac{v^2}{2a_b} + 2(s_{TS} + s_{TL} + s_{OL}) + v(t_{RF} + t_{VD} + t_{RR} + t_{BT}) \quad \textit{Equation 57}$$

The formula can also be used for rhomboid shaped loop if the speed is assumed to be constant throughout the loop.

In the real world perfect crossing points are highly unlikely to occur, and as an example Figure 36 illustrates a possible delay distribution models that exist. When analysing the loop length it is important to take advantage of these models. Assuming that the delay distribution in Figure 36 is valid for a given scenario, then it would make sense to let the BT be somewhere around 180 s in order to capture as many trains as possible without making the loop unnecessary long. Trains travelling within this delay would still be considered to be on-time as they do not impose the delays on to other trains. The BT has a large impact on the length of the crossings at high speeds. Figure 43 illustrates the variation in loop lengths based on the design speed and BT:

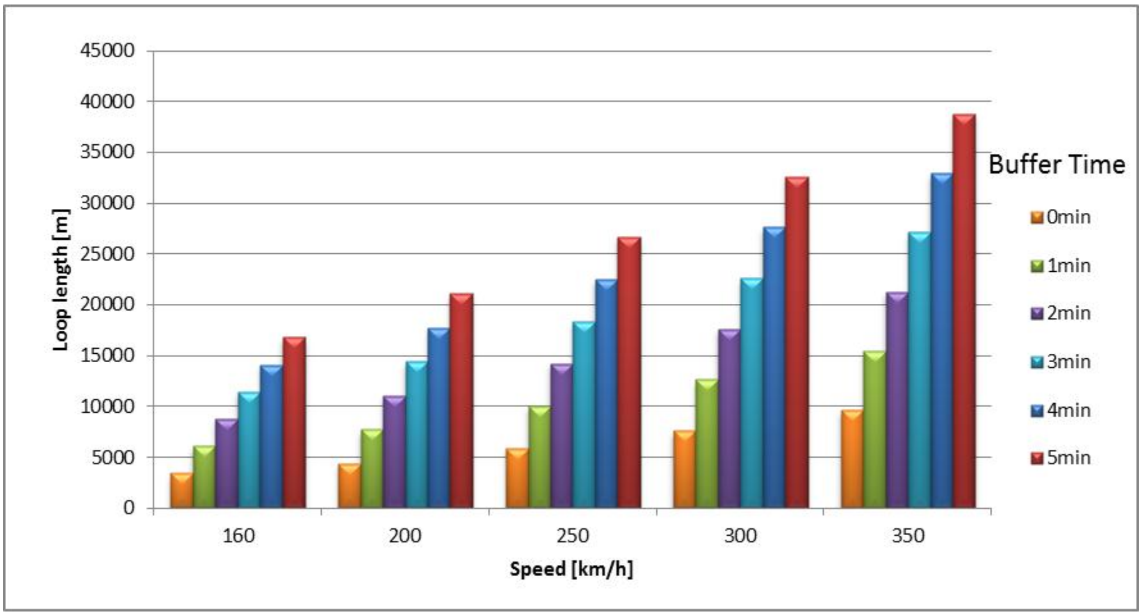

Figure 43 – Minimum flying meet loop length based on different speeds and buffer times (Author)

This figure clearly illustrates the effect of the BT on loop lengths. At 250 km/h the loop is required to be circa 6 km long for a perfect meet without any BT and nearly 27 km long with 5 min buffer time. However, as discussed previously a 3 min BT is perhaps a sensible value for a European operator, thus the loop length of 18.3 km, 22.5 km and 27.1 km for respectively 250 km/h, 300 km/h and 350 km/h is required.

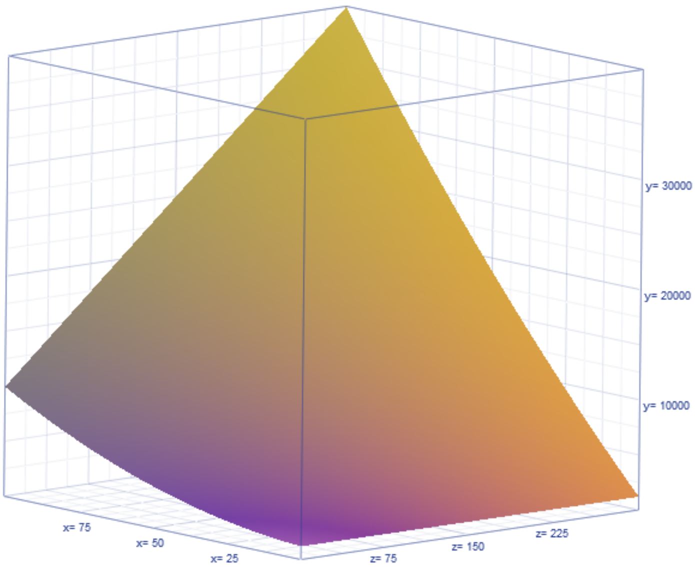

Figure 44 - Minimum flying meet loop length (Author)

Figure 44 illustrates the same as Figure 43, however with speed (x-axis [m/s]), loop length (y-axis [m]) and BT (z-axis [s]) as variables from nil to 100 m/s, 40 000 m and 300 s respectively. The distinctive pyramid shape of the plot indicates that further increase beyond what is presented of speed and BT will have momentous consequence on the loop length.

Obviously, the cost of building additional tracks for the loop is something which planners would avoid as the initial preference was to build a single track. Therefore there must be a trade-off between increasing the length of the loop by increasing the BT and the potential delay imposed to the passengers.

In Figure 45 the speed curves of two trains passing each other on a trapezoid shaped loop is illustrated. The blue train is the non-diverging train in this scenario, and the red train represents the diverging train. Assuming that the blue train will pass the loop at full line speed it will be the determinant of the minimum loop length. However, the red train would need to reduce the speed to the diverging speed limit on the turnout, and dependent on the length of the loop there are two alternatives for how the red train will continue. The first option is to continue at the reduce speed as it must pass the returning turnout at the reduced speed in addition. Though, if the loop length is long enough the red train can increase the speed up to line speed again before decelerating for the second turnout section. The latter option do offer the advantage to recover some lost running time, though needless to say the energy consumption would naturally increase and it must be considered if the increased energy consumption can be justified.

