The sustainable freight railway: Designing the freight vehicle – track system for higher delivered tonnage with improved availability at reduced cost

SUSTRAIL

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FUTURE VEHICLE PERFORMANCE REQUIREMENTS

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Executive Summary

The present document reports major considerations and contributions to the performance requirements of the future SUSTRAIL freight vehicle. In detail, duty requirements have been defined with reference to the increase of maximum speed with the aim of achieving potentially double the life of track components when combined with low impact vehicles.

In line with the Annex I – DOW and the tasks divisions reported over there, the following issues have been investigated in D2.4:

- Suspension and running gear;
- Brakes;
- Accelerations and speed requirements;
- Aerodynamic requirements;
- Noise requirements.

All these features have been investigated in D2.4 taking into account the project objective of running freight trains at higher speed (up to 120 km/h and potentially to 140 km/h) ensuring at the same time lower impact on the infrastructure.

Suspension and running gear should provide for a reduction in damage to the track (rail wear and surface damage, track vertical settlement and lateral stability) and to the vehicle (wheel wear, component damage and load integrity) while maintaining a safe operation level against derailment and track lateral shift.

The SUSTRAIL freight vehicle will benefit of a combined wheel-slide and brake control system. Analysis on accelerations and speed requirements highlighted that higher time savings can be obtained by increasing the speed up to 120 km/h with respect to today situation whilst lower benefit can be achieved from 120 km/h to 140 km/h, mainly due to speed limits imposed by railway crossing, switches and curves with high radius and sections with high gradient.

From the aerodynamics investigations a series of options to improve the aerodynamics of the freight vehicle have been identified.

Regarding noise mitigation, it came out from the study that for the range of operating speeds of the SUSTRAIL wagon, rolling noise will be the dominant source.

Detailed results of the study are described in the following of this document.

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1. INTRODUCTION

The SUSTRAIL project aims to contribute to the rail freight system to allow it to regain position and market share. It is proposed that the contribution is based on a combined improvement in both freight vehicle and track components; this holistic approach is aimed at achieving a higher reliability and increased performance of the rail freight system as a whole and profitability for all the stakeholders. The SUSTRAIL integrated approach is based on innovations in rolling stock and freight vehicles (with a targeted increased in speed) combined with innovations in the track components (for higher reliability and reduced maintenance), whose benefits to freight and passenger users (since mixed routes are considered) are quantified through the development of an appropriate business case with estimation of cost savings on a life cycle basis.

Starting from one of the project general targets, relevant to the increase of maximum speed for freight trains, WP 2 aims to define duty requirements for vehicles and track that achieve potentially double the life of track components when combined with low impact vehicles.

Today the top speed of freight services is usually between 75 and 100 km/h. The standard axle load in Europe is 22.5 tonnes (limited to 20 tonnes in some regions).

The SUSTRAIL target is to increase speed to 120 km/h or more, up to a maximum speed of 140 km/h.

1.1 Structure of the document

This document, led by TRAIN, includes contributions from different Partners (UNEW, MMU, USFD, SIRV and KES).

Chapter 2 summarizes the objectives of the Work Package and the goal of the deliverable, including some considerations from other Work Packages.

Chapter 3 introduces the technical requirements of a 4-axle freight wagon to be designed, which will be manufactured and tested within SUSTRAIL project from the perspective of SIRV.

Chapter 4 provides the limits for acceptable ride quality and dynamic performance, for existing and new freight traffic flows identified in WP 1. Moreover the design specifications for improved bogie/suspension characteristics considering total vehicle mass, unsprung mass and fatigue life are defined.

Chapter 4 describes the requirements for the development of a combined wheel-slide and brake control system with comprehensive diagnosis functionality for modern, innovative freight cars.

Chapter 6 defines the requirements for acceleration and describes the effects of the increased speed on one of the case studies identified in WP 1; a “Green Label” scheme is introduced, i.e. a certification assigned to vehicles on the basis of eco-friendly materials and technologies used for their construction and the expected environmental impact of their operation.

In Chapter 7 methods for reducing aerodynamic drag and their effects are considered; other aerodynamic effects associated with the pressure differentials and wind induced by the train are also studied.

Chapter 8 provides a summary of EU legislation and other existing guidelines for railway operation, and specifies the duty requirements for future vehicle and track systems. Different sources of noise, including rail-wheel interface, brakes, engine, and aerodynamic noise are taken into account.

Finally Chapter 9 reports the main outcomes of the deliverable to be used as guidelines and basic requirements for the vehicle component design and manufacturing across WP 3 and for testing in WP 6.

2. OBJECTIVES OF TASK 2.4

This work package has the aim of identifying the future vehicle performance requirements; each specific subtask of this work package addresses a specific technical field, such as suspensions and running gear, brakes, acceleration and speed, aerodynamics, and noise.

Aspirations are to maintain vehicle performance and harmonise operation of freight and passenger traffic on mixed traffic railways.

The final goal is to have line-speed operation of freight traffic, but this may not be reached given the three year time horizon for the core research. It shall be taken into account that smaller increases in freight speeds have the potential for disproportionate benefits; closer harmonisation of passenger and freight traffic performance can result in increased availability of paths thereby increasing capacity. Similarly, closer harmonisation of passenger and freight traffic performance will result in high speed passenger traffic needing to operate at lower cant deficiency (offering the potential for reduced wheel/rail wear and lower maintenance requirements).

Output of Task 2.4 is this deliverable D2.4 “Future vehicle performance requirements” (M12).

Task 2.4 is split in 5 subtasks:

- 2.4.1 - Suspension and running gear (led by MMU): this task is to establish limits for acceptable ride quality and dynamic performance, for the existing and new freight traffic flows identified in WP 1. It also consists in the design of specification for improved bogie/suspension characteristics, considering total vehicle mass (and thus payload capacity), unsprung mass, and fatigue life.
- 2.4.2 – Brakes (led by KES): this task is to define high level performance and reliability requirements for braking systems to achieve the performance required by the new freight traffic flows identified in WP 1. Issues include braking force build-up time, emergency performance, fading over long periods of braking and impact of braking system design on vehicle mass and unsprung mass. Based on these requirements, design specifications are to be drafted for an innovative brake solution for higher speed freight bogies, which will be developed within WP 3.
- 2.4.3 - Acceleration and speed requirements (led by TRAIN): in this task, the value of improved acceleration and the effects of increase of speed are to be analysed. The focus is on the value of increasing freight train acceleration versus removal of discrete line speed constraints associated with the infrastructure.
- 2.4.4 - Aerodynamic requirements (led by USFD): available technologies are reviewed in terms of the drag reduction and the practicalities of application, leading to specification of drag reduction technology for the freight vehicles to be developed in WP 3. The potential drag reduction is assessed using published literature.
- 2.4.5 - Noise requirements (led by TRAIN): noise pollution is of increasing importance in railway operation as EU legislation raises awareness of this issue. Using this legislation and other existing guidelines for railway operation the duty requirements for future vehicle and track systems are specified. Sources of noise considered include rail-wheel interface, brakes, engine, and aerodynamic noise.

The activities performed across Task 2.4 have used inputs from other work packages, especially WP 1 and other tasks of WP 2. The outputs of Task 2.4 will useful inputs for WP 3.

Within this framework, Figure 2.1 shows how Task 2.4 is linked to other relevant project tasks.

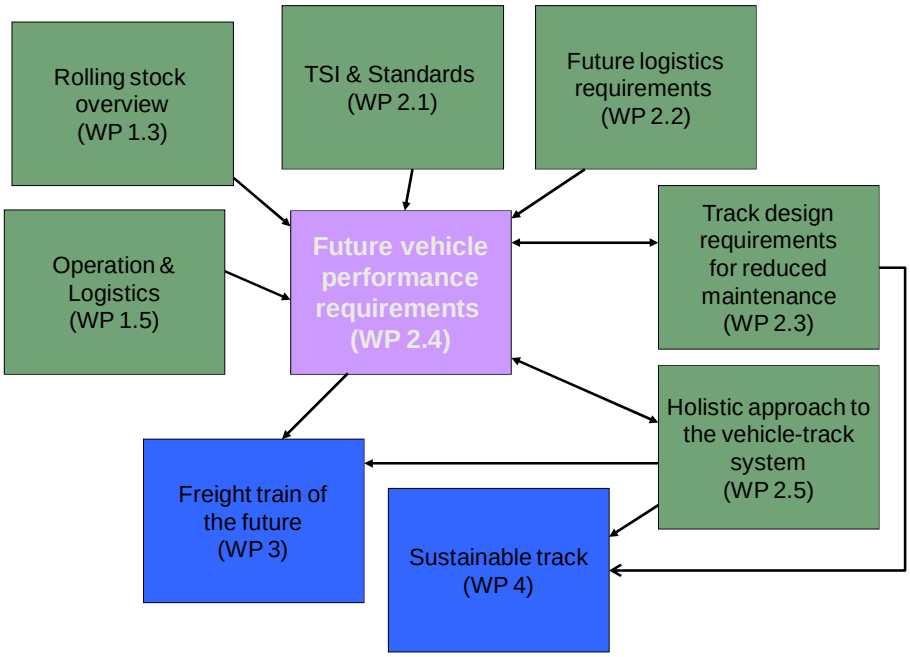


Figure 2.1: WP 2.4 links to other work packages

In WP 1 the benchmarking of the current freight system to establish the existing 'zero state' for subsequent comparative and enhancement activities has been analysed.

Three routes (case studies) have been selected to identify the current situation and potential for improvements, and their characteristics have been described:

- Spain;
- Bulgaria;
- United Kingdom.

Task 2.4 takes into account the standards and TSI collected in Task 2.1 and the future logistics requirements identified in Task 2.2 [69]. More details about this input are provided in section 2.1.

Task 2.4 outputs are mainly used to support the development of WP 3 in the definition of the freight train of the future. Indeed across WP 3 the key areas where recent and future developments can lead to improved running behaviour resulting in reduced impact, reduced system maintenance and lower operating costs for both vehicle and track will be identified

2.1 Considerations from Task 2.2

As introduced before, three case studies have been selected in the project to analyse the current situation and in which to identify the potential for increases of freight train speeds.

Starting from the data gathered in WP 1, in Task 2.2 a study has been performed in order to show the actual situation on these routes, with a view to defining future trends.

2.1.1 Bulgaria

Freight traffic has a typical line speed of 75 km/h apart from the section between Parvomaj – Jabalkovo during which freight can travel at up to 120 km/h. Maximum speed of freight trains is usually 80 km/h. Currently some parts of the route are being modernised, which could lead to new average data on speed in the future.

Maximum permitted axle load for freight wagons is 22.5 t.

There are several projects under examination, concerning modernization with increasing velocities, axle load, capacity and other technical parameters for the corridor under study. Some of these projects (for an important length of the corridor) are planned to be completed by 2013-2014, and other projects for the remainder of the corridor are planned to be finished in 2015-2016, 2017.

For the future, following the trend of recent years, it can be expected that the share of goods transported to and from the plants of the heavy industry, especially the metallurgical industry, will diminish. Concerning domestic and international (cross-border) transport, intermodal transport is expected to gain in importance.

2.1.2 Spain

The route average speed of freight trains is 52 km/h, but in some sections the maximum speed for freight movement is 120 km/h; there are currently no plans for freight trains to be scheduled to run faster, and most of them run at 100 km/h. On some track-sections local speed restrictions apply.

The average permitted length of freight train compositions is 450 m; this depends on the track section.

The maximum permitted weight of freight trains, given current locomotives, either electric or diesel, can be up to 1200t to 1600 t.

The maximum axle load allowed for freight wagons is 22.5 t; this is planned to be increased to 25 t.

Objectives for 2020

The Spanish Government shares the EU´s policy to promote rail freight transport and believes that increasing rail freight can contribute to realizing the potential of Spain as a logistical platform, reducing external costs and improving the competitiveness of the Spanish economy.

The target is for the railway to return its market position to that of a decade ago (in 2003 it carried 5.7% of freight by tonne-km compared to only 4.1% in 2008). The objective for 2020 is to reach 8-10% of modal share (Ministerio del Fomento, 2010). Steps to reach this target have been defined.

2.1.3 United Kingdom

Regarding the infrastructure, on the West Coast Main Line or other lines shared with passenger services, most of the route is laid out for running freight trains at a speed of 120 km/h max., but on other sections, freight runs at well below its potential speed (often averaging around 48 km/h over some sections) due to going into loops or slow lines and because of being stopped for passenger services. The average speed between Southampton and Warrington is considered to be 80 km/h. Most container-carrying wagons can be operated at a speed of 120 km/h max (laden or empty).

In the UK, according to the freight route utilisation study by Network Rail, it is expected that the demand for rail freight will continue to grow by 26-28% by 2014/2015, compared with the year 2007 (Network Rail/Rail Freight Operations' Association, 2010, p. 33). Important future market segments will remain the carriage of coal (for power production), ore (for the steel industry), and containers (for all kinds of cargo).

2.1.4 Conclusions from Task 2.2

Sustainable future rail vehicles should be interoperable in use on different national railway networks, have a lower tare weight and an improved aerodynamic performance, cause less noise and be able to run at a higher speed.

There is a general need across the case study routes to increase average freight operating speeds, although the specific requirements vary by route. The primary motivation is to maximise track capacity and service reliability by better integrating freight trains with passenger services. Increasing freight train maximum operating speeds is a key to increasing average speeds towards line speed.

On the Mediterranean Corridor, 120 km/h capability is seen as an appropriate target, and is being achieved by some containerised freight on parts of the route. Barriers to be overcome include the speed limitations for some wagon types, signalling systems, and the interaction with short-distance passenger trains on the network around urban areas. On the UK route, raising the speed of all freight trains to 120 km/h would be valuable, and to 130 or 145km/h more so. On the Bulgarian route, a general need for increasing speed has been highlighted, without detailed indications about target speed.

There is also an economic interest in increasing axle loads, although not necessarily for all types of freight: for bulk freight, greater vehicle payloads offer cost efficiencies for the operator, which might be partially/wholly offset by the cost increment in track maintenance – this is a subject for further investigation in WP 5.

2.2 Increase speed on freight lines – examples and future developments

Research relating to the development of high speed freight corridors is on-going. The concept and the maintenance of these kinds of lines can differ in certain respects (UIC Report "Maintenance of high speed lines" 2010) [66].

Some examples of high speed lines designed and used also for freight transport are available in Europe, e.g.:

- Italy: the Italian lines have been designed as High Speed/High Capacity (HS/HC or AV/AC: Alta Velocità/Alta Capacità). They are not yet used for freight, but the design characteristics have been defined in such a way they could also handle freight traffic.
- United Kingdom: DB Schenker Rail operates freight trains on the High Speed 1, the railway between St Pancras in London and the Channel Tunnel.
- France: TGV-Postes, with a top speed of 270 km/h, are the fastest freight trains in the world.
- Germany: at the time the first high-speed lines were opened, DB introduced the pilot service under the name of "Intercargo Express". This service was provided by freight trains running at top speeds of 140/160 km/h and making use of the new section between Hanover and Würzburg.
- Switzerland: AlpTransit freight system, for HS freight transit on the line is planned to be operational in 2016.

High speed rail freight is an interesting specialist market with competitive advantages for express freight (including parcel/palletised freight), vis-à-vis air and road modes. It is, however, a very specific market with unique technical requirements for high speed operation that would warrant separate study.

2.3 Target maximum speed and type of vehicle

Considering the three routes analysed in WP 1 and the findings of Task 2.2, an increase of speed for the freight traffic up to 120-140 km/h is expected. The increase of speed is the main target for SUSTRAIL, rather than a combined increase of speed and axle load, together with an increase of the performance of the vehicle with respect to ride comfort, braking efficiency, noise emissions, and aerodynamics.

A maximum speed of 120 km/h will be considered as main target for the “conventional SUSTRAIL vehicle”, while 140 km/h will be considered for the “futuristic vehicle”.