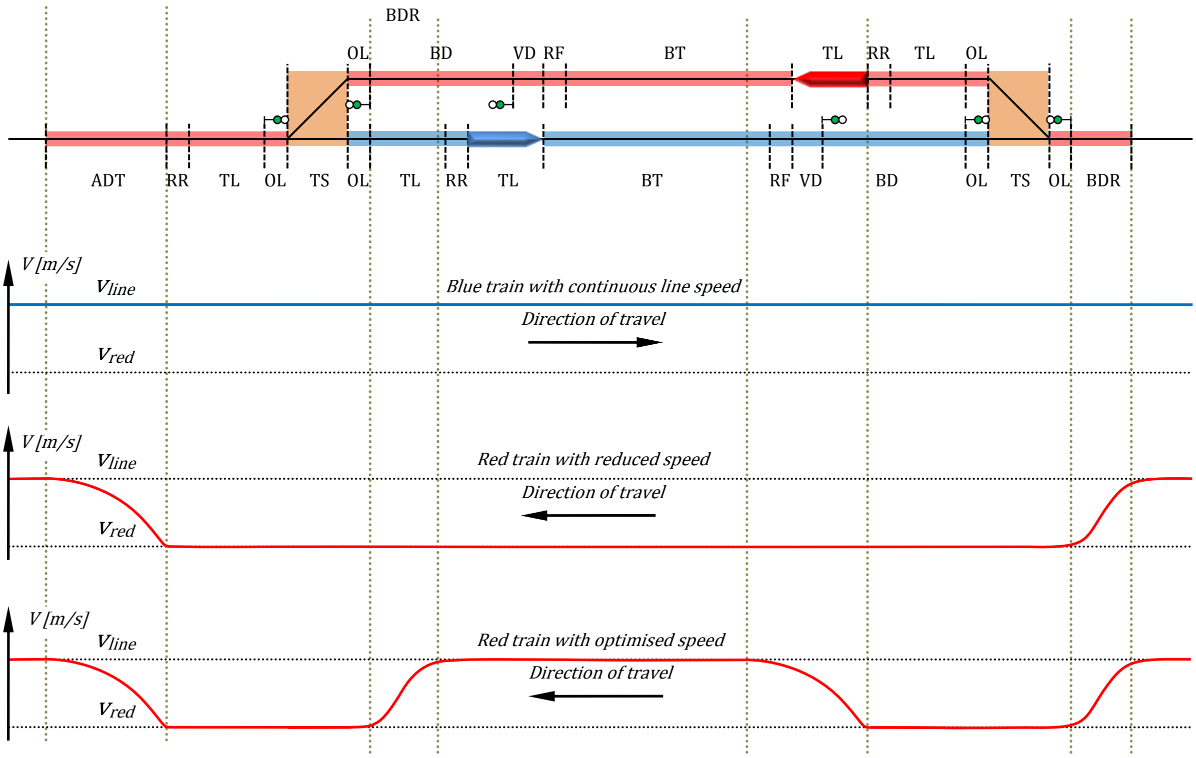

Figure 45 – Principle of delays caused by speed restrictions on diverging tracks (Author)

Figure 45 also demonstrates a further central principle of delay caused at loops. The red train is affected by the speed restriction before entering the loop and after exiting it which must also be considered in the delay estimates. The turnouts become a major influence of how much time is lost for the red train.

The total delay of the red train compared to the blue train is illustrated in Figure 46:

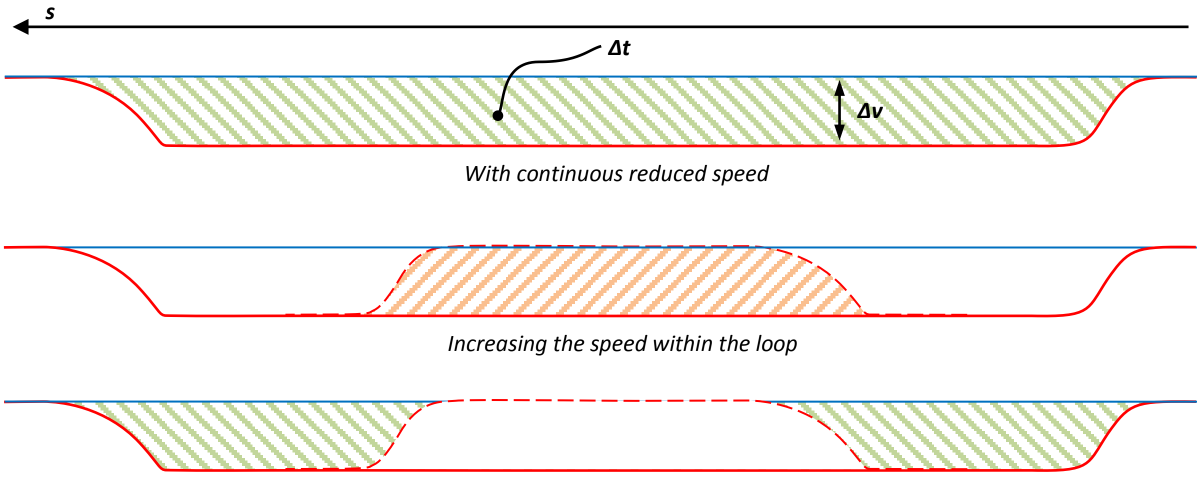

Figure 46 – The effective delay of the red train compared to the blue train (Author)

Δt is the difference in time or delay between the red and the blue train, and is effectively the area shaded in the figure above.

The following table demonstrates the effect of delay for the red train running at continuously reduced speed compared to the blue train which runs on line speed, for different operating speeds and for different turnout speeds:

Table 14 - Delayed caused by passing loops on diverging train (Author)

Line Speed\ Diverging speed	160	200	250
250	*185 s*	*80 s*	*0 s*
300	*306 s*	*176 s*	*68 s*
350	*450 s*	*295 s*	*161 s*

The delaying effect of the loop is quite significant. Considering a scenario similar to Figure 40 with 8 passing loop the delay from running at 250 km/h and reducing the speed to 160 km/h for the turnout caused the train a total of 12 minute delay if the trains alternate on priority (4 crossings). The same scenario with line speed of 350 km/h causes a total of 30 minute delay, which is quite significant taken into account that there is no stop on the line.

5.7 Deadlock

On single track lines a situation referred to as "deadlock" may appear when trains are not run to schedule, where two trains in a passing loop section is blocked by oncoming trains from both directions. The movement for any train is impossible without having one or more trains to reverse its path. It is reasonably straightforward to avoid deadlock in the timetable design, particularly if there are few trains and several passing loops. However, in a situation where disruptions have occurred and the trains are manually dispatched the risk for a deadlock rises significantly. Consequently all single track lines should have strict operational rules for manual disruption management to prevent this type of situations (Mills and Pudney, 2003) (Landex, Kaas and Hansen, 2006).

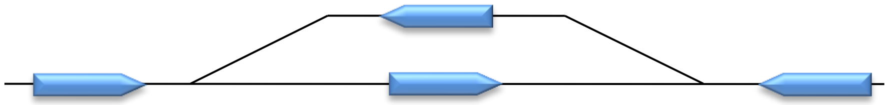

Figure 47 – A potential deadlock situation (Author)

Furthermore, train lengths longer than the passing loop or operational rules can limit the possibility for trains to use some passing loops supplementing the problem. On the other hand, a high speed single track line will most likely consist of homogeneous rolling stock and the design will be purpose built so the latter issues would be less of problem.

6 Impact of Capacity on Infrastructure

6.1 Principle of Ratio

It is difficult to operate a single track railway network without having passing loops. The need for passing loops is indisputable and required to guarantee success of operations. However, passing loops are essentially double track sections and increasing the number of TPH increases the need for passing loops.

The relationship between double track and single track can be obtained by examining the length of the passing loop and the HD length. The HD is effectively the meeting point if the trains are running at constant speed with regular interval. The meeting point is in the middle of the loop length. As the numbers of crossing and the length of the HD directly related to the capacity this must be included in the calculations, thus the HD must be a function of the TPH:

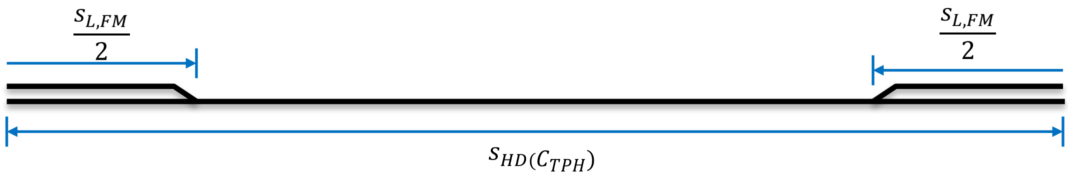

Figure 48 – Principle of passing loop ratio on total track length (Author)

This principle does not include secondary loops. Based on the figure above the ratio must therefore be:

$$R = \frac{s_{L,FM}}{s_{HD(C_{TPH})}} \qquad \text{Equation 58}$$

The flying meet loop length is:

$$s_{L,FM} = \frac{v^2}{2a_b} + 2(s_{TS} + s_{OL} + s_{TL}) + v(t_{RF} + t_{VD} + t_{RR} + t_{BT}) \qquad \text{Equation 59}$$

The HD as a function of capacity is, with TPH in only one direction:

$$C_{TPI} = \frac{t_I \cdot v}{2s_{HD}} \qquad \text{Equation 60}$$

$$s_{HD} = \frac{t_I \cdot v}{2C_{TPI}} \qquad \text{Equation 61}$$

The ratio is therefore:

$$R = \frac{s_{L,FM} \cdot t_I \cdot v}{2C_{TPI}} \qquad \text{Equation 62}$$

$$R = \frac{C_{TPI}\left(\frac{v^2}{2a_b} + 2(s_{TS} + s_{OL} + s_{TL}) + v(t_{RF} + t_{VD} + t_{RR} + t_{BT})\right)}{1800 \cdot v} \qquad \textit{Equation 63}$$

6.2 Double Track Ration Calculations

In the graph below the ration curve has been plotted for 160 km/h and 350 km/h respectively with 3 min BT. The relationship between TPH and the ration have a near linear increase which is sensible. The ratio is affect by the number of crossing which have a defined distance. Therefore, increasing the TPH is the same multiplying the number of passing loops divided by the total length which has a linear relation. However, what is noteworthy is the neglecting difference between speeds. This is a results of as speed increases the distances between the loops gets longer, equally the length of the passing loop in increased.

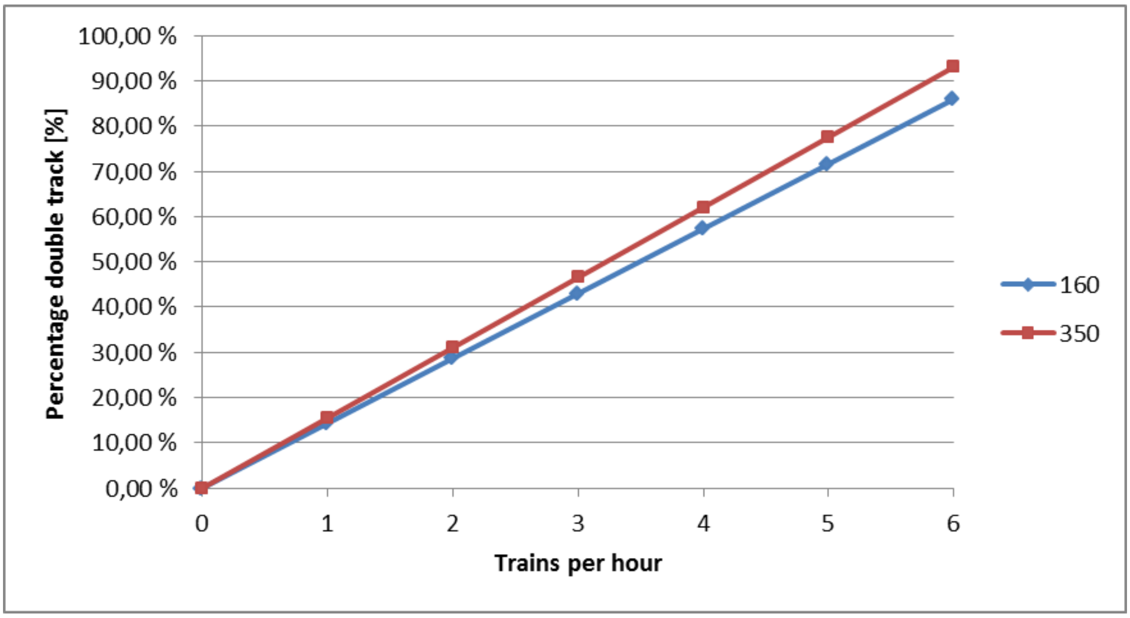

Figure 49 – Double track ratio based on TPH, with 3 min BT (Author)

It is important to notice that the plot is not correctly presented with a smooth line as e.g. 1.26 TPH does not exist. However the Author has chosen this plot type to provide a better visual presentation of the relationship between TPH and double track ratio.

Another observation of this can be done with the buffer time set to for example 3 min for different numbers of TPH. From the low speeds there is a steep decline in the ratio before the curve flattens out. Higher number of trains per hour seems have their lowest ration point at 120 km/h. The curve then starts to rise towards higher speeds, but the increase seems to be relatively low. In the figure below 4 TPH seems to have lowest double track ratio at 120 km/h, however the overall difference in the range from 100 km/h to 350 km/h seems to be very low.