Concerning the vehicle type, container wagons have been selected following the identification of requirements in Task 2.4 and therefore this will be used for WP 3’s detailed study of the vehicle of the future. The detailed analysis will consider the option of a new wagon design or the option of retrofitting an existing vehicle. The reference bogie design is the Y25.

3. TECHNICAL REQUIREMENTS

The technical requirements refers to a 4-axle freight wagon to be designed, manufactured and tested within SUSTRAIL project from the perspective of UVA (SIRV).

The wagon will be manufactured according to current UIC regulations and leaflets and to EN, UIC, RIV, ISO EN SR regulations. Standards have been described in the Deliverable D 2.1 “Summary of standards and externally imposed definitions of duty” [68].

Detailed requirements will be specified in the Work Package 3, which aims at outlining the technical requirements of freight vehicles in order to lead to improved running behaviour of railway vehicles resulting in reduced system maintenance and operating costs, reduced environmental impact and greater sustainability and efficiency.

4. SUBTASK 2.4.1 – SUSPENSION AND RUNNING GEAR

This subtask aims to establish the limits for acceptable ride quality and dynamic performance for existing and new freight traffic flows identified in WP 1. Furthermore it aims to define the design specification for improved bogie/suspension characteristics considering total vehicle mass (and thus payload capacity), unsprung mass and fatigue life.

Previous tasks (see D2.2) provided information about the specific target system to focus on in Task 2.4. This is intermodal freight vehicles with slightly increased speed suggested around +20% depending on the country and current running conditions, and possibly carrying high value goods, i.e. requiring a higher ride quality. Section 4.1 describes this target vehicle's characteristics and the multibody dynamics model used for simulations. The target routes chosen are given in Section 4.2 for Spain, the UK and Bulgaria. They are mixed traffic routes. The characteristics of the routes made available in the form of recordings from track measurement trains are described in Section 4.2 and simulation cases chosen. The methodology applied for the vehicle dynamics simulations is described in Section 4.3 while the analysis of the outputs are given in Section 4.4 considering vertical damage, tangential damage and ride quality. Based on these outputs the limits for acceptable ride quality are established in Section 4.5 and some guidelines as regards design specification are discussed in Section 4.6.

4.1 Existing intermodal freight vehicles and agreed benchmark vehicle

The type of vehicle of interest for SUSTRAIL is a flat container wagon (UIC type R) for carrying intermodal freight. Information collected by WP 1 summarises the most common types of vehicle (e.g. for the UK: FEA, IKA, FAA, etc...), which are flat container wagons dominated by the Y-series type of bogies. Other types of bogie are also present but less numerous. There are many '3-piece' bogies. These are widely used in the USA, Canada, China and Russia, but are generally not a favoured option on EU track because of their relatively bad ride quality and high unsprung mass. On the other hand there are other types of bogies termed track-friendly (TF), which use passenger vehicle technology, for example viscous dampers rather than coulomb friction damping to improve the ride performance. These are however often too expensive to buy and maintain, so are not widely used. The focus is therefore on the Y-series type of bogie which can be found in a very large number of different configurations (and under different names). The main variations concern:

- the axle wheelbase, either 1.8 or 2m and
- the primary spring (spring characteristics) and Lenoir link arrangement.

Because the primary suspension characteristics of a Y-series bogie is very complex and the ride behaviour is very sensitive to loading (whether tare or laden) it is not possible to model all variations of such bogies. It was therefore decided to use one specific Vampire® model that was available at MMU of a FEA container flat wagon with Y33 series bogies. This model is deemed to be a good example, representative of a large percentage of current traffic. This model has previously been validated for vertical ride studies. Regarding the lateral ride characteristics and more particularly the effect on wear and RCF, it is not possible to find a well validated model in the industry or academia. It was therefore decided to use a number of available models of the same type, so that they could be compared with respect to tangential track damage to verify if their behaviour is similar or if a larger spread may be anticipated.

4.2 The target routes and their characteristics

The data is taken directly from the track measurement vehicles as supplied by the networks. It can be used as input for the vehicle dynamics and provide further information:

- Distance
- Curvature
- Cross level
- Lateral alignment (usually filtered below 70m and 35m)
- Vertical level (top left and top right filtered below 70m and/or 35m)
- Gauge variation
- Line-speed (for information or simulation)
- Recorded vehicle speed (as recorded during the measurement – for information or simulation)

The line-speed and the vehicle's recorded speed may be used to determine the actual operating speed on the line and the effective cant deficiency. This provides a useful insight into the running condition of a specific vehicle and depending on its steering capabilities, on the balancing of forces across all wheels in a bogie.

4.2.1 Spain

ADIF supplied data for the Spanish route from the Mediterranean corridor (Valencia-Tarragona) between Oropesa and Vinaros (start Pk 95.0-95.2, end Pk 110.0-110.2). The data covers only a very short length of track around 15 km, includes only one curve in the middle, and ends in the middle of another (the curves have around 2200m and 1300m radius respectively). This length of route is not deemed sufficient to run a full vehicle dynamics analysis at this stage. This can be done later within WP3 or WP4 if more data is made available.

Figure 4.1 shows the characteristics of the data as measured by the Spanish track recording vehicle; this can be directly compared with plots for the UK data (Figures 4.3 to 4.6).

Figure 4.2 gives a summary of the track quality per 200m section. The selected Spanish section appears to be of a better quality than the selected UK sections, both in vertical and lateral direction; this is mainly due to the higher line-speed of the Spanish track.

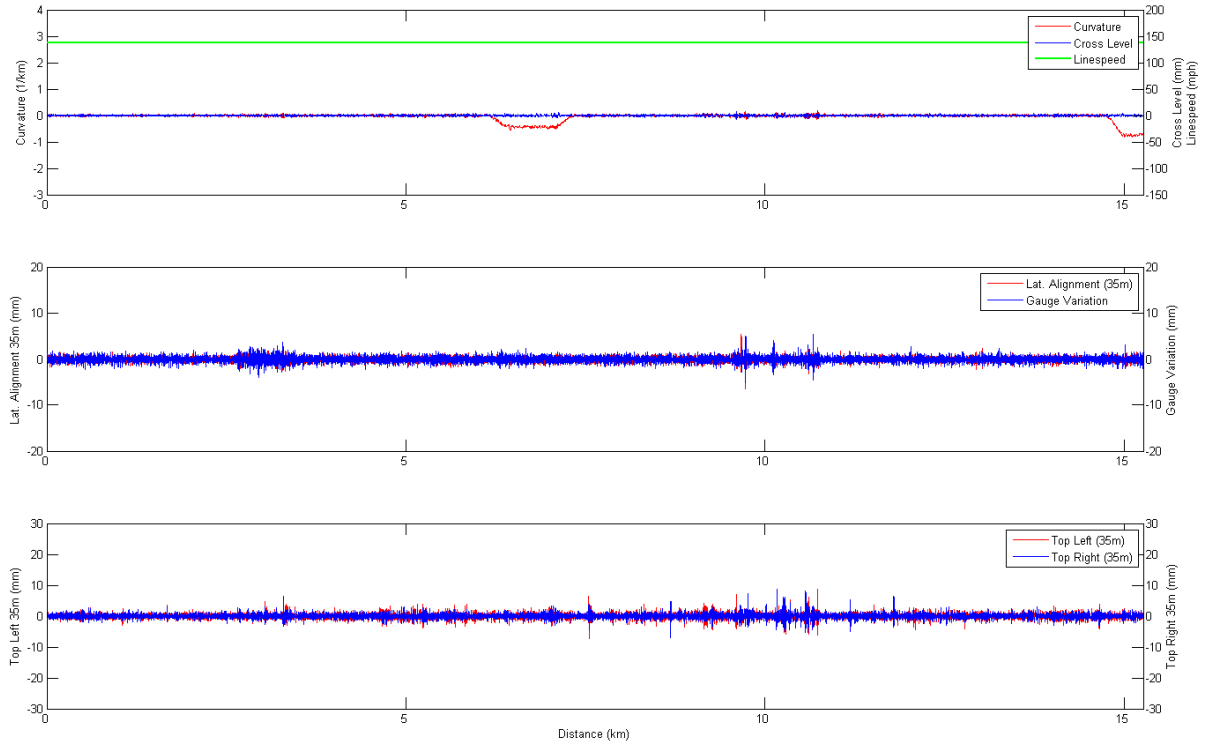


Figure 4.1: Spanish track data between Oropesa and Vinaros - curvature, cross level and line-speed (top), lateral alignment and gauge (middle), top left and right (bottom)

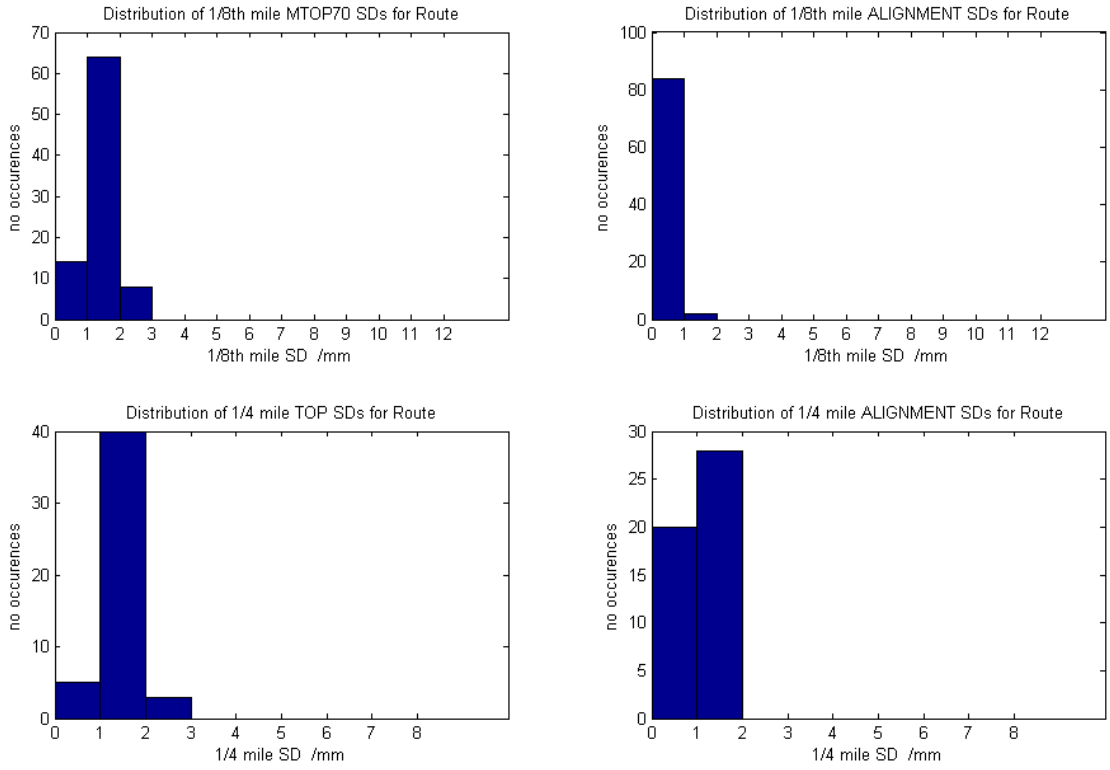


Figure 4.2: Spanish track data between Oropesa and Vinaros – quality distribution per 200m for mean top (left) and alignment (right).

4.2.2 UK

Network Rail supplied data for 4 routes:

- DCL 2100:
  - Chester Line Jn 53mi 12ch to Leamington Spa Jn 106mi 25ch
- EMP 2100
  - Ely North 71mi 63ch to Peterborough Jn 100mi 2ch
- BML1 1100
  - Northam Short Jn 77mi 68ch to Basingstoke Jn 47mi 52ch
- LEC2 to LEC5
  - Nuneaton 87mi 10ch to Crewe 158mi 0ch

Figure 4.3, Figure 4.4, Figure 4.5 and Figure 4.6 show the characteristics plotted against distance for the 4 routes. Figure 4.7, Figure 4.8, Figure 4.9 and Figure 4.10 show the quality distribution per 200m sections. Figure 4.11, Figure 4.12, Figure 4.13, Figure 4.14 show the radius, line-speed and cant excess/deficiency distribution along the routes. Note that the line-speed is quoted in mph.

The following can be noted about the UK track data:

- The quality of the recording in places is unreliable and cannot be used for simulation. This happens when the speed of the measurement vehicle drops below approximately 40 km/h and the inertial measurement system does not work properly. This can be observed for example on DCL track around 65 km or on LEC around 50 km where the signals drop to zero for a few kilometres. Some simulation had to be shortened for this reason.
- None of the selected track contains small or very small radius curves (below 600m), except for one curve on EMP which has a radius of around 350m. DCL has the widest representation of curves while EMP contains the fewest.
- For all tracks the lateral alignment is generally of a better quality than the horizontal profile. Most routes have a few 200m-sections with vertical track quality below ‘very poor’ (as defined in the UK’s track standard RT5021, Table 7), but the majority of the routes are within acceptable limits.

For simulation purposes it was decided to use the DCL track from 0 km to around 65 km from which point the signal becomes unreliable. Additional runs were also performed on the entire length of EMP.

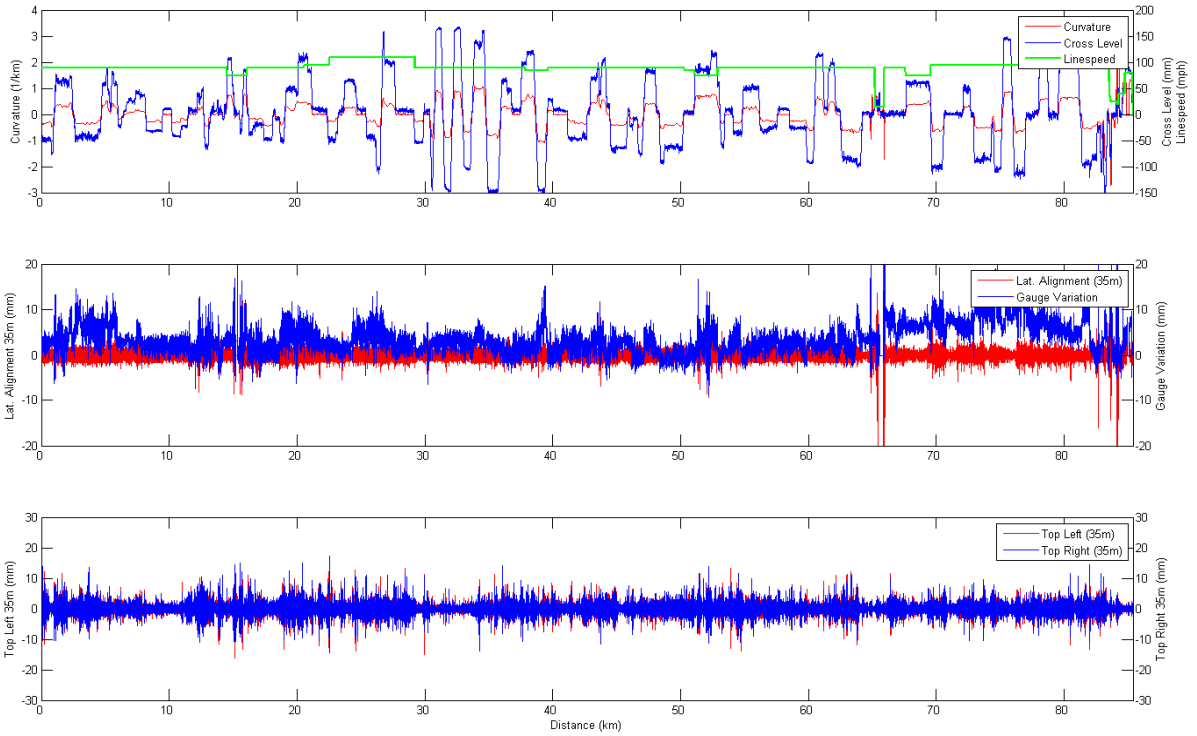


Figure 4.3: UK track data DCL – curvature, cross level and line-speed (top), lateral alignment and gauge (middle), top left and right (bottom)