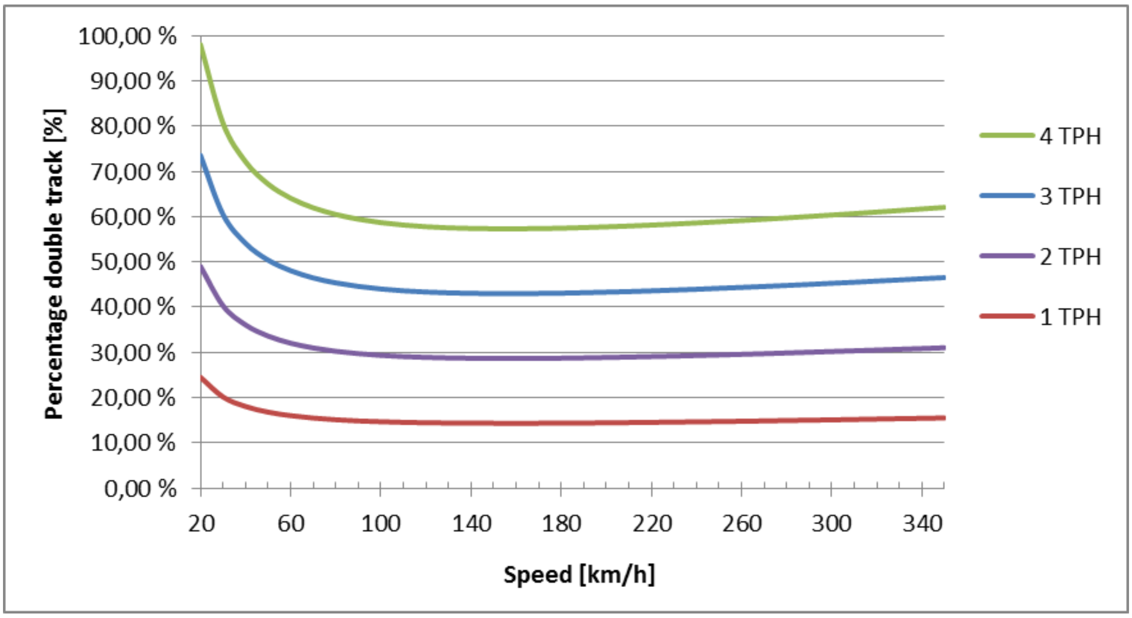

Figure 50 – Double track ratio based on speed, with 3 min BT (Author)

The next graph demonstrates how the buffer time affects the ratio and capacity. Given that the speed has little effect on the ratio the graph is plotted with trains running at 350 km/h. As the plot is relatively linear the BT only adjust the steepness of the plot.

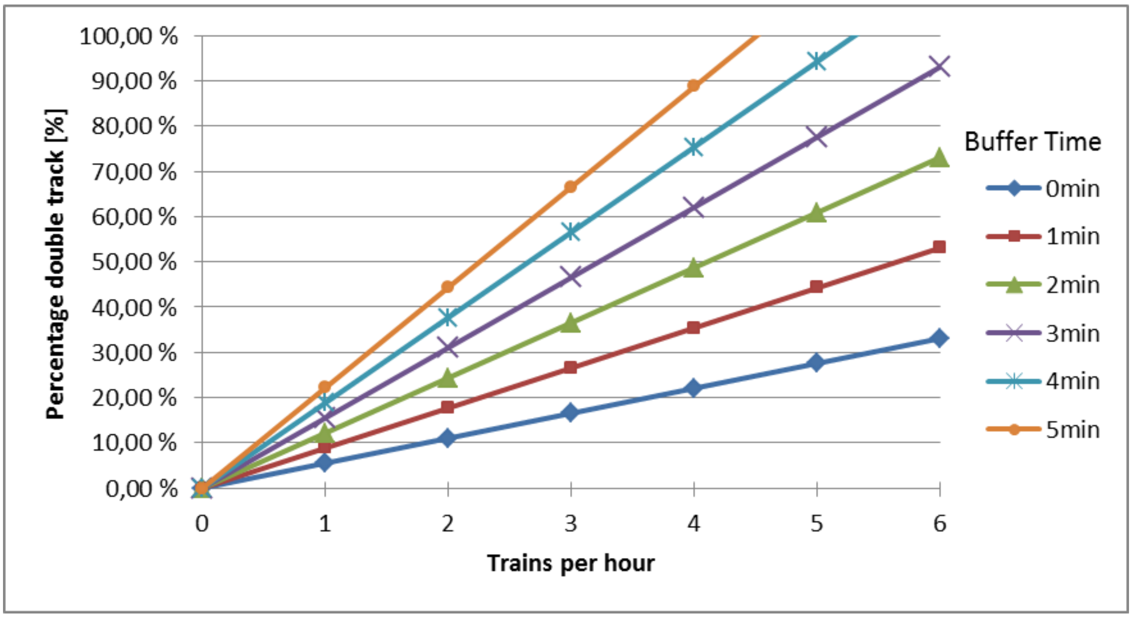

Figure 51 – Double track ratio based on TPH and BT with fixed speed of 350 km/h (Author)

The final remark on double track ratio is what is the real definition of single track? As it is evident from the calculations done in this report, passing loops are a necessity of single track operations. And as stated several times, passing loops are effectively double track sections, so single track is not really 100% single track. When does it become partly double track? At 50%? Or where should the threshold be for double track ratio before it is sensible to add the additional cost of building a complete double track line? As long as there are single track sections on a network the network adapts the constraints of single track operations.

7 Other Associated Issues

7.1 Punctuality and Robustness

Punctuality is an important measurement of performance for passengers, competitiveness and quality of service (Goverde et al., 2001). Railways are complex systems which are highly interdependent on all its subsystems and interfaces to function. As an example the rigidness of the system does not allow trains to bypass hinders on the line. There are many sources of disruption which can be difficult to manage and the possible event of something malfunctioning in the subsystem has the potential to take down the whole system. As a result of these factors the risk of disruption to a railway system is very high and the successful operation of railways relies on the concept of high level of Reliability, Availability, Maintainability and Safety (RAMS).

The sources for disruption can be divided into two main types (Goverde, 2005):

Primary Delay:

"A primary delay is the deviation from a scheduled process time caused by disruption within the process." (Goverde, 2005)

Secondary Delay:

"A secondary delay is the deviation of a scheduled process time caused by conflicting train paths or waiting for delayed trains." (Goverde, 2005)

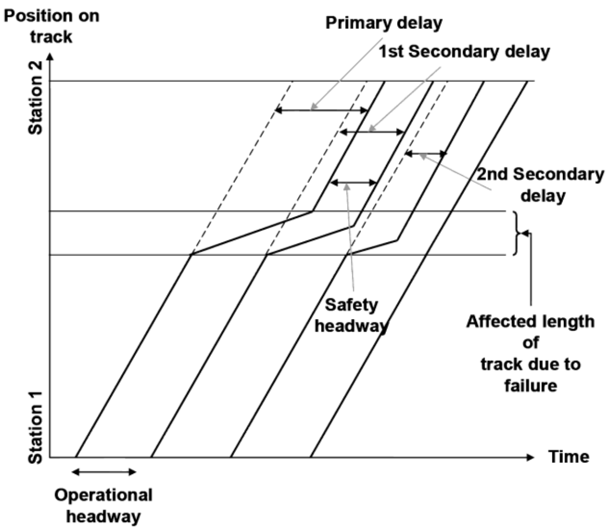

Figure 52 – Primary and secondary delays exemplified in a timetable (Patra, Kumar and Kraik, 2010)

The key difference between the types of delay is that the primary delays can be unpreventable or uncontrollable such as weather conditions etc. Secondary delays are effectively the consequence of the primary delays and can be limited with good management rules and preventative measurements. However, a secondary delay becomes more difficult to manage with increased complexity and saturation of a system, which is the case for single track operation. This can be resolved by adding the secondary loops.

Table 15 - List of the most common primary delays (Goverde, 2005)

Infrastructure: Technical Malfunctioning, Maintenance & Construction	
Rail network	Tracks; Switches; Structures (tunnels, bridges)
Electrification	Supply; Catenary
Signalling	Signals; Interlocking; Train detection (track circuits, axle counters); Automatic level crossings
Train Operators	
Rolling stock	ATB-application; Malfunctioning traction, engine, brakes, running gear, doors;
Personnel	Driver and conductor behaviour (experience, routine, discipline, stress, illness)
Logistics	Loading/unloading; Catering
Train circulations	Shunting; Cleaning; Braking test
Passengers	Volume alighting and boarding; Supporting disabled; Aggression; Nonpaying passengers
Railway Traffic Management	
Systems	Disposition; Traffic control; Communication; Automatic Route Setting
Personnel	Dispatcher behaviour (experience, routine, discipline, stress, illness)
Plan	Timetable bottlenecks; Rolling stock scarcity; Crew scarcity
External	
Weather	Frost; Heat; Wind; Sight; Lightning; Slipperiness (leaves on track)
Vandalism	Track obstruction
Environment	Incidents at level crossings; Animals on tracks; Trespassers on tracks; Suicides

Table 16 – List of the most common secondary delays (Goverde, 2005)

Type	**Example**
Hinder	Slow leading train
	Conflicting train route
	Occupied platform track
Synchronization	Transfer connection (waiting for delayed feeder train)
	Rolling stock connection (coupling/decoupling, turn)
	Crew transfer

The BT includes the average risk of delay by adding supplementary time between train paths and therefore captures a great deal of the minor primary delays. The integration of this in the timetable is therefore not regarded as delays by the train controller’s point of view. The same is considered for delay or lost running time caused by scheduled loops. The latter is also known as conflict delay (Higgins, Kozan and Ferreira, 1997).

The Author recommends the sources of delays are further investigated to provider additional advice on how a single track railway can be as reliable as possible.

7.2 Station design

Stations could potentially be one of the biggest bottlenecks on line capacity (Abril et al., 2008) if it is inadequately designed to cope with the traffic demands that are present of the time of construction and especially the traffic demands which will arise in the future. The number of stopping trains, passing trains and dwell time are essential to determine a functional station design. In theory the line capacity is a factor of the time period divided by the headway time as described in section xx. The need for a train to decelerate, dwell and reaccelerate adds on to the headway time calculations and occupies significant parts of the line capacity.

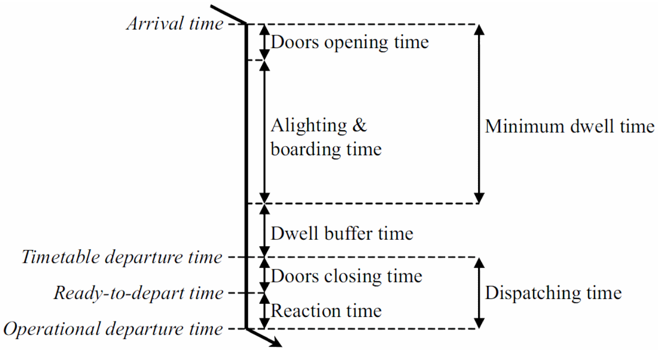

Figure 53 – Components of dwell time (Goverde, 2005)

To reduce the impact of a stopping train at stations it is necessary to provide additional tracks at the stations to allow for dwell time. The additional tracks allow subsequent trains to approach the stations closer to or at line speed as there is no train obstructing the train path ahead. The number of tracks needed is determined by the dwell time and especially if there are trains terminating at the station. In most cases for a high density railway with only non-stopping trains, two station tracks per line will provide sufficient capacity.

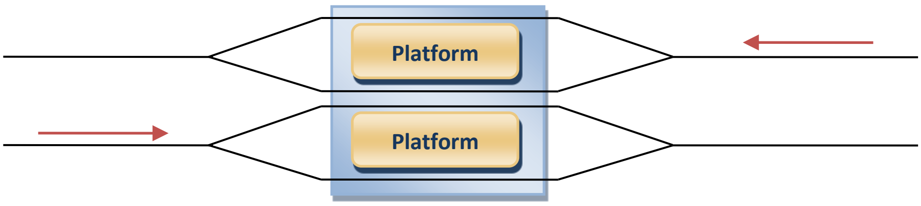

Figure 54 – Adding additional track at the stations increases capacity (Author)

There are mainly two station concepts that can be considered for none terminal stations. The most typical is the side platform station. As the name imply the platforms are placed on each side of the tracks to be used separately for each direction of travel. To connect the platform there can be a passenger bridge, tunnel or the platforms can be elevated to create a station area below. On very high density services such as in Japan and some other countries an extra set of passing tracks could be laid in between providing nonstop opportunities at line speed for passing trains. However, it is very unlikely that this could be considered as an option on a single track high speed line as service is very limited. A lighter version of this concept if traffic volumes are low is to eliminate platform B and only keep platform A on the one side.

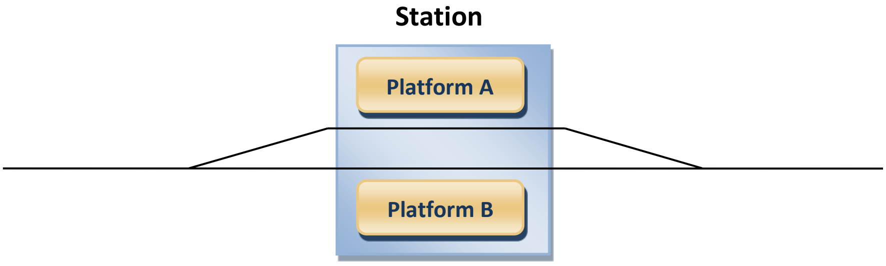

Figure 55 – Side Platform Station (Author)

A less expensive construction method is the island platform design. This concepts is to use the same platform for both directions of travel, therefore the tracks are placed on both sides of the platform. To reach the platform it is necessary to provide a passenger bridge or tunnel as the platform is only accessible by passing the tracks.

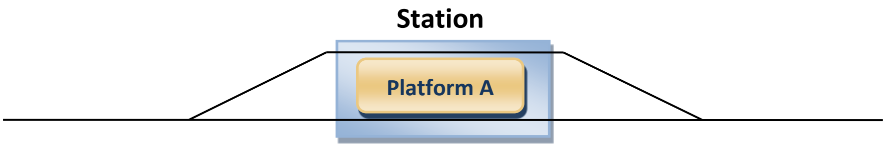

Figure 56 – Island Platform Station (Author)

7.3 Stopping Pattern

There are many factors which need to be considered in the design of the stations. Firstly, the stopping pattern needs to be resolved. It is strategic that future changes in timetables and flows must be kept in mind. Stopping pattern for the high speed service may include a lower stopping frequency on intermediate stations where traffic flows are low.