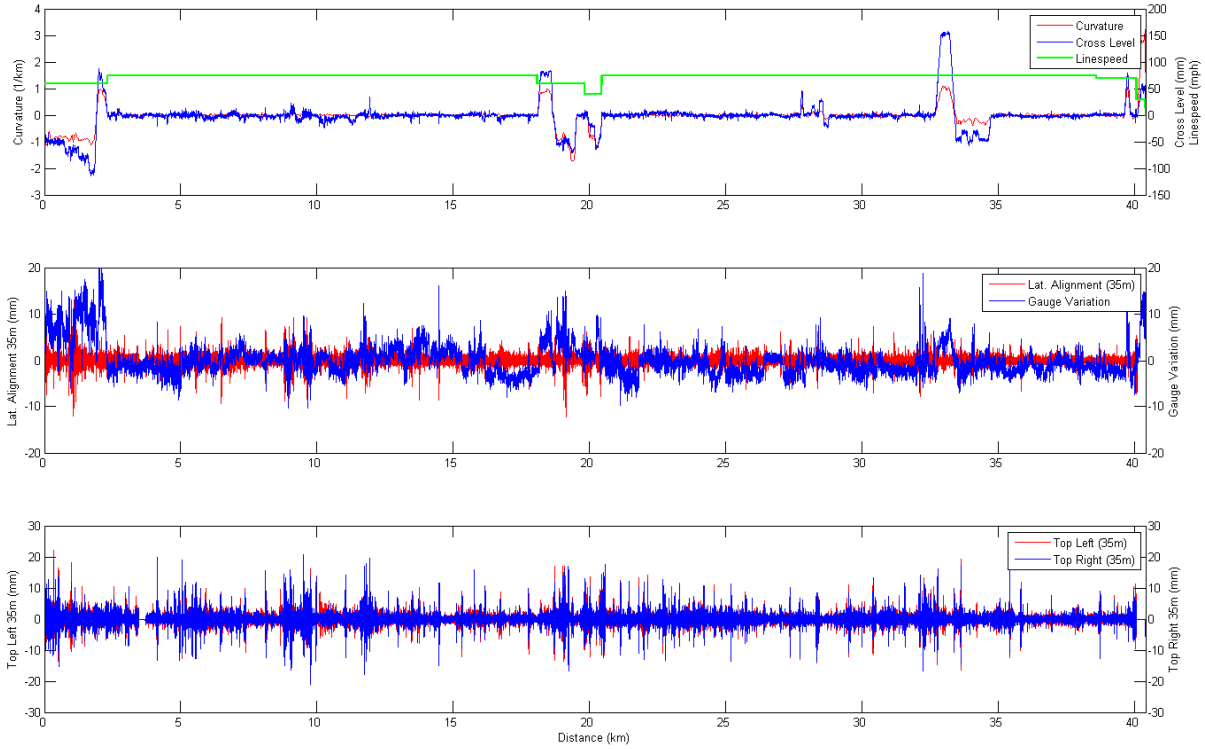


Figure 4.4: UK track data EMP – curvature, cross level and line-speed (top), lateral alignment and gauge (middle), top left and right (bottom)

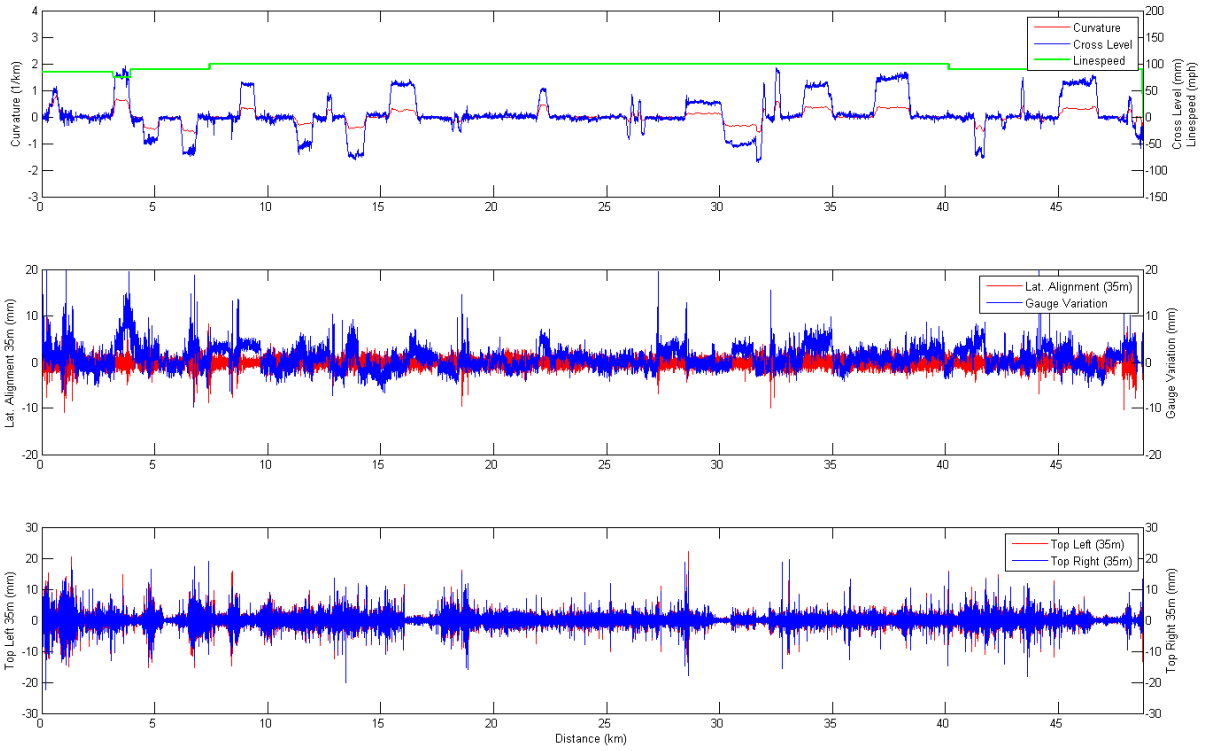


Figure 4.5: UK track data BML – curvature, cross level and line-speed (top), lateral alignment and gauge (middle), top left and right (bottom)

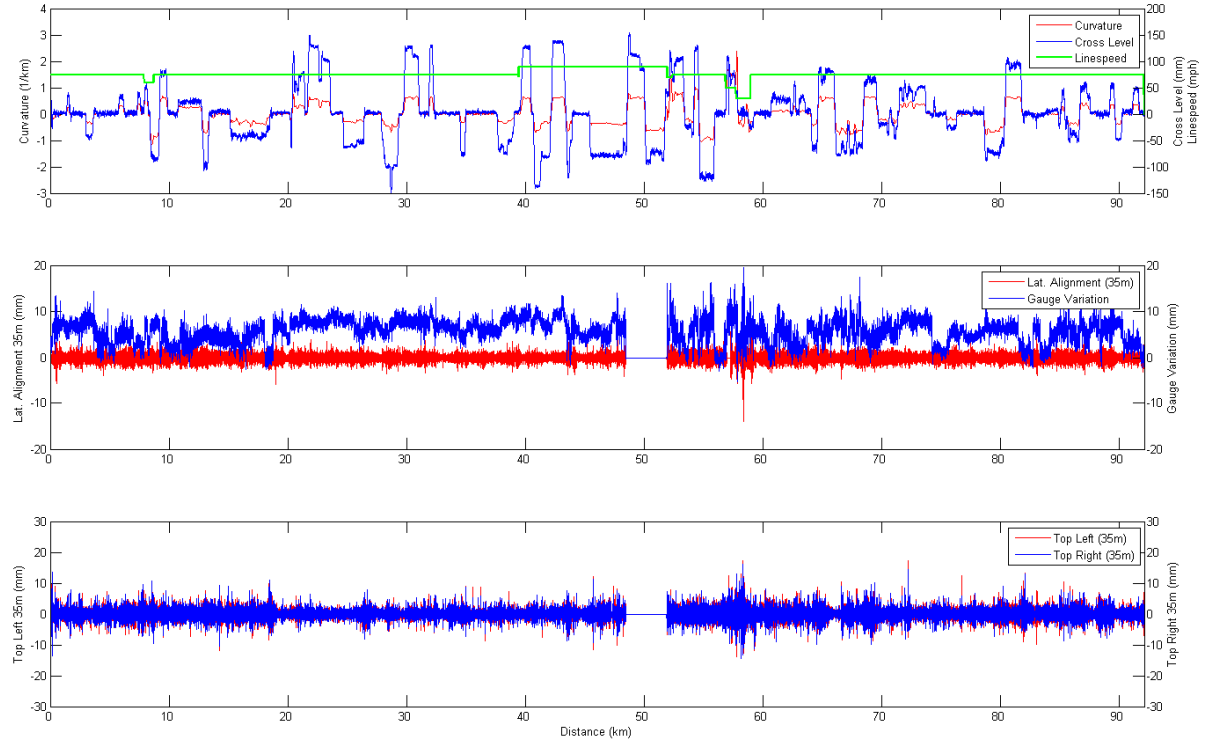


Figure 4.6: UK track data LEC – curvature, cross level and line-speed (top), lateral alignment and gauge (middle), top left and right (bottom)

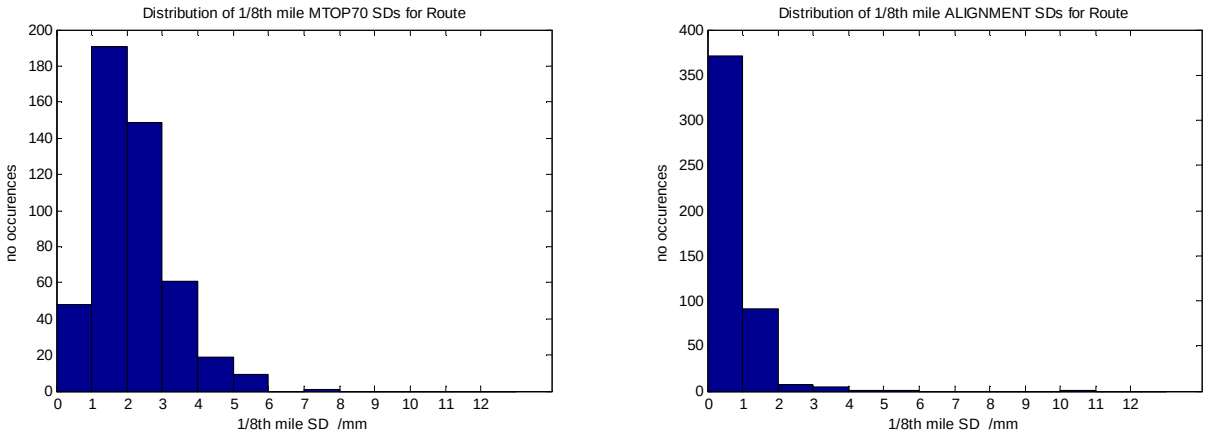


Figure 4.7: UK track data DCL – quality distribution per 200m for mean top (left) and alignment (right).

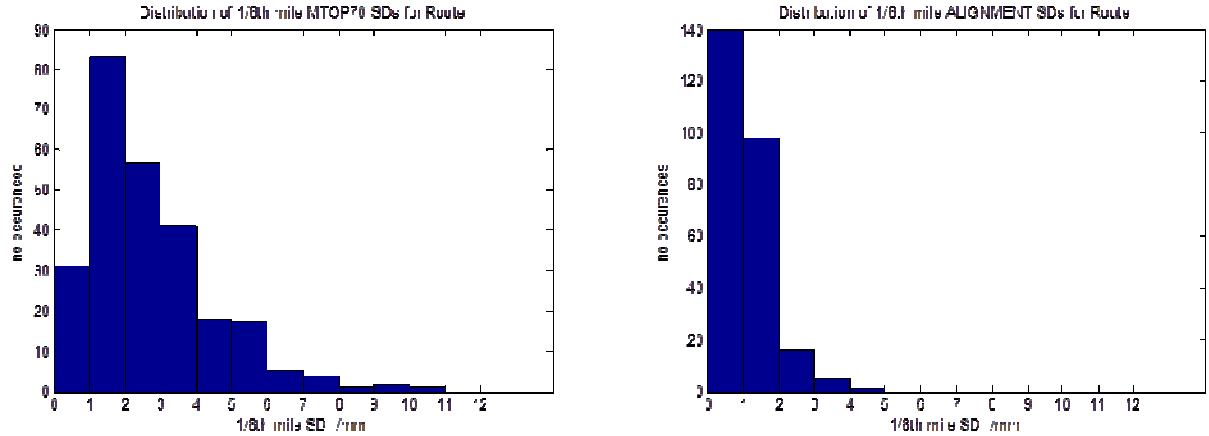


Figure 4.8: UK track data EMP – quality distribution per 200 m for mean top (left) and alignment (right).

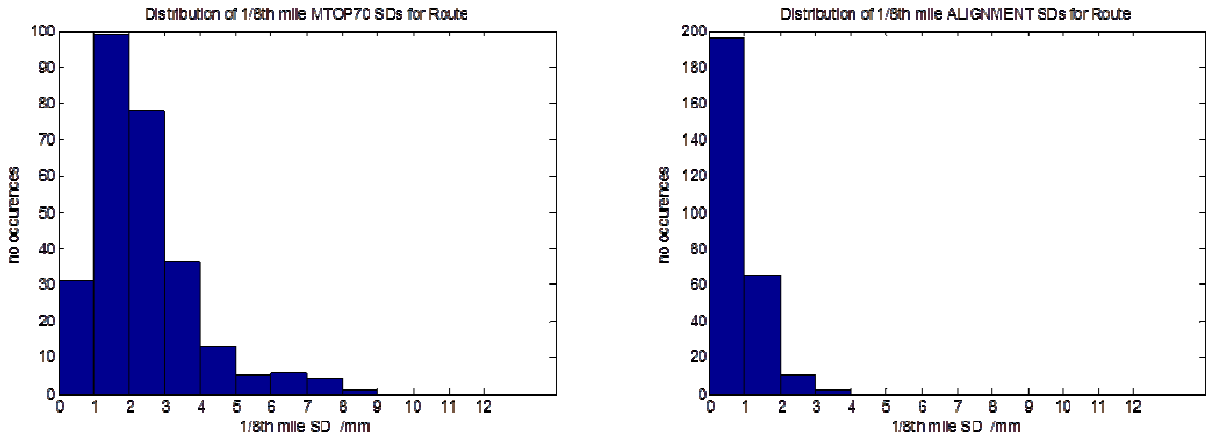


Figure 4.9: UK track data BML – quality distribution per 200 m for mean top (left) and alignment (right).