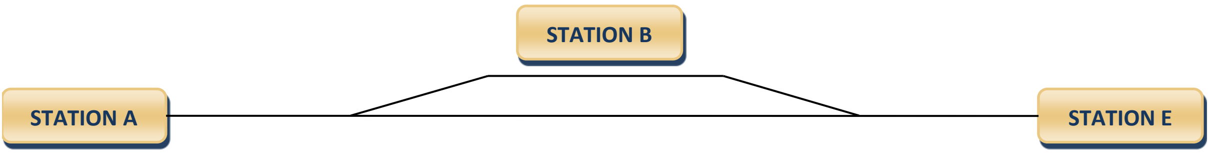

Figure 57 -Alternating stopping pattern (Author)

In an example seen in the figure above of a service where we have a high speed service from terminal station A to terminal station E, via intermediate station B. Given that there is a high flow of passengers between A and E requiring a service departing every 30 minutes from each terminal station. The flow of passenger from station B is limited so therefore it is not necessary that all trains will stop at this station. Assuming that an hourly service would provide enough capacity the alternating train could pass the station without stopping saving time. At station B there therefore be a train stopping every 30 minutes alternating on the terminus station A or E.

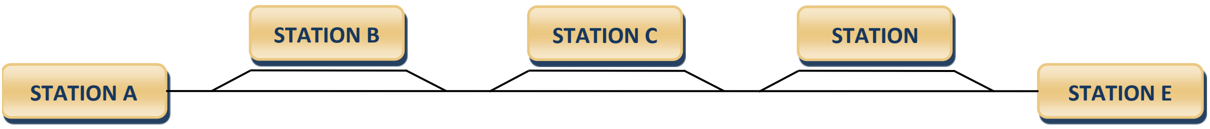

Figure 58 – Alternating stopping pattern (Author)

If several intermediate stations are required then the concept could be expanded to train service AEX stopping a stations A – B – D – E and train service AEY stopping at station A – C – E, and likewise from the other direction train service EAX stopping at E – C – A and strain service E AY stopping at station E – D – B – A. The use of this concept would also benefit in reduced overall cost of building the stations and travel time by reducing the number of stops. As the stopping train is standstill while the other oncoming train will pass the length of the loop can be reduce in contrast to a passing loops where both trains are travelling on line speed.

8 Conclusion

8.1 Findings

As single track operations are inherently dependent on the placement of loops the rolling stock performance is of great influence and importance to the planning process as it provides information on train locations based on the infrastructure. The rolling stock performance is influenced by the mass of the train, level of adhesion available, the power and motoring limits and the resistance forces. The latter can be divided into two categories, inherent resistance which is consist of mechanical and aerodynamic resistance and incidental resistance which consist of grade, curvature, wind and vehicle dynamic resistance. These complex factors can lead to inaccurate performance data, thus there is a need to control and evaluate all the inputs and outputs.

In future, trains might have additional performance enhancements but this benefit is limited to acceleration and deceleration phases, and operation on gradients and in tunnels. If the service consist of mostly constant speed at grade this enhancement will not provide much running time improvement. However, in situations where there are several gradient sections, tunnels and many effective speed limits such as in passing loops, these future trains can provide great improvements in running time.

The relation between the timetable, the infrastructure and the rolling stock performance is very important in single track operations and design. Once the timetable and the infrastructure are locked there is little room for adjustments to the plans. If there is a need to change the departure times from one end of the line, an equal change is required on the other end. If this is not met the trains would not meet at the designated places and new passing loops must be built.

Double track offers more than twice the capacity offered by single track in the area investigated by the author. For a 180 s buffer time the capacity on a double track can be up to 5 times as much as on a single track. While capacity of double track operation reduces when the speed increases, the opposite occurs with single track operations, where increasing the speed also increases the capacity.

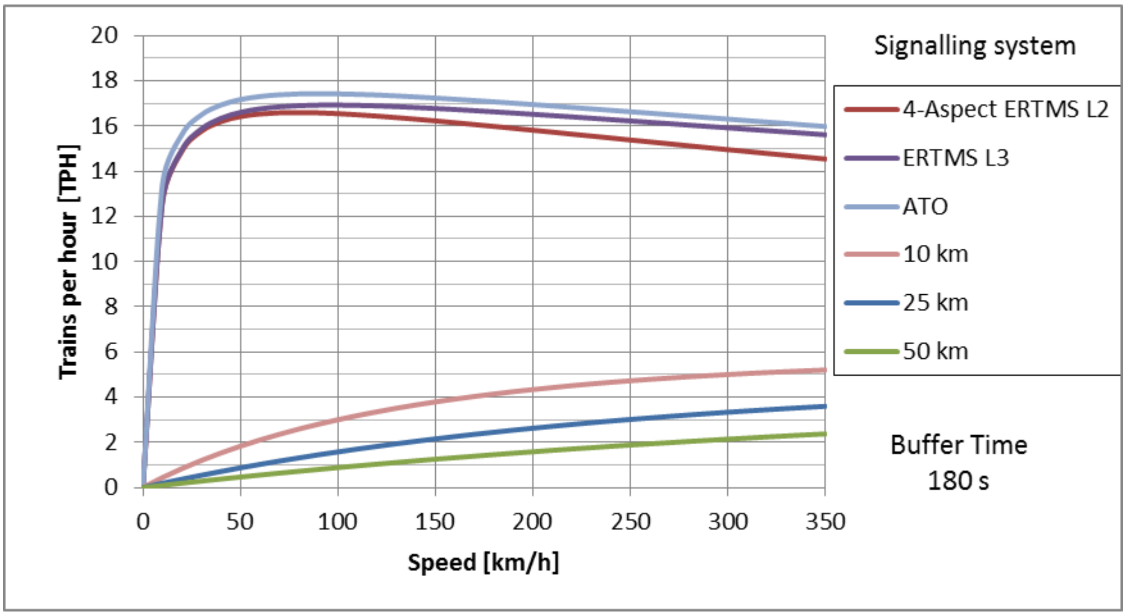

Figure 59 – Theoretical capacity of double and single track, 3 min buffer time (Author)

For single track operations 3 types of passing loops have been identified; scheduled loops with a passenger stop, scheduled loops without a passenger stop and secondary loops. The latter two have been investigated in this report. Flying meet requires long loop lengths which increase with speed. For 180 s buffet time at 300 km/h, at least 22.5 km of loop length is required for a flying meet.

Simple timetable with homogenous rolling stock and regular intervals are easiest and most appropriate for single track operations. Adding additional services, i.e. a 30 min peak hour service to an already existing hourly service with the same rolling stock performance continues the cyclic pattern of passing loops by a factor of two. However, adding heterogeneous services increases the number of required loops by a factor greater than two dependent on the speed difference, and the passing loops will be disproportionately spaced.

The impact of running more trains gives a higher share of double track ratio. The relationship is nearly linear and can be found in figure [x]. However, there is a lack of definition towards what can be considered single track and partial double track, before reaching the level where the additional cost of building a double track justifies the increase on flexibility and robustness in the operations. A railway which can fulfil the required capacity demands with 2 trains per hours in each direction and the required level of reliability with 3 min buffer times needs 30% of the line to be passing loops.

As single track is inherently interconnected to the infrastructure and all of its subsystems it is very important to have a high reliable system. There are many types of delays which can occur and this report considers two types of delays – primary and secondary. Primary are delays that can be caused by poor management, lack of investments and maintenance, but most importantly uncontrollable events such as weather and other external influences. Secondary delays are caused by the poor management of primary delays and can be controlled with the appropriate set of management rules.

The station design can be the main capacity consumer as it involves acceleration, deceleration and dwell time which is integrated in the buffer time. Increasing the number of station track is a good way of increasing the capacity. Increasing the train length or adding an additional deck to the train is a very cost-effective method of increasing the capacity if the infrastructure can handle such modifications to the train.

Not all services are required to stop at all stations in order to save running times. Alternating stopping patterns is a good method for providing high frequency service to the main stations and a lower frequency to the smaller station.

The train performance calculator introduced in this report is a great tool for assessing the same topics that have been covered in this report. With simple input changes the user can quickly assess new results.

8.2 Recommendations

High speed trains on single track can be a good solution if the ratio of double track is below the acceptance criteria and at the same time being satisfied with the level of service provided in terms of capacity, frequency and travel times with the given reliability levels. Areas where land expropriates are very high, or places with topography which requires a large share of tunnels, bridges and viaducts, can benefit from single track operations.

Single track operation is not suitable for handling heterogeneous traffic without the need of substantial infrastructure investments in additional loops, and reducing the capacity. It is therefore recommended by the Author to only allow homogeneous traffic on single track railways.

As this report is highly theoretical it is recommended that a simulations tool is used on a full scale scenario. This can provide information which has not been captured in this report. The concept of the TPC can also be used to develop a simulator for calculating the performance impact of single track operation.

An area which absolutely should be investigated further is costs – the costs related to additional track, the cost of delays, etc. Cost is the main driver of projects and it is also the main reason why single track rail is in focus.

Finally, as understood by the Author during literature reviews there might be a need for a cultural change to improve the reliability, which reduces the buffer time which has a direct relationship to the capital costs. Low level of delay and high level of reliability are two key elements in successful single track operations. However, in Europe there is not a good enough culture and discipline to handle this compared to the Japanese!

8.3 Review of Approach

This report has been investigated by the use of analytical approach. It has been a very intensive and time consuming investigation with heavy use of mathematical calculations. The Author realised late in the process that the train performance calculator was needed, thus loosing valuable time doing it the hard way mostly through the duration of the dissertation. The Author has learned significant valuable lessons and can now command good knowledge in the topics of rolling stock performance, capacity and loops, which provides confidence in examining these aspects in future work.

As the research has been conducted by the Author solely by himself there is a need to validate the calculations and the content. The Author did encounter several setbacks during the project when faults in the calculations were discovered. However, the continuous process of assessing the calculations and using the train performance calculator has resulted in what the Author believes to be logical and sensible findings.

If it is required to conduct a similar analysis again the Author would have considered the use of an existing simulator to simulate the single track railway. However, with the research done in this report the Author now have a better understanding of the outputs of an simulator, thus providing additional quality assurance to such project.

The train performance calculator was developed in Excel, however at this stage without the use of Visual Basic coding. Excel is a great tool for resolving a large number of calculations, especially repeating and connected calculations. However, there interface for working with long and complicated formulas can be very confusing and this is a potential source of error in this report.

Due to the amount of time spent in solving the calculations analytically in the first period, and the time spent on creating the train performance calculator, it was not possible to investigate all the aspects of single track that the Author had initially considered, e.g. costs, conveying trains etc.

It must be stressed that the scenarios presented in this report are theoretical and does not reflect all aspects of real situations.

8.4 Word Count

There are 16 320 words between sections 1.1 and 8.3.

9 References

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10 Appendix A

The formulas used to calculate the time and distance based on variable acceleration online with WolframAlpha

http://www.wolframalpha.com/

Speed	EMU 1
0-108km/h	integrate((445*1.06)/(300-(4.45+0.06*v+0.0075*v^2)),0,30)
108-250km/h	integrate((445*1.06*v)/(9000-(4.45*v+0.06*v^2+0.0075*v^3)),(108/3.6),(250/3.6))
250-300km/h	integrate((445*1.06*v)/(9000-(4.45*v+0.06*v^2+0.0075*v^3)),(250/3.6),(300/3.6))
300-350km/h	integrate((445*1.06*v)/(9000-(4.45*v+0.06*v^2+0.0075*v^3)),(300/3.6),(350/3.6))
0-108km/h	integrate((445*1.06*v)/(300-(4.45+0.06*v+0.0075*v^2)),0,30)
108-250km/h	integrate((445*1.06*v^2)/(9000-(4.45*v+0.06*v^2+0.0075*v^3)),(108/3.6),(250/3.6))
250-300km/h	integrate((445*1.06*v^2)/(9000-(4.45*v+0.06*v^2+0.0075*v^3)),(250/3.6),(300/3.6))
300-350km/h	integrate((445*1.06*v^2)/(9000-(4.45*v+0.06*v^2+0.0075*v^3)),(300/3.6),(350/3.6))

Speed	EMU 2
0-108km/h	integrate((400*1.06)/(400-(4+0.055*v+0.0065*v^2)),0,30)
108-250km/h	integrate((400*1.06*v)/(12000-(4*v+0.055*v^2+0.0065*v^3)),30,(250/3.6))
250-300km/h	integrate((400*1.06*v)/(12000-(4*v+0.055*v^2+0.0065*v^3)),(250/3.6),(300/3.6))
300-350km/h	integrate((400*1.06*v)/(12000-(4*v+0.055*v^2+0.0065*v^3)),(300/3.6),(350/3.6))
0-108km/h	integrate((400*1.06*v)/(400-(4+0.055*v+0.0065*v^2)),0,30)
108-250km/h	integrate((400*1.06*v^2)/(12000-(4*v+0.055*v^2+0.0065*v^3)),30,(250/3.6))
250-300km/h	integrate((400*1.06*v^2)/(12000-(4*v+0.055*v^2+0.0065*v^3)),(250/3.6),(300/3.6))
300-350km/h	integrate((400*1.06*v^2)/(12000-(4*v+0.055*v^2+0.0065*v^3)),(300/3.6),(350/3.6))

11 Appendix B – Train Performance Calculator

11.1 Intro

The Train Performance Calculator (TPC) was created to perform all the calculations needed in this report rapidly with high precision. Much effort has been invested in creating the TPC due to the amount of calculations needed and the number of formulas and connections, however the result is in the view of the Author a decent tool that can be used for simple train performance calculations. The tool is able to evaluate different types of rolling stocks and signalling system impact and can calculate simple, theoretical values of rolling stock performance, capacity and infrastructure elements.

The TPC assumes that the user has the necessary rolling stock and infrastructure data available.

The TPC comes in two versions, the first is the original unprotected Excel workbook with all formulas and sheets available and modifiable. This version is to be used when evaluating the TPC. The second version is the protected version where only the cells and sheets that is needed for the end user is available. This version is intended to be the final end-user version of the calculator.

All the formulas and calculations in the TPC are all based on the assumptions and equations found in this dissertation. It is only valid for a small section of the railway and it does not consider external factors.