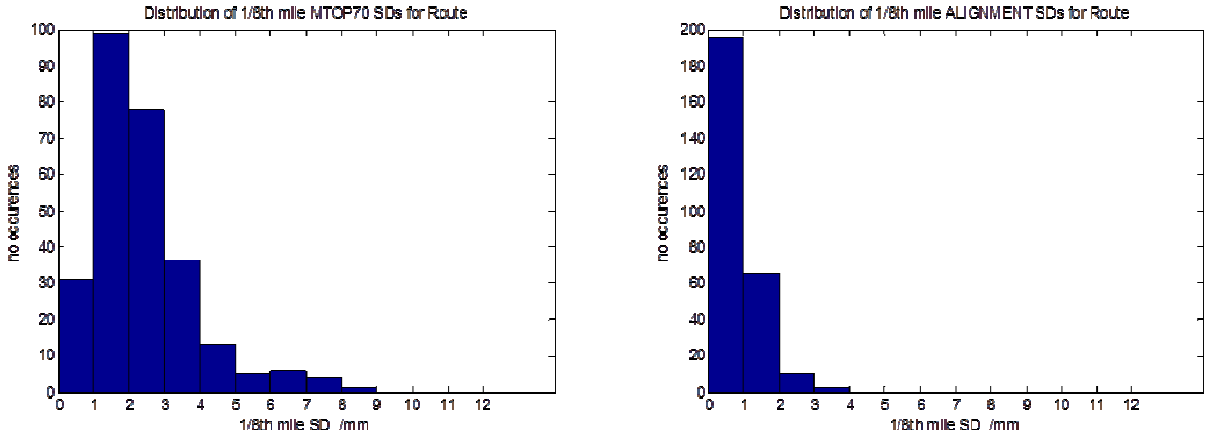


Figure 4.10: UK track data LEC – quality distribution per 200 m for mean top (left) and alignment (right).

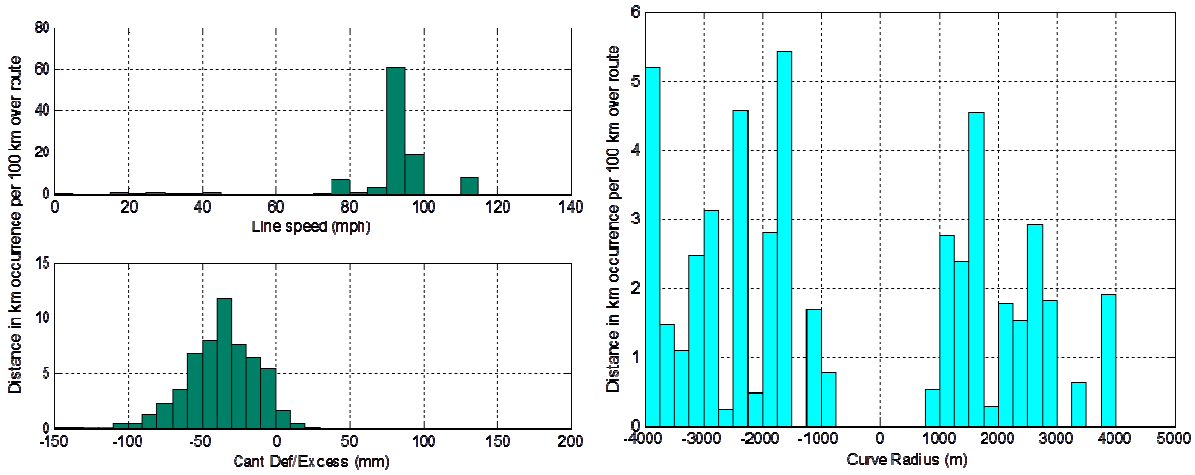


Figure 4.11: UK track data DCL – line-speed (upper-left), curve radius (right) and cant deficiency/excess (lower-left) distribution.

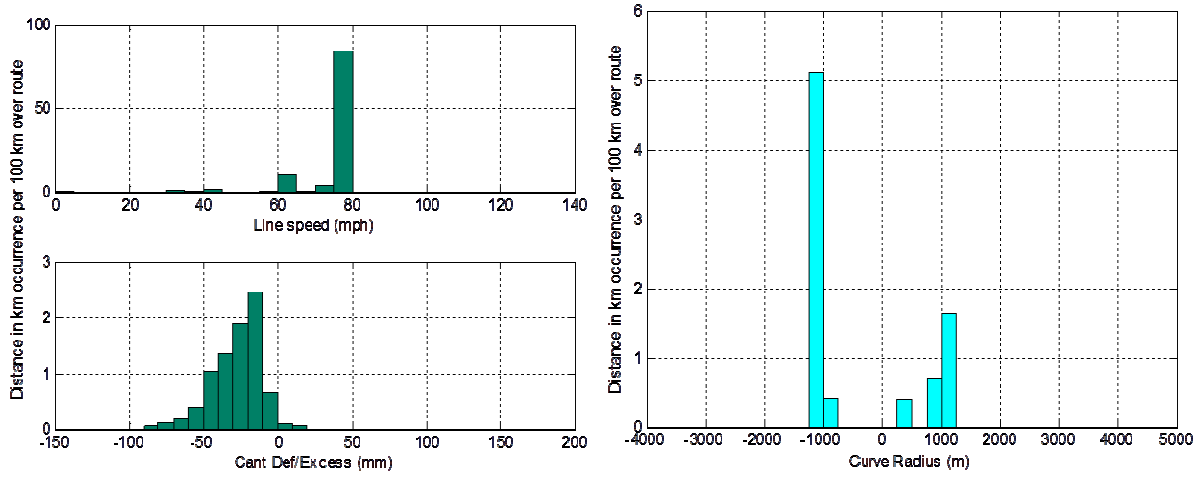


Figure 4.12: UK track data EMP – line-speed (upper-left), curve radius (right) and cant deficiency/excess (lower-left) distribution.

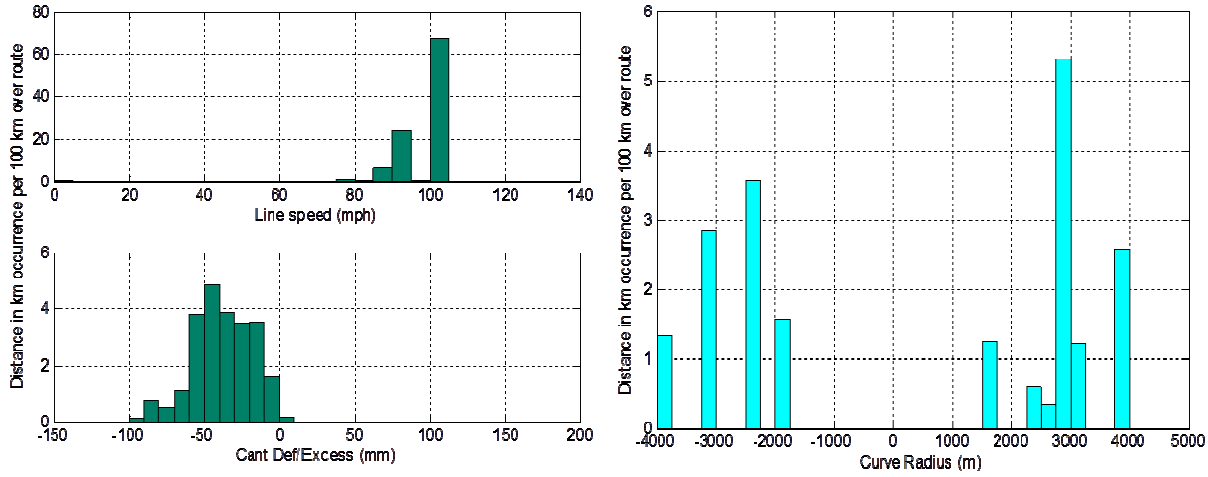


Figure 4.13: UK track data BML – line-speed (upper-left), curve radius (right) and cant deficiency/excess (lower-left) distribution.

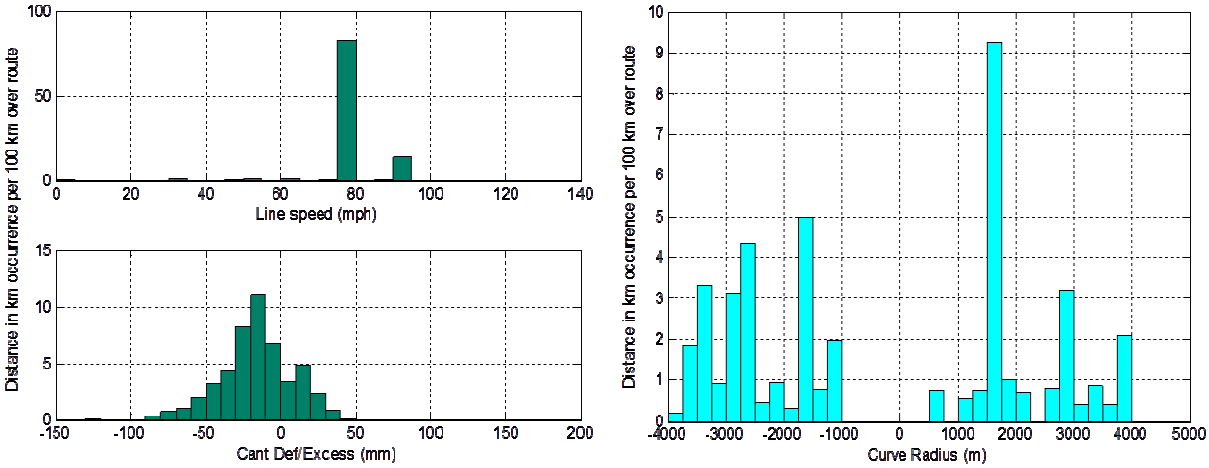


Figure 4.14: UK track data LEC – line-speed (upper-left), curve radius (right) and cant deficiency/excess (lower-left) distribution.

4.2.3 Bulgaria

No data was supplied for the Bulgarian network. Simulations carried out on other networks could be used to extrapolate the results to the running conditions of the Bulgarian routes. This will be possible when Bulgarian data on track quality and layout is made available at a later date during the project.

4.3 Vehicle dynamics simulation and methodology

For the purpose of establishing limits and design specification for the freight vehicle to be developed in SUSTRAIL (in later activities in WP3), it is necessary to understand the current characteristic behaviour of common freight vehicles. The quantities of interest can be categorised in terms of the damage they may produce as well as their associated ride quality. Damage has a direct impact on cost of operation while the ride quality may produce indirect costs related to damaged goods or safety aspects:

- Damage: track geometrical deterioration (ballast settlement and horizontal level, alignment and buckling), rail surface damage (wear, rolling contact fatigue – RCF)

and track components damage (sleeper cracking, rail pad deterioration, rail fatigue, fastening deterioration).

- Ride quality: vertical lateral and longitudinal accelerations experienced by the goods transported.

Various models exist to quantify in engineering terms some of the aspects listed above. Engineering terms means that the damage produced can be measured, e.g. a number of mm of material remove on the rail surface per km or per MGT (Million Gross Tonne of traffic over the line), a number of mm vertical settlement per annum or per MGT. The models are either straightforward analytical calculations, or are based on the post-processing of the outputs from vehicle dynamics simulations. In terms of damage the quantities of interest may be summarised as:

- Track vertical deterioration:
  - **Ride force coefficient and constant** – obtained from simulation and quantifies a vehicle's attenuation of the vertical forces induced by track roughness (at a specific speed). It is defined to be the parameters of the linear regression that best fits results for the dependence of vertical dynamic force on track roughness (see Section 4.4.1.1 for details).
  - **P2 force** – obtained from analytical calculation. This is an estimate of the high frequency forces occurring at the wheel-rail contact when a wheel passes over a rail joint. It is mainly dependent on the axle unsprung mass and the vehicle speed.
  - **Ballast settlement** – obtained from simulation. A large number of models exist in the literature, they all consider the wheel quasi-static (Qqst) and or dynamic (Qmax) vertical load, often raised to a power of three (ORE studies [71]). Some models also consider the vertical acceleration of rail or sleeper (Sato [72]).
- Rail surface damage:
  - **Wear** – obtained from simulation. This uses the work done by the forces in the contact, calculated by multiplying the creep forces by the creepages in the lateral and longitudinal directions to obtain $T\gamma$. This may be further post-processed considering the coefficient of friction and the contact area (e.g. Archard wear model).
  - **RCF** - obtained from simulation. This uses the $T\gamma$ output defined above and applies a filter so that the combined effect of wear and RCF is considered. The filter has been developed and validated for UK track conditions and is used within the tool called Whole Life Rail Model (WLRM). Also referred to as weighted-$T\gamma$.
- Track lateral deterioration:
  - **Lateral track shifting force** - obtained from simulation. This is $\Sigma Ymax$, sum of the axle lateral guiding forces low-pass filtered at 20Hz and processed through a 2m sliding mean so that any damaging force is required to be sustained over a distance of 2 meters to take effect. There is a limit ($\Sigma Ymax,lim$) specified in the standard EN14363 that is based on Prud'homme's work [88] and defined as

- $\Sigma Y_{max,lim} = k_1.(10 + 2Q_0/3)$ in kN

where the constant $k_1 = 1$ for locomotives, power cars, multiple units and passenger coaches or $k_1 = 0.85$ for freight wagons and Q_0 is the static vertical force.

- Track component damage:
  - **Combined vertical and lateral force** – obtained from simulation. The suggested damage parameters are Bqst (quasi-static) and Bmax (dynamic); these combine the effect of the vertical and lateral force at the wheel-rail contact. These forces influence the bending stresses of the outer rail in plain curves. They are defined as
    - Bqst = Yqst + 0.83 Qqst
    - Bmax = Ymax + 0.92 Qmax

    where Y and Q are the lateral and vertical wheel force respectively, usually of interest is the contact of the leading wheel on the high rail. Indices 'qst' and 'max' stand for quasi-static and maximum force respectively.

  These values are included in the latest draft of EN14363 and some limit values have been suggested, but are not currently in force. These parameters are also expected to reflect the fatigue damage experienced by the rest of the track components, i.e. sleepers, pads and fastening.

In terms of ride quality, the quantities of interest are:

- Running safety criteria:
  - **ΣYmax, (Y/Q)max** – these are the sum of the axle lateral forces (highest on leading axle usually) and the derailment coefficient defined by the ratio of lateral by vertical force at any wheel; the quantities are obtained from measurement or simulation. These are used for the assessment of the risk to derailment.
- Vibration behaviour:
  - **Car body lateral and vertical acceleration** – obtained from simulation. These are the acceleration of the car body generally measured at both ends above leading and trailing bogies. They are directly of interest for SUSTRAIL objectives as they offer a direct comparison of the quality of the ride for the goods transported.

The methodology used in Task 2.4.1 was to set up a series of Vampire® dynamics simulations using the chosen representative freight vehicle model and one or more of the available tracks to produce the quantities listed above. The schematic of the process is presented in Figure 4.15. The initial parameters that were studied were:

- The increase of speed from 120 to 140km/h
- Various axle loads (tare-5t, part-laden-11t and laden-20t)
- The quality of the track (adding a factor for track vertical and lateral irregularities)
- Lower unsprung mass (20% reduction)

- Comparison of various freight vehicle models (for lateral damage)

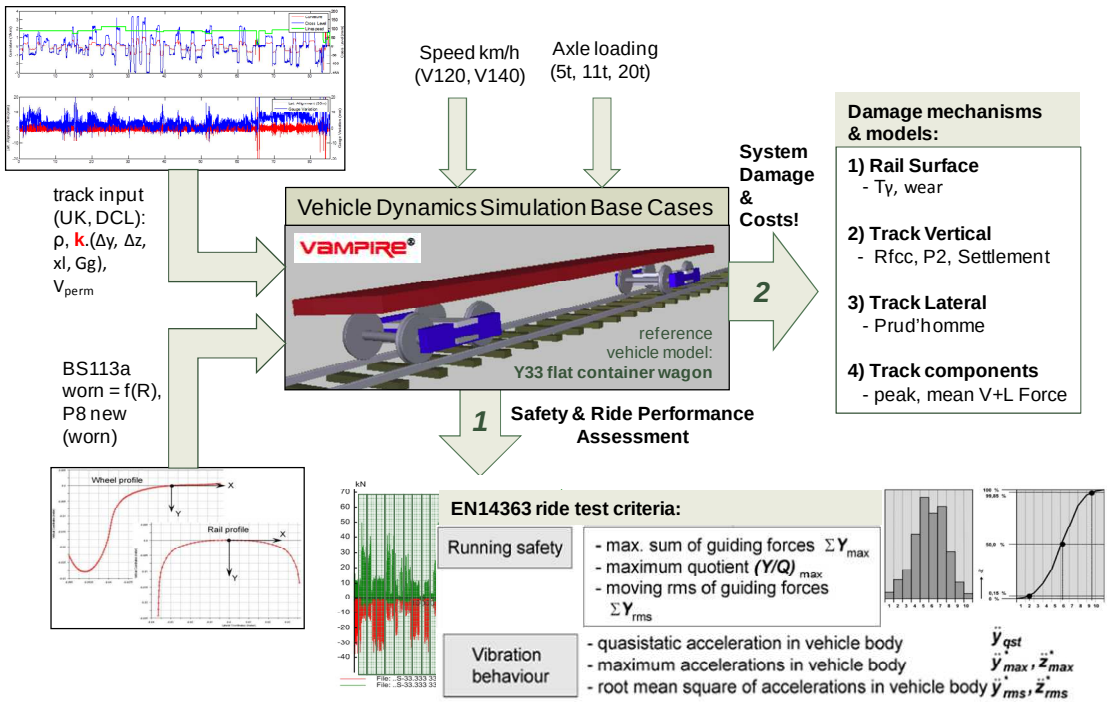


Figure 4.15: Simulation process for the assessment of vehicle performance requirements

The data produced will then need to be translated into cost linking with activities in WP5. For this purpose it is suggested that every damage mechanism may impact on a specific maintenance or renewal activities as shown in the matrix in Figure 4.16. The matrix can be populated with zeros whenever there is no link or a factor between 0 and 1 so that the total effect for one maintenance/renewable activities takes into account the damage mechanisms in their correct proportion. Note that Figure 4.16 is only a starting draft and this will have to be developed during the course of the project with other partners, mainly based on information available from infrastructure managers.

	Damage Model and Influence Factors (Σ<=1)						
	RAIL SURFACE		VERTICAL TRACK			LATERAL TRACK	COMPONENTS
	Suspension design Axleload W/R profile Friction levels	Suspension design Axleload W/R profile Friction levels	Suspension design Axleload Un-sprung mass	Axleload Un-sprung mass P2 Forces	Suspension design Axleload Un-sprung mass	Suspension design Axleload Un-sprung mass W/R Profile friction level	Suspension design Axleload Un-sprung mass
Damage Type/Indicators	**1. Tγ** (J/m)	**2. Wear** (mm^2/1000axles)	**3. Vert Ride Force** F_{dyn} SD (kN) <20hz	**4. P2 Forces** F_{max} (kN) <500Hz	**5. Ballast Settlemt** Fmax (kN) <20Hz	**6. Ali. Degradation** Fmax (kN) <20Hz	**7. Comp. Fatigue** V+L Fmax (kN) <20Hz
Vampire simulation required outputs	creepages (x, y, spin) creep forces (x, y, spin)	creepages (x, y, spin) creep forces (x, y, spin)	Axle Force (z) or high rail Force (z) in curves	No -> analytical only	Axle Force (z) rail or sleeper acceleration (z)	Axle Force (y) - Σymax	high rail combined forces (y,z)
Rail Maintenace & Renewal							
Wear (sidecut & headlos	x	0.9	x	x	x	x	x
Plastic flow	0.5	0.1	x	0.4	x	x	x
RCF initiation	0.9		x	x	x	x	x
RCF propagation	0.5	x	x	x	x	x	0.3
Corrugation	0.5	x	x	0.3	x	x	x
Shelling/Spalling	x	x	x	x	x	x	x
Bolt hole crack/elongati	x	x	x	0.9	x	x	x
IBJ	x	x	x	0.4	x	x	0.4
Support Maintenace & Renewal							
pads	x	x	0.9		x	x	x
Fastening/Clips	x	x	x	x	0.9	x	0.9
ballast deterioration	x	x	0.9	x	x	x	x
Sleeper degradation	x	x	0.2	0.2	x	x	0.5
Geometry degradation							
Lateral alignment	x	x	x	x	0.1	0.7	0.1
Vertical alignment	x	x	0.9				
Gauge	x	x	x	x	0.1	0.7	0.1

Figure 4.16: Damage mechanisms – maintenance activities matrix (for illustration, to be developed)

A tool developed in the UK that is also used in this project and is jointly owned by RSSB and Network Rail is VTSIM. It combines several damage and simulation tools such as MiniMarpas, Whole Life Rail Model (WLRM) and Vampire® and a costing database. Network Rail has been using VSTIM to carry out various cost analysis for future traffic scenarios. They are presented in D2.5 [89] and use the results from the Vampire® simulations presented here.

4.4 Outputs and analysis

The section contains some initial analysis of Vampire® simulation output post-processed according to several damage models. This allows defining the current freight traffic damage envelop against which any other technology improvement made in WP3 and WP4 can be compared.

4.4.1 Vertical damage

4.4.1.1 Ride Force Coefficient and Constant (RFCC)

The Ride Force Coefficient calculation is used to quantify the dynamic behaviour of a vehicle as a function of the quality of the track it runs on. It is produced by running a model over a track of varying vertical quality. This was done here using three tracks from the Vampire® library used for that purpose: track 110, track 120 and track 140 where the number refers to the track line-speed. Additionally this was also done on the UK DCL route for comparison. The standard deviation of the total vertical axle load is averaged every 200m and plotted against the standard deviation of the corresponding vertical top level of the track ('track SD'), Figure 4.17. A first-order linear regression is performed on the data and two parameters are obtained: the slope; and the intercept at zero track SD. The RF constant is considered to be the dynamic force contribution for low values of track SD, while the RF coefficient indicates how the dynamic forces are expected to rise as the quality of the track worsens. VTSIM uses these

two values to predict the level of vertical track degradation; however from experience at MMU, this factor has practically no effect on the cost results obtained.

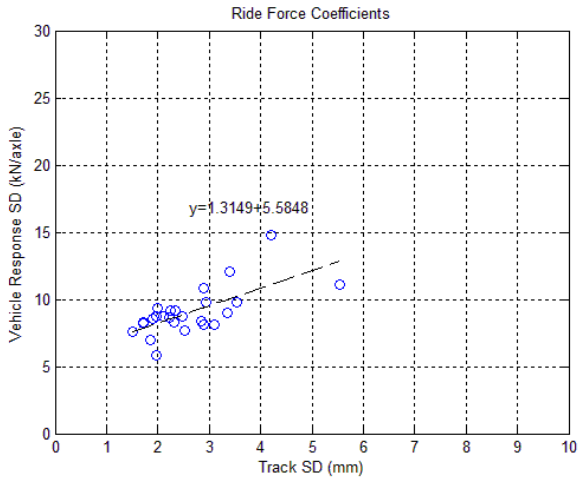


Figure 4.17: Example of a Ride Force Coefficient calculation results from Vampire® results

Figure 4.18 shows the dynamic force obtained for a track SD of 2mm, comparing the passenger vehicle with the freight vehicle at various axle loads, and for two speeds (120 and 140kph). The following are observed:

- The passenger vehicle shows much lower dynamic ride forces (down by 65% at 14t equivalent at 120kph),
- Increasing the speed gives rise to a significant increase of the dynamic forces, more so for the passenger vehicle (37%), followed by the part-laden freight (28%), then the freight tare (16%), and laden freight (8%).
- Lowering the unsprung mass by 20% gives benefits by reducing the dynamics force by up to 8% in the case of the tare load. The advantage is not observable for high payloads.
-

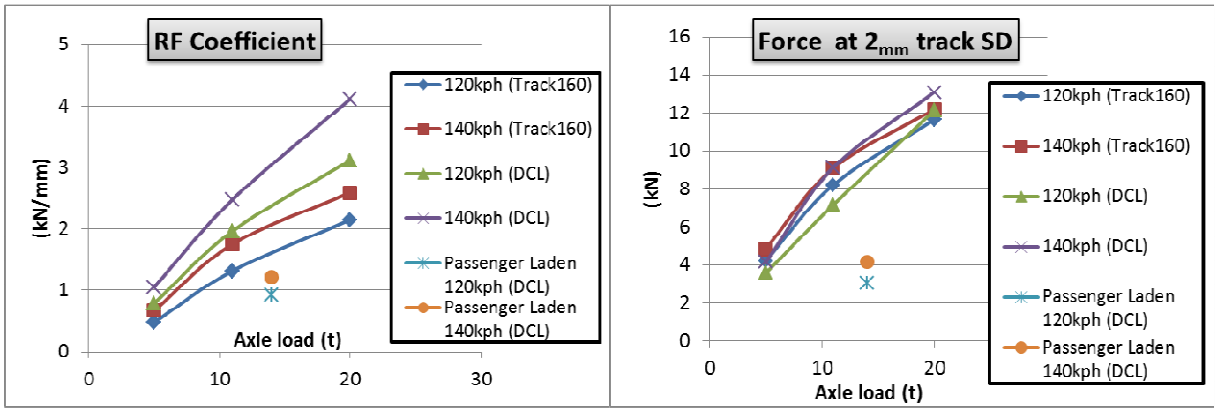


Figure 4.18: Comparison for different track and speed for RFC (left) and Force at 2mm track SD (right)

For more detailed analysis, refer to Deliverable 2.5.

Comments on further work: As shown, the dynamic force for a specific track SD may be estimated from the RFCC. Knowing the vertical quality distribution of the target SUSTRAIL

route, as shown in section 4.2.2 - Figures 4.7 to 4.10 for UK, it is possible to make a reasonable estimate of the dynamic force representative of the entire route, or subsections thereof. This is an indicator that has been used in studies in the UK for freight banding and access charges for example. An absolute evaluation of cost is not easily done without reliable data but this type of analysis will be useful for comparing the design technology developed or proposed in WP3 against current traffic.

4.4.1.2 P2 force

The calculation of P2 force is given in UK track standard GM/TT0088, "Permissible Track Forces for Railway Vehicles". The equation is reproduced below. The standard specifies a limit value of 322kN per wheel based on tests carried out in the 1960's on a class 55 Deltic locomotive. Work from Jenkins and BR [90] suggest a lower limit as the speed reduces from 100 mph (160 kph) to 60 mph (96 kph) with a reduced limit value of 250 kN. The larger permissible value for higher speeds is a consequence of the track being maintained to a higher standard.

$$P_2 = Q + (A_z.V_m.M.C.K)$$

where

$$M = \left[\frac{M_v}{M_v + M_z}\right]^{0.5}$$

$$C = 1 - \left[\frac{\pi \cdot C_z}{4[K_z(M_v + M_z)]^{0.5}}\right]$$

$$K = \left(K_z.M_v\right)^{0.5}$$

Q = maximum static wheel load (N)

V_m = maximum normal operating speed (m/s)

M_v = effective vertical unsprung mass per wheel (kg)

A_z = 0.020 rad
(total angle of vertical ramp discontinuity)

M_z = 245 kg
(effective vertical rail mass per wheel)

C_z = 55.4 x 10^3 Ns/m
(effective vertical rail damping rate per wheel)

K_z = 62.0 x 10^6 N/m
(effective vertical rail stiffness per wheel)

Calculations (details to be found in D 2.5.1) have shown that:

- Freight vehicles generally have a lower unsprung mass than a modern passenger multiple unit (MU) and therefore lower P2 forces.
- A laden freight vehicle (20t axle load) with a 1.2t unsprung mass has the same P2 force as a crush laden MU (14t axle load) with a 1.8t unsprung mass.
- Freight vehicles that are part-laden (11t axle load) and tare (5t axle load) will give 25% and 40% lower P2 forces than the passenger vehicle, respectively.
- Increasing the speed from 120 to 140 kph gives rise to an increased P2 force: 10% (passenger and part-laden freight), 8% (laden freight) and 13% (tare freight).
- Reducing the unsprung mass by 20% (if achievable) can allow running a freight vehicle at increased speed (from 120 to 140 kph) for the same P2 force.

Comments on further work: This straightforward calculation allows a fast comparison of the likely vertical damage of various suspension and running gear designs for the SUSTRAIL vehicle. The results can be compared to existing fleets.

4.4.1.3 Settlement

Vertical settlement is attributable to the total vertical force associated with the wheel-rail contact. Work carried out at KTH for Trafikverket based on models proposed by Öberg et al. [91] shows that the total force can be split into several components as per equation (1), in which Qr is the static wheel load, Qc the quasi static contribution (changing in curves with non-compensated accelerations), Qd20Hz, dynamic contribution below 20Hz, and Qdhf dynamic contribution in the range 20-90Hz.

$$Q_{tot} = Q_r + |Q_c| + Q_{d20Hz} + Q_{dhf} \quad (1)$$

Based on KTH's preliminary analysis [92] of Qtot using a Y25 series freight model, the following can be said:

- The main influence factor is the vehicle axle load; the larger this is the more vertical damage there is.
    - Tare vehicles provide very little damage in comparison with laden wagons
    - Part-laden vehicles give a small proportion of damage compared to fully laden wagons.
- There is little influence from speed (2%) for a 22.5t vehicle with 20 kph increase.
- There is hardly any influence from the unsprung mass (0.5% increase with 10% increased unsprung mass).
- Track quality has a significant influence on Qtot.
- Suspension design has the greatest influence on Qtot.

Comments on further work: More detailed analysis from the specific SUSTRAIL routes will be carried out using the Vampire® software to predict Qd20hz.

4.4.2 Tangential or surface damage (RCF and wear)

Some initial analysis of RCF damage generated from several Y-series freight vehicle at different axle loads have been compared to a crush laden passenger multiple unit (MU) on the UK DCL route. Figure 4.19 shows how the level of damage on a plot varies with axle load. This includes two speeds - 120 and 140 kph. The passenger vehicle damage can be significantly improved by increasing the operating cant deficiency, which is not as evident from the Y-series vehicles, especially once loaded. This is because of their poor curving abilities. Part-laden freight appears to be as damaging as, or more damaging than the MU vehicle.

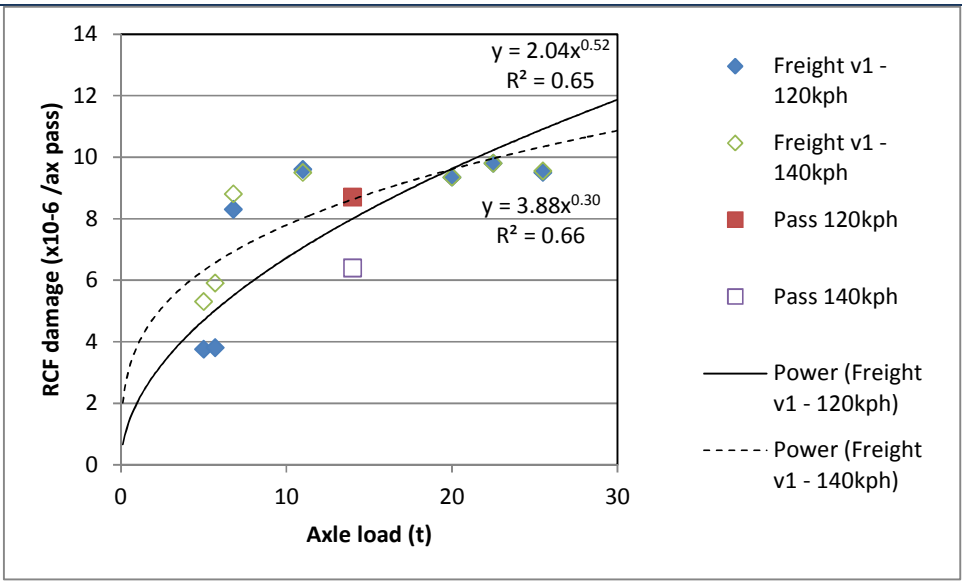


Figure 4.19: RCF damage for benchmark vehicles and passenger MU

4.4.3 Component damage

Component damage can be estimated from a combination of the vertical and lateral wheel load. The main driver is vehicle axle load and the most damaging vehicles are laden freight. On the other hand, the tare vehicles in curves show poor riding performance and thus increased dynamic lateral forces. More results are presented in D2.5 [89].