11.2 How to use the TPC

There are three tabs for this worksheet which are of interest for the end-user, “Input”, “Graphs” and “Signalling”. In the Input tab the user can change the data after requirements. Those cells which are locked are results of the inputs, and cannot therefore be edited. However, a shot description is available in the following sections

11.3 Input

Performance Characteristics

Here the rolling stock performance characteristics are typed in as given by the rolling stock manufacturer for both EMU1 and EMU2. EMU2 must have better performance values than EMU1 to get the calculations to function correctly. However, the Mechanical resistance is assumed to be 10N per ton and therefore it is locked. Also, the maximum speed and acceleration and the calculation step is locked.

Acceleration Performance

This is a comparison between the EMU1 and EMU2 of acceleration in time and distance for a given speed range. They are also compared against each other at the same point of travel to reflect the true performance difference between the two trains. Only the speed range is available for editing.

Infrastructure Characteristics

In this part all cells are looked except the "Choose signalling type". Based on the signalling type all the values will change based on the selection except the turnout section length which is looked to 270m (this will not affect the calculation significantly, but is required to simulate high speed turnouts).

Performance Characteristics			EMU1	EMU2
Rotating Mass Factor	f_p		1,06	1,06
Maximum Starting Force	F_{max}	*kN*	300	400
Total Mass of Train	m	*tonne*	445	400
Power of all Motors	P	*kW*	9000	12000
Mechanical Resistance	r_0	*kN*	4,45	4,00
Viscous Mechanical Resistance	r_1	$kN\ s/m$	0,060	0,055
Aerodynamic Resistance	r_2	$kN\ s^2/m^2$	0,0075	0,0065
Maximum Speed	V_{max}	m/s	101,80	118,20
Maximum Acceleration	a_{max}	m/s^2	0,66	0,99
Average Deceleration	a_b	m/s^2	0,70	0,70
Train Length	*S-TL*	*m*	200	200
Grade	α	*%*	0,00	0,00
Calculation Accuracy (Speed Interval)			0,10	

Acceleration Performance		From	To
Speed Range	m/s^2	44,4	97,2
Distance Travelled	*m*	37796,8	15251,6
Time Spent	*s*	463,4	197,4
Distance to reach same point	*m*		22545,2
Time difference at same point	*s*	+34,1	

Infrastructure Characteristics			Value
Choose signalling type			Aspect (Aspect / ATO / ERTMS L2 / ERTMS L3)
Route Formation	t_{RF}	*s*	
Visual Distance	t_{VD}	*s*	
Route Release	t_{RR}	*s*	3
Buffer Time	t_{RR}	*s*	180
Overlap Length	s_{OL}	*m*	200
Turnout Section Length	s_{TS}	*m*	270

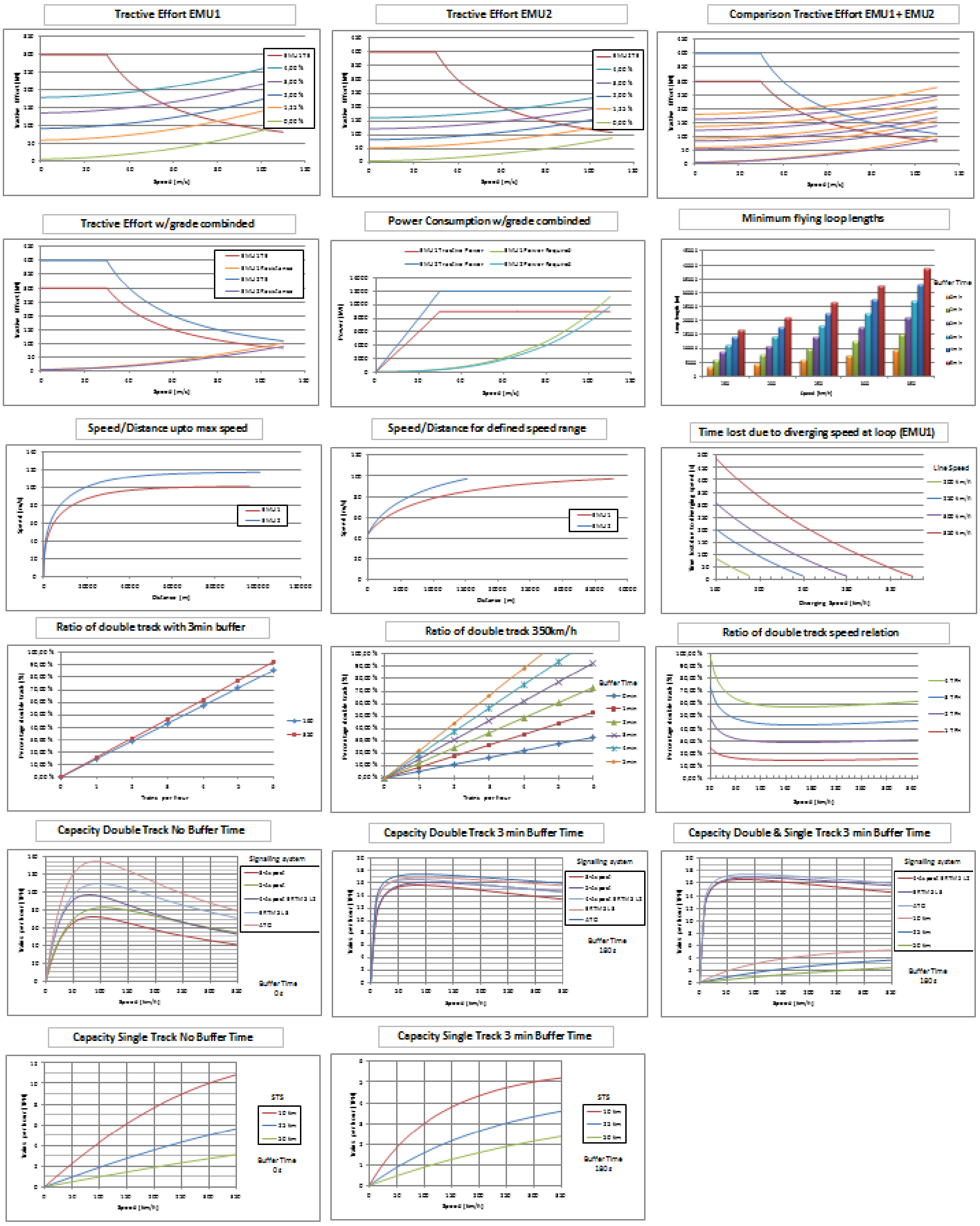
11.4 Signalling

The signalling tab is to adjust the values for each signalling system used in the Infrastructure Characteristics table in the Input tab. The parameters adjusted in this section will automatically be updated in all calculations.

			Aspect	ATO	ERTMS L2	ERTMS L3	ST
t_{RF}	Route Formation	[s]	5	5	6	6	10
t_{VD}	Visual Distance	[s]	8	1	5	5	8
t_{RR}	Route Release	[s]	3	3	3	3	3
t_{BT}	Buffer Time	[s]	180	180	180	180	180
s_{OL}	Overlap Length	[m]	200	20	50	50	200

11.5 Graphs

In this tab all the result based on the calculations are displayed in various graphs, which can be found in this dissertation. This is only an output tab and does not allow for any input.



11.6 All other tabs

All other tabs are meant only to be used to review the calculations done and should not be edited.