4.4.4 Ride quality

Ride quality of the existing benchmark vehicle and the proposed SUSTRAIL vehicle will be compared using EN14363 requirements for vehicle testing.

4.5 Establish limits for acceptable ride quality

- It is suggested that the SUSTRAIL vehicle presents at worst the same or better safety and damage criteria than the benchmark vehicles (Y25 series); This will be assessed using all criteria listed in section 4.3 on specific SUSTRAIL routes, comparing the results from the SUSTRAIL vehicle to the benchmark vehicle results presented in section 4.3 and compared with standard limit values in EN14363.
- It is suggested that the SUSTRAIL vehicle presents at worst the same or better acceleration levels of the cargo (measured above bogie) at 140kph in comparison with the benchmark Y series vehicles at 120kph.

4.6 Design specification

The suspension and running gear for the freight vehicle of the future should provide for a reduction in damage to the rail and track in terms of the following damage mechanisms:

- Derailment possibility (predicted by lateral/vertical forces)
- Track vertical settlement (evaluated from predicted vertical wheel-rail forces)
- Rail damage (wear and rolling contact fatigue predicted from ‘Tgamma’)
- Lateral force (compared with the ‘Prud’Homme’ limit)

All of these must meet all vehicle acceptance standards (e.g. EN14363) at the loads and speeds proposed and must be the same or better than the Y25 benchmark vehicle at 120km/h.

The work so far has indicated that:

- lowering the unsprung mass by 20% allows increasing the speed from 120 to 140 kph while maintaining an equivalent level of vertical damage (from P2 calculations);
- Lowering the level of track SD by 20% leads to a reduction of the peak dynamic force contribution by up to 14% (tare) and 5% (part laden). No improvement is observed for the laden condition.
- Maintaining a low axle load will significantly contribute to maintaining acceptable ride quality and low damage properties. Studies on representative UK traffic (RSSB project T889) has shown a large proportion of containers transported (40% of traffic) weighed between 9t and 13t and another 40% of containers were empty or nearly empty. This is equivalent to an axle load in the range 15-19t (±1t depending on bogie design).

5. SUBTASK 2.4.2 – BRAKES

5.1 Introduction

This chapter describes the requirements for the development of a combined wheel-slide and brake control system with comprehensive diagnosis functionality for modern, innovative freight cars. Special attention is paid to the increase of efficiency in goods traffic through a more effective use of existing resources and implementation of modern technologies in the entire vehicle sector. These long-term aims should also be considered while designing and developing the brake system. These are:

- increase of the vehicle speeds to 120/140 km/h;
- high axle loads of 22.5t;
- adaptation of the performance data of traction and braking to the passenger car level;
- increase of the maintenance interval through high MTBF (Mean Time Between Failure) values, at the same time reducing the maintenance effort;
- minimizing the wear, in order to optimize LCC;
- high interoperability for application in different states and systems.

The present specification is part of project SUSTRAIL and gives the specifications required according to Sub-Task 2.4.2.

5.2 Definition of the “Safe Condition”

In general “safe condition” describes a condition to which a system drops back in case of an error or the condition which the system generates in this case in order to avoid further damages or risks.

In the present project, a modern brake system for freight car applications, the safe condition is generally defined as the condition “Braking”. In order to comply with the high demands regarding functional and technical safety, where appropriate, crucial elements of the system should incorporate redundant design features.

5.3 Norms and standards

The complete system has to be tested according to the requirement of the following norms:

- type test according to EN 50155 with vibration test, temperature test in the climate chamber and isolation test;
- EMC test according to EN 50121-2-3 with measurement of interfering voltage according to EN 55011 and measurement of interfering fields according to EN 55011 and EN 50155;
- EMC test according to EN 50121-2-3 with measurement of interference resistance according to the norms from IEC 1000-4-2 to IEC1000-4-6 and 50155;
- software development according to EN 50128;
- proof of safety and reliability according to EN 50126 and EN 50129, where applicable.

The system has to be designed in accordance with protection class IP65 which describes the solidness of the system against ingress of water.

5.4 System overview

5.4.1 Vehicle composition

Project SUSTRAIL develops solutions in modern freight traffic in the near future. In particular, within the scope of this project, solutions for a freight car for the transport of containers are to be elaborated. This refers to a car with 2 bogies and 4 axles in total.

5.4.2 Build-up of the brake system

The system applied for this project must contain an innovative, forward-looking brake system. This brake system must be designed in such a way that it considers the environment, reduces noise emission, allows higher speed (140 km/h), reduces maintenance and overhaul costs, increases availability of the system and last but not least improves effectiveness. For such an innovative brake system a modern electronic distributor valve combined with a wheel-slide protection system has to come into consideration. For a higher availability and safety the brake control unit and the WSP system should be separated through separate components. Moreover, crucial functional units of the brake control should be redundantly designed for the same reason.

The specification of the brake system is thus divided into the four following sectors:

- vehicle components such as bogie and brake equipment, air reservoirs, etc.;
- brake control, controller and pneumatic components for the activation of the brake cylinder;
- wheel-slide protection with axle rotation speed measurement and dump valves;
- independent and reliable power supply for the control devices in the vehicles with axle generator and battery pack. It is known that the freight car has no on-board power supply. Therefore it is important to design also the power supply like axle generator or similar.

5.4.3 Brake calculation

Within the scope of this development a brake calculation for the existing vehicle has to be carried out. For this calculation the following operating conditions have to be taken into consideration:

- load conditions: due to the fact that we cannot test every mass condition between empty and 100% load, it is considered that it should be tested in the empty, 50% load and 100% load;
- wheel diameter: new and worn;
- operational speeds: it is important to make the above test with different speed range, in order to test and monitor the brake distances. Therefore, it should be considered to carry out the tests with the speed ranges of 60, 80, 120 and 140 km/h;
- operational states: in order to test the brake pressure development in the brake cylinder and the air consumption in the system, it is necessary to carry out tests in emergency conditions and in service brake.

5.5 Vehicle components

The present chapter defines the requirements regarding the vehicle equipment, in order to achieve the required functional and safety-related aims in accordance with UIC and EN norms which are very important to achieve the final approvals. Detailed requirements regarding the individual controls for the brake and the wheel-slide protection will follow in chapters 5.6 and 5.7 of the present document.

5.5.1 Bogies

The known and proven two-axle bogies of the type Y25 will be used for the existing container wagon. The bogies are UIC approved and are available in the market in their current designs. For increased requirements designs for application in SS-capable vehicles (with reference to UIC bulletin 541-04) and for speeds of up to 140 km/h are available. The following basic conditions have to be fulfilled:

- speed range of up to 120 km/h, or up to 140 km/h as an option;
- axle load 22.5t;
- wheel diameter new: 920 mm in accordance with the technical requirements “bogie parts”;
- rotating mass still to be defined;
- total weight of the bogie to be defined.

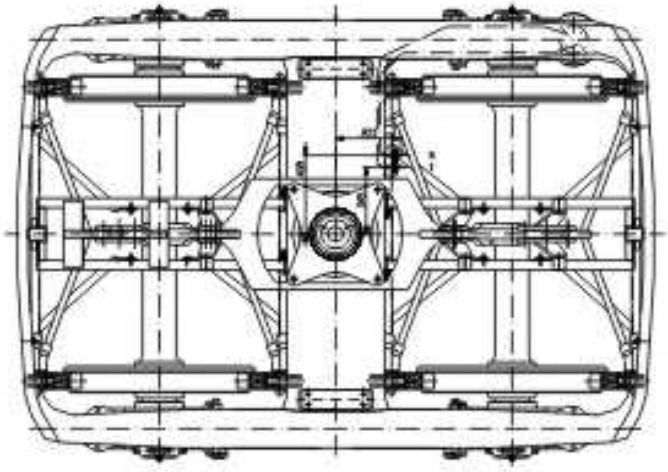


Figure 5.1: Bogie Y25

5.5.2 Brake disks and brake pads

The existing cast tread brakes cause a rough surface of wheelsets. This again contributes to a high noise emission of the vehicle which is not suitable for a future, modern and innovative wagon type. A K-tread brake would help to avoid rough surface of wheelsets, but they are not suitable for a speed of up to 140 km/h. The disk brake is a solution which has been used in passenger cars for a long time and which gives a very good result with regard to noise emission and brake characteristic. The application of vehicles in various areas should be considered. For these areas different uphill grades and downhill grades (e. g. Gotthardt, Switzerland) should be observed. Especially with regard to downhill grades, it has to be safeguarded that in case of continuous operation of the disks during braking, the disks do not overheat and that the thermal characteristic is not exceeded. These conditions have to be considered in the brake calculation. Depending on the brake calculation and the heat

characteristic of the disk, one or two disks per axle should be considered. The disks and the brake pads used are to be designed according to the brake calculation and the requirements according to references [58] to [61].

5.5.3 Brake cylinder

For the present project the brake cylinders and brake leverage have to be selected in accordance with the disk brake device applied. For this purpose, one brake cylinder has to be used for each brake disk. An 8” to 10” brake cylinder is required for the application. In combination with the brake calculation the size of the brake cylinder will be determined.

5.5.4 Supply air reservoir

For the local storage of the main brake pipe pressure and the brake cylinder pressure resulting from it, one or more pressure reservoirs are to be installed according to the air consumption of the vehicle which can be fed by the main brake pipe and which are protected against exhaustion by a check valve. The total volume to be installed should be 90 litres as a minimum to overcome the exhaustion of the brake.

5.5.5 Braking of the Load

For the detection of the load condition two weighing valves in accordance with applicable norm UIC 541-04 type 1 and task 3.4 “condition monitoring” are to be installed (one per bogie of the vehicle).

5.5.6 Control elements

If possible, the freight cars should be ready for operation without special measures. In order to reach this target, the usual control elements should also be applied here. These are as follows:

- “brake on / off” lever;
- release valve drag-bar which is necessary to release the brake if the distributor is overloaded;
- G/P lever, used to switch between freight car mode (G) and passenger car mode (P) depending on the brake distribution in the entire train; in accordance with UIC requirements (as described in section 6.2) the development of the brake cylinder pressure in the G and P positions is different. It means that this development in P position is much shorter than in G position.
- Brake indicator.

Apart from the above-mentioned elements further control elements might become necessary, e.g. for diagnosis purposes or within the scope of an optimized maintenance. Such components can also be specified in task 3.4.

5.6 Brake control

The brake control detects a brake demand triggered by the driver and reduces the main brake pipe pressure causing the subsequent activation of the brake cylinder. Project SUSTRAIL focuses on developing a system that is simple and effective to maintain; this can only be reached by using a control with a high degree of intelligence and, above all, the ability for self-test in accordance with task 3.4 “condition monitoring”. For this reason the brake control design specified as follows has to be implemented.

5.6.1 Electro pneumatic control (Electronic Distributor)

An electro pneumatic control should calculate and set the brake cylinder pressure in connection with the brake pipe pressure and the actual load measurement. Apart from the mentioned, basic functions, this control should fulfil the entire functionality according to the UIC as in references [58] to [61]. Moreover, it should contain comprehensive diagnosis functions which are characteristic for a modern control in accordance with 3.4 “condition monitoring”. It should be possible to monitor the correct functioning of all components of the brake control permanently and without external interaction and thus to identify possible failures and to announce them. The diagnosis function integrated into the brake control forms the basis for an effective maintenance and a more cost-optimized operation. With today’s composition of the wagons and the availability of the brake in the entire train this takes hours before departure. It is important for a future-oriented and innovative brake system to reduce this brake test time. Therefore, it makes sense to prepare the brake system for SUSTRAIL for the future testability of the brake system in the entire train automatically.

5.6.2 Pneumatic backup system

By the use of an electronic brake control in combination with the existing increased requirements with regard to maintenance intervals and the failure tolerance of the system, the integration of a redundant, merely pneumatic backup system is mandatory. Therefore, the system to be implemented needs to be able to take over the main functions in the brake sector automatically, in case that the electronic control fails. In this way, not only double safety in a major part of brake control should be achieved, but on the other hand an extension of the maintenance intervals and thus the reduction of operational costs of the vehicle should be obtained.

5.6.3 Mechanical design

The entire brake control should be implemented as a compact unit with a protection class of IP 67. The device should be suitable for the unprotected application on the car body of the freight car.

Furthermore, special attention should be given to the maintainability of the control. In order to achieve minimum immobilization times due to a necessary maintenance, the control as such should be easily removable and a replacement unit should easily be fitted.

A joint mechanical design with a wheel-slide protection control according to chapter 5.7 is admissible.

5.7 Wheel-slide protection

The existing brake system in freight cars can cause wheel flats and thus damage the mechanics of the vehicle – and also the rail. The removal of these wheel flats incurs high costs. Due to the high speeds which should be achieved by the vehicle and the (probable) reduced stopping distances, avoiding flats on the wheels and minimizing the wear of the wheelsets using a modern, electronic wheel-slide protection system is recommended as part of the brake system.

A wheel-slide protection control should be implemented axle-wise, in order to reach optimum performance. A wheel-slide protection system which is completely independent from the brake control as described in chapter 5.6 is proposed for safety-related reasons.

5.7.1 Speed measurement

In order to detect a sliding state the axle rotation of each axle needs to be recorded. For this purpose, one phonic wheel with one speed sensor needs to be installed on each axle. Standard speed sensors with rectangular output should be used. The phonic wheels should have 80 teeth at module 2 which is commonly used in passenger cars. The 80 teeth are necessary to achieve high accuracy in the calculation of the low vehicle speeds.

5.7.2 Wheel-slide protection control

An electronic control should be used to detect the axle rotation, to calculate the vehicle reference speed The accuracy of the reference speed is very important to have a very good knowledge of the sliding axles. A measurement of the speed over ground would give a very high accuracy of the existing speed of the wagon. It should be considered whether a measuring system like laser or similar in low cost version could be identified. In operational states in which the vehicle starts to slide this control should be able to adapt the actual brake force axle-wise via the dump valves, in order to achieve optimum brake performance and a minimum wear at different adhesion values between rail and wheel.

The functionality of the system has to fulfil the requirements according to the UIC541. Moreover, it should contain comprehensive diagnosis functions which are characteristic for a modern control in accordance with task 3.4 “condition monitoring”. It should be possible to monitor the correct functioning of all components of the brake control permanently and without external interaction and thus to identify possible failures and to announce them. The diagnosis function integrated into the wheel-slide protection system forms the basis for effective maintenance and a more cost-optimized operation.

5.7.3 Dump valves

In case that the wheel-slide protection control detects an excessive slip of one of the vehicle axles, the brake force at this axle needs to be reduced. For this purpose, dump valves customary for railway applications which can fulfil this task are to be used. The connecting pipe should have the same or greater diameter as the nominal diameter of the dump valve. Most of the dump valves have a nominal exhausting diameter of about 12 mm. Therefore, a value of 1/2“ is to be determined as connecting diameter. The dump valves should be mounted on the body of the car near the brake cylinder in order to achieve very short exhausting times..

5.7.4 Mechanical design

The entire wheel-slide protection control should be implemented as a compact unit with a protection class of IP 67. The device should be suitable for the unprotected application on the car body of the freight car.

Furthermore, special attention should be given to the maintainability of the control. In order to achieve minimum immobilization times due to a necessary maintenance, the control as such should be easily removable and a replacement unit should easily be fitted.

A joint mechanical design with the brake control according to chapter 5.6 is admissible.

5.8 Power supply

The brake system and wheel-slide protection system depend on a reliable power supply. In the case of a freight wagon without a permanent power supply the power could be generated by an axle generator. An external connection for power supply should be provided for as an

option. However, all electrical components have to be optimized with regard to power consumption and need to incorporate intelligent power management. This is also mandatory from an ecological perspective.

5.8.1 Axle generator

For an independent power supply of the vehicle a power generator has to be designed. In the present application this should be realized as an axle generator to be mounted on the axle directly. The generator must have a minimum power output of 75W at a minimum speed of 60 km/h. The output voltage has to be determined in such a way that the connected battery pack can be charged with a nominal voltage of Ubatt= 24V during driving mode. The generator has to be equipped with a voltage stabilizer which limits the output voltage (which is rotation speed dependent) to a maximum of 27V. The voltage can be lower in a lower speed range. The 75W will be used during WSP system actions only. Therefore a power consumption of 75W will only prevail for a maximum of 1 minute. The innovative brake system is optimized by a power management program, so that a minimum consumption can be reached.

5.8.2 Backup battery

For freight cars no power supply of the entire train set is available, so the power required for the operation of the controls has to be generated locally. This task is carried out by the axle generator specified in chapter 5.8.1. However, its energy has to be stored, in order to safeguard the required functionality when in operational states such as low speed or standstill. For this purpose, a set of backup batteries has to be integrated into the control or has to be placed in an individual housing. In the latter case, mechanical requirements comparable to chapters 5.6.3 or 5.7.4 have to be fulfilled.

5.8.3 Power management

Generally, power management is a crucial issue. For this reason, a power management system has to be developed and implemented. The use of the available power resources is of special importance for freight cars as they have no on-board train power-supply voltage. The power is exclusively supplied by the axle generator and thus very limited. In order to safeguard a long battery life, the capacity of the battery has to be dimensioned in such a way that the battery charge is sufficient for 24 hours. This will help in situations in which the train composition and brake testing are carried out hours before departure.

5.9 Diagnosis functions

Apart from the basic functions described in chapters 5.5 to 5.7, the brake system with integrated wheel-slide protection system designed for this purpose should also have extensive diagnosis functions. This diagnosis functionality serves the purpose to increase efficiency of the maintenance works and to extend the maintenance intervals. The following chapter specifies the core functions of the diagnosis system in project SUSTRAIL.

5.9.1 Ability for self-test

The ability for self-test should comprise all inputs and outputs including the monitoring of internal components such as the micro-controller surroundings of an electronic control. Whenever possible, a validation of process data should be carried out. Detected failures should be classified according to their severity and their influence on the functioning of the system and should be revealed subsequently and depending on their classification – immediately or within the scope of a later test.

5.9.2 PC service system

In order to further simplify maintenance, a PC-based service system should be integrated. This system can easily furnish the relevant data regarding a failure to the operator. Furthermore, it should serve to download the operational data which can be used for supporting service activities.

The service system should be run capable in connection with the system software Microsoft XP or higher version.

In order to connect a PC, both the brake control and the wheel-slide protection system have to dispose of a suitable service interface.

5.9.3 Memory card interface

In order to be able to make extensive records of individual process data or operational data on a long-term basis, the brake system or the wheel-slide protection system need to dispose of an optional memory card interface. The latter is able to store important data also in case of larger intervals between maintenance works and thus to give important indications of possible problems and wear.

5.9.4 GPS/GSM communication interface

When using intelligent systems, above all in combination with long maintenance intervals it is often difficult to receive the required data on a failure incident from the vehicle. The same applies if for reasons of efficiency a needs based maintenance is desired and if updated data on condition and wear of the vehicle is necessary. The system to be designed should therefore offer the possibility to transmit the process data or failure information to a control centre via wireless communication. An optimum GSM interface has to be designed to suit this purpose.

When implementing this functionality it has to be assured that the communication via GSM interface does not influence the functionality of the brake control or the wheel-slide protection system.

As an additional option the GSM interface should be expanded by a GPS function so that service data can be complemented by positioning information which will further increase the significance of the data. Thus an optimum traceability of the vehicle fleet and a maximum utilized capacity of the vehicles can be achieved.

5.10 Safety requirements

5.10.1 Preface

The complete system, both brake system and the wheel-slide protection, should be designed for a safety-relevant environment. Wrong releasing of the brakes is an example of a failure which needs to be avoided.

Therefore, within the scope of the present development project safety targets and risk assessments for the brake control function and for the function of the wheel-slide protection have to be drawn up. All possible emergency scenarios have to be listed and classified according to the classes given in chapter 5.10.2.

5.10.2 Classification of the hazard level

The hazard levels are defined as follows along with the requirements for safety and reliability that apply to the present system:

Hazard level 0:	The failure is uncritical, it is detected by self-test and has no major outward effects. A possible problem can be solved as a matter of routine within the scope of the next service.
Hazard level 1:	The failure is little critical and is detected by self-test. There is no risk of personal injuries or major damages to property. An MTBF value for operational time of 10^5 - 10^6h applies for this case.
Hazard level 2:	The failure is critical. It may not be detected by self-test and there is the risk of individual personal injuries or major damages to property. An MTBF value of 10^6h - 10^7h applies.
Hazard level 3:	The failure is calamitous and should never happen. It may not be detected by self-test and major personal injuries or considerable damages to property are probable. An MTBF value of 10^7h - 10^8h applies.

5.11 Parameters

5.11.1 Battery voltage

At present, most freight cars lack a power supply. The choice of the system nominal voltage and thus the nominal voltage of the battery pack can be chosen freely. To standardise the systems and peripheral components a nominal voltage of the battery of Ubatt=24Vdc could be chosen for this system.

The charging connection of the axle generator has to be designed according to these requirements; the same applies for the dimensioning of the battery pack which may require a series connection or a parallel connection of individual cells.

5.11.2 Admissible pressure of the main brake pipe

The entire system should be designed for a standard main pipe pressure of up to 10 bar. The regular operational pressure of a brake pipe is between 4 and 6 bar, however, in case of a pressure surge a maximum pressure of 10 bar may be reached.

5.11.3 Admissible brake cylinder pressure

The maximum admissible brake cylinder pressure depends on the application and can generally be taken from the brake calculation of the respective vehicle. As a rule the brake cylinder pressure should be in accordance with UIC as in the references [58] to [61].

5.11.4 Temperature range

The working temperature range of the entire brake system should be from -40°C to +70°C. Forced cooling or heating of the system should be avoided where possible.

5.11.5 Air pressure

All pneumatic components are to be designed for a standard maximum working pressure of 10bar.

5.11.6 Air quality

All pneumatic components are designed for operation with an air quality which at least complies with the requirements specified according to DIN ISO 8573-1, class 3. The requirements of pneumatic components in railway applications are operation with dry air. The condition of dry air is specified in the above mentioned DIN.

6. SUBTASK 2.4.3 – ACCELERATION AND SPEED REQUIREMENTS

6.1 Introduction

The objective of subtask 2.4.3 is the identification of the requirements for acceleration and speed.

The increase of freight trains' speed shall be done on the whole fleet; it has a low impact to have some high speed freight trains. Having freight trains run at a higher speed than today will lead to a harmonisation of operation of freight and passenger traffic on mixed traffic railways, thus reducing waiting times for goods transport and improving the ability to organize priorities.

6.2 Standards for acceleration and braking

Rules, regulations and standards for cargo exist at a national as well as international level for rail transport. The railway as a whole and each railway subsystem is regulated by standards and specific TSI's defined by the UIC, EU, and by national regulations.

In Task 2.1 a summary of standards related to railway engineering in general and more specific standards for vehicles and track was issued.

In the scope of Task 2.4, the potential technological improvements to the vehicle in order to reach a higher speed (compared to today's speed of freight trains) were analysed, always taking into account the existing standards at EU and national level.

6.3 Impacts of more intensive/faster operation on vehicle maintenance requirements and infrastructure

Transport of freight at a higher speed increases maintenance costs; this is mainly due to higher forces, leading to a faster wear of tracks and wheels.

A study from UIC ("Operating high-speed lines carrying mixed traffic: experience gained and current trends", 2001) [64] highlighted that operating of goods trains on a high-speed line (considering high speed above 250 km/h) might increase the track maintenance costs by up to 20 or 25% as compared with a situation where the line is used exclusively for passenger traffic. Since these costs represent about 40% of the total cost of fixed installations (tunnels, bridges, formation, signalling, communications, overhead equipment, power supply) the extra cost attributable to operating mixed traffic would be of the order of 10%.

As the SUSTRAIL selected routes are for mixed traffic, the layout is designed based on regional passenger train speeds and therefore freight is running in cant excess in curves. Increasing the speed from 120 kph to 140 kph on these lines will bring freight closer to balance speed or into cant deficiency.

It would not be possible to preserve the geometrical characteristics adequate for operating high-speed trains, without incurring prohibitive maintenance costs (UIC Report "Operating high-speed lines carrying mixed traffic: experience gained and current trends", 2001).

Increasing the speed in freight transport would require adapting the existing infrastructure. Moreover, signalling system would need to be adapted in order to take into account increased speeds of freight trains.

6.4 Simulations on speed increase effects

Computer simulation is particularly important for evaluating different railway improvement strategies for a number of reasons (understanding capacity, highly interrelated infrastructure, high cost of rail infrastructure).

Simulation is performed through the construction of a model replicating the observed railway operations with the existing infrastructure, rolling stock and schedule. Once the model has been calibrated it can be used to investigate many issues including effects of speed increasing or evaluating the impact of rolling stock changes.

In the scope of subtask 2.4.3, relevant to the identification of the future vehicle performance requirements, simulations have been performed in order to understand how the increase of speed of freight trains (to 120 km/h and then to 140 km/h) would free additional paths on selected routes.

In particular the Bulgarian route has been selected to run simulations. This is mainly due to the fact that the detailed data of this route has been made available from WP 1, including track profile, curves, gradients and speed limits, as detailed in paragraph 6.4.2.1.

The software OpenTrack has been used to perform simulations. A description of the tool, including input data and output is described in the following paragraphs.

6.4.1 OpenTrack simulator tool

OpenTrack began in the mid-1990s as a research project at the Swiss Federal Institute of Technology. The aim of the project, Object-Oriented Modelling in Railways, was to develop a user-friendly tool to answer questions about railway operations by simulation.

Today, the railway simulation tool OpenTrack is used by railways, subways, the railway supply industry, consultancies and universities in different countries.

OpenTrack supports the following kinds of tasks:

- Determining the requirements for a railway network’s infrastructure;
- Analysing the capacity of lines and stations;
- Rolling-stock studies (for example future requirements);
- Timetable construction, analysing the robustness of timetables (single or multiple simulation runs, Monte-Carlo simulation);
- Analysing various signalling systems, such as discrete block systems, short blocks, moving blocks, LZB, CBTC (communication-based train control), ETCS Level 1, ETCS Level 2, ETCS Level 3;
- Analysing the effects of system failures (such as infrastructure or train failures) and delays;
- Calculation of power and energy consumption of train services;
- Simulation of Tram/Streetcar and Light Rail systems;
- Simulation of Metro/Subway/Underground systems;
- Simulation of Maglev systems.

OpenTrack administers input data in three modules: network (infrastructure), rolling stock and timetable. Users enter input information in these modules and then run the simulation.

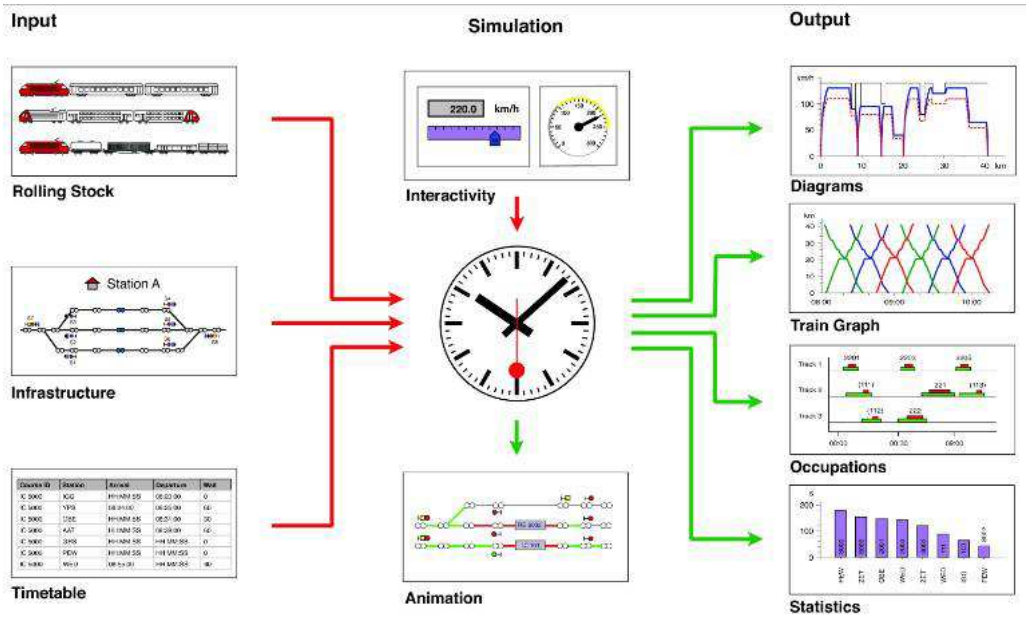


Figure 6.1: OpenTrack Process: Input – Simulation – Output

The simulation is carried out with the user defined input data: predefined trains move on predefined track layout on the conditions of the timetable data.

OpenTrack uses a mixed discrete/continuous simulation process that calculates both the continuous numerical solution of differential motion equations for the vehicles, and the discrete processes of signal box states and delay distributions.

6.4.1.1 Input data

6.4.1.1.1 Network data

The track layout consists of a description of the physical infrastructure that is being simulated. This includes actual infrastructure such as track segments (edges), signals, stations, etc., as well as virtual elements such as vertices and routes.

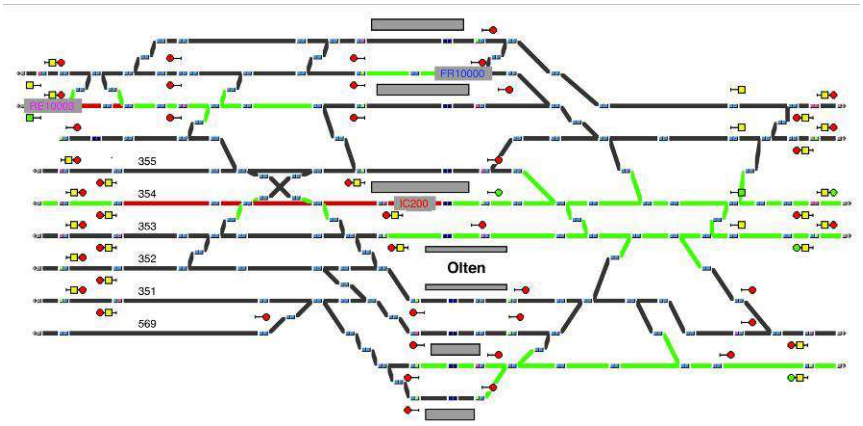


Figure 6.2: Example of a station network

6.4.1.1.2 Rolling-stock data

OpenTrack stores each locomotive's technical characteristics, including tractive effort/speed diagrams, load, length, adhesion factor, and power systems in a database. A simulated train uses one or more locomotives from the database together with a number of passengers' or freight cars (carriages or wagons). Trainsets are also organized in a database.

6.4.1.1.3 Timetable data

Timetable data consists of information on the movement of trains. This information includes desired arrival and departure times, minimal stop time, and connections to other trains.

6.4.1.2 Simulation

The objective of the OpenTrack simulation process is for the user-defined trains to fulfil the user-defined timetable on the user-defined track layout: predefined trains run according to the timetable on a railway network.

During the simulation, OpenTrack calculates train movements under the constraints of the signalling system and timetable (occupied tracks and restrictive signal aspects may impede a train's progress).

The user can watch the simulation in an animation mode, which shows the trains running and lets the user analyse occupied tracks, reserved tracks and signal aspects. Moreover, OpenTrack handles single simulation runs as well as multiple simulation runs where random generators produce different initial delays and station delays. The motion of trains is modelled by the solution of the (continuous) differential equation of motion combined with signal information (discrete). The differential motion equation calculates the train's forward motion based on the maximum possible acceleration per time step (the acceleration rate is determined using train performance and track layout data such as maximum tractive effort, train resistance, track gradient, track radius, segment maximum speed…). The train speed is obtained using integration and the distance covered using reintegration.

6.4.1.3 Output data

After a simulation run, OpenTrack can analyse and display the resulting data in the form of diagrams, train graphs, occupation diagrams and statistics. For a train, the software offers diagrams such as acceleration vs. distance, speed vs. distance, and obstructions. For a line, there are evaluations in the form of diagrams of train movements, route occupation and line profiles. Every station produces output about all the trains that used it, including arrival, stopping and departure times.

In the following figures, some examples of typical OpenTrack output are presented.

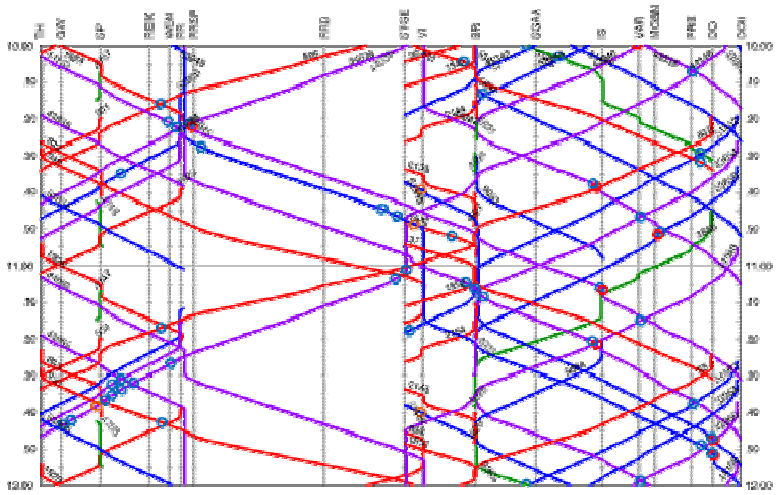


Figure 6.3: Train diagram

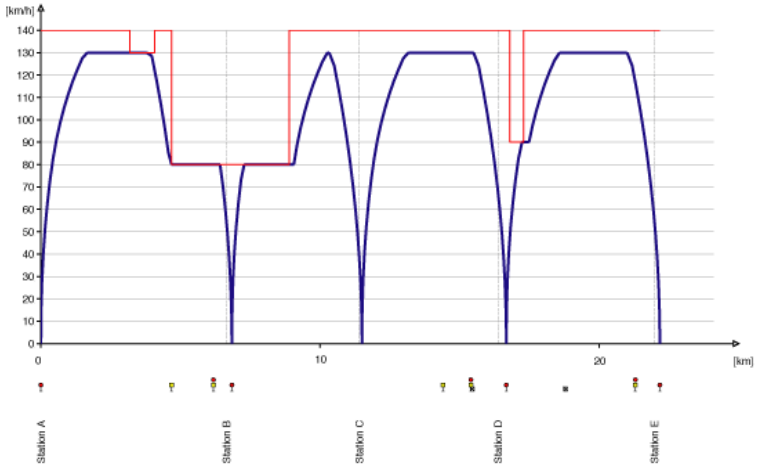


Figure 6.4: Speed-distance profile

6.4.2 The Bulgarian case study

As introduced before, the case study selected for simulations in Subtask 2.4.3 is the Bulgarian one. Bulgarian selected route is from Dimitrovgrad S to Kapikule for a total length of about 375 km. The traffic mix on this line is freight and passenger. The freight on this line is a combination of local and international traffic. No tunnels are along this line.

Today freight traffic in Bulgaria has a typical line speed of 75 km/h apart from the section between Parvomaj and Jabalkovo over which freight can travel at up to 120 km/h.

6.4.2.1 Input data for simulation

6.4.2.1.1 Track

The line section selected has been split in many subsections, initially defined by the stations. From one station to the following one, the track has been split into different uniform subsections, each subsection having the same characteristics in terms of gradient and curvature.

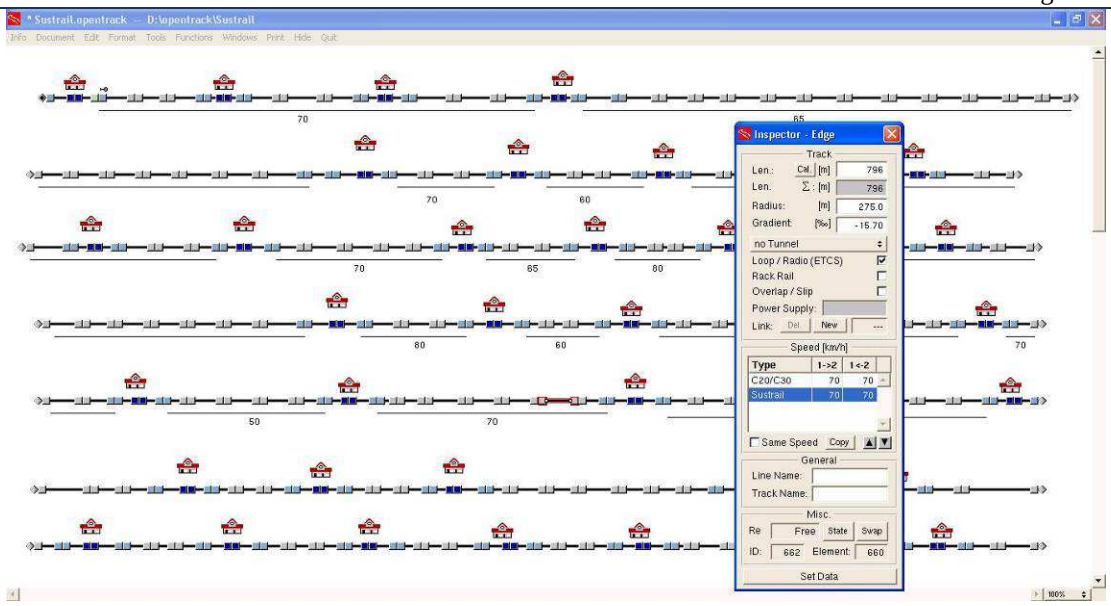


Figure 6.5: Track Input Data

As shown in Figure 6.5, for each segment of the track the length, radius, gradient and speed has been set. The picture is the schematic representation of the simulated section.

6.4.2.1.2 Train

Characteristics of the trains used for simulations have been defined in OpenTrack.

The train length has been estimated as 500 m, while the weight as 960 t.

Parameters have been inserted in the system as shown in Figure 6.6, where also the diagram used to define the traction effort linked to the different speeds is represented.

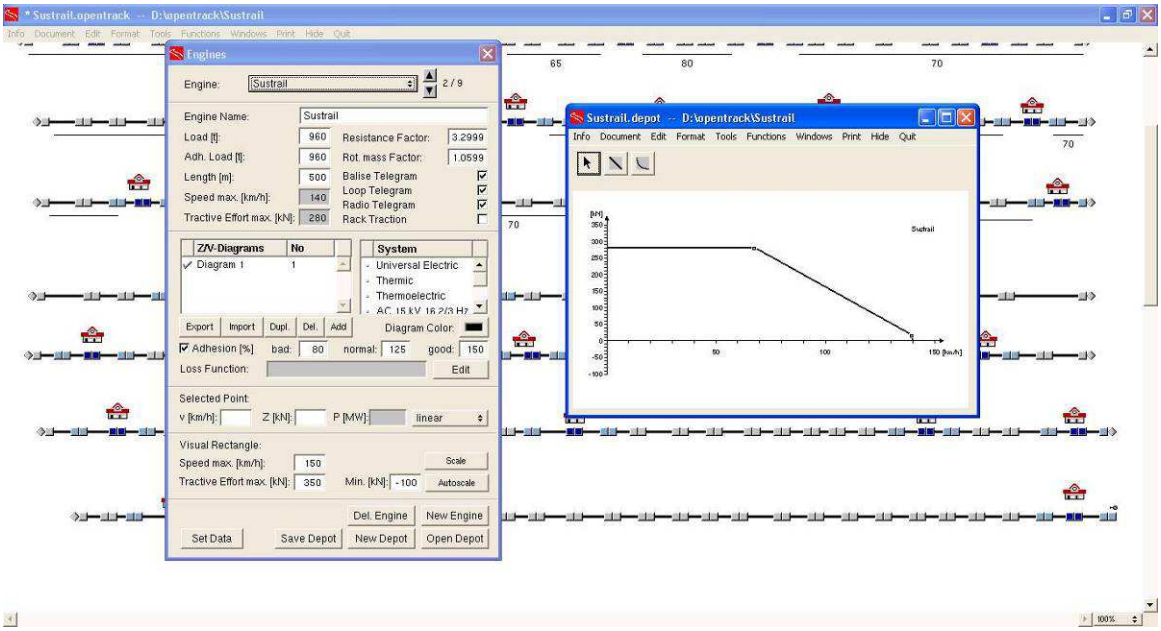


Figure 6.6: Train Input Data

6.4.2.2 Simulations on the Bulgarian route

Three different simulations have been run through the OpenTrack simulator tool:

1. with actual speed limits of the selected line;
2. using a speed of 120 km/h ("conventional" SUSTRAIL vehicle);
3. using a speed of 140 km/h ("futuristic" SUSTRAIL vehicle).

The same vehicle has been used for simulation purposes; average resistive curve of the vehicles have been used. Speeds along the line are shown from Figure 6.7 to Figure 6.9; the figures underline speeds for each track section. Figure 6.10 compares speeds of the three simulations. The SUSTRAIL vehicle (particularly 'futuristic' one) is intended to have better traction/braking characteristics so improvements would be increased; those characteristics will be detailed in the design phase.

For the simulation cases 2 and 3, the maximum speed respectively of 120 km/h and 140 km/h, has been set only in the sections where the current speed was already above 80 km/h (taking into account today limits); in the other subsections, a lower speed has been set, considering slopes and curves.

Near stations all speeds have been set to 50 km/h.

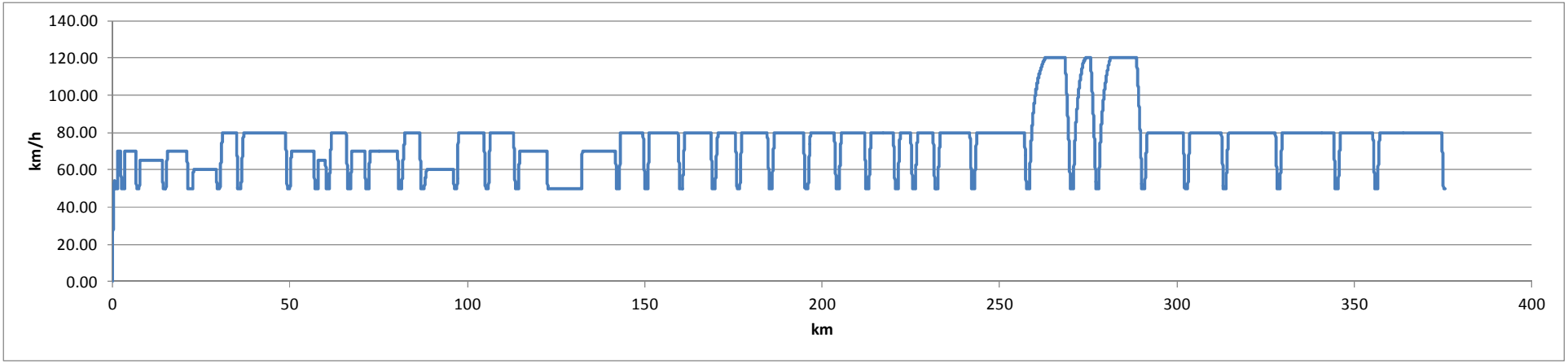


Figure 6.7: Speed diagram with actual speed limits

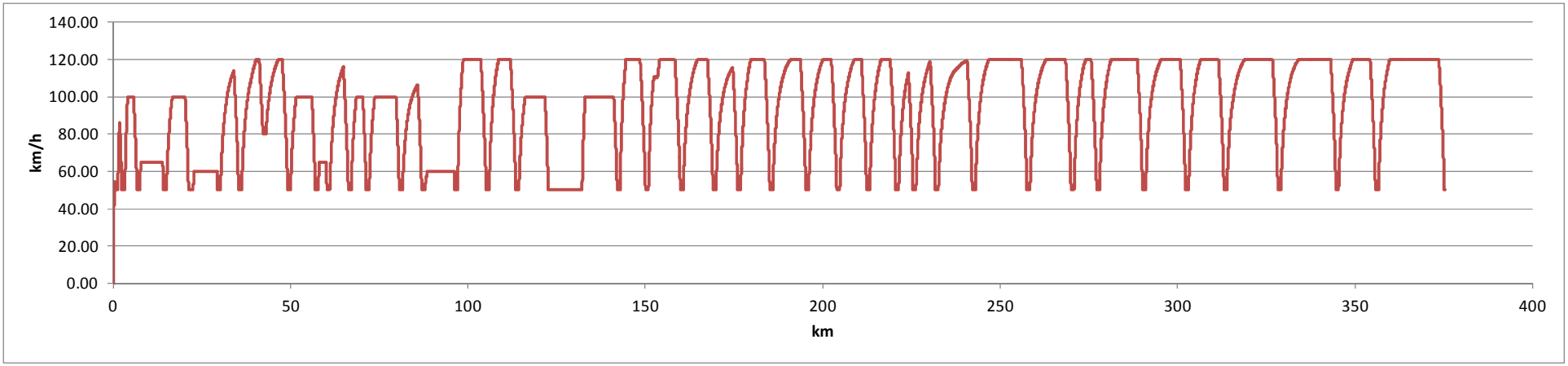


Figure 6.8: Speed diagram with maximum speed of 120 km/h

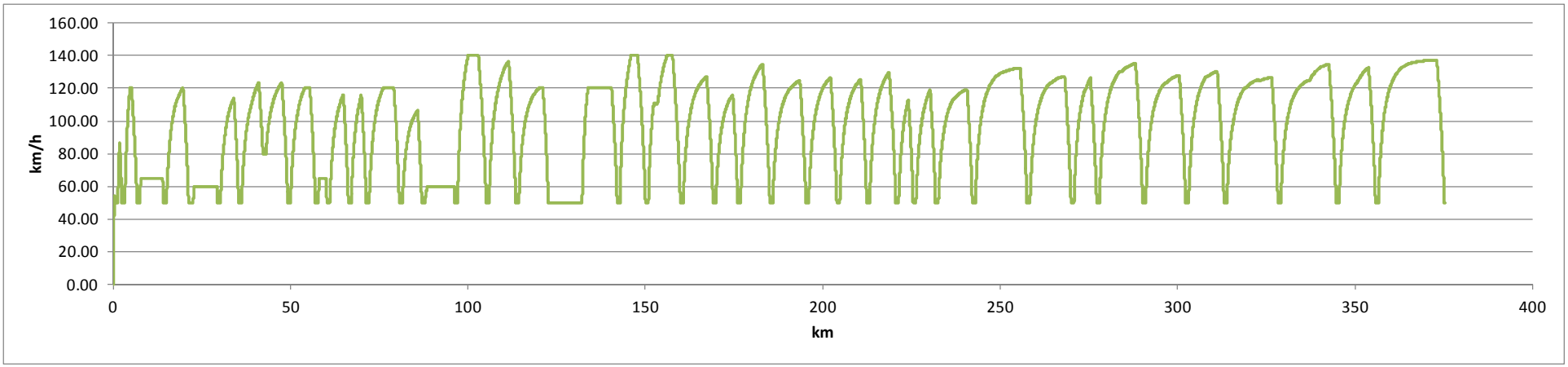


Figure 6.9: Speed diagram with maximum speed of 140 km/h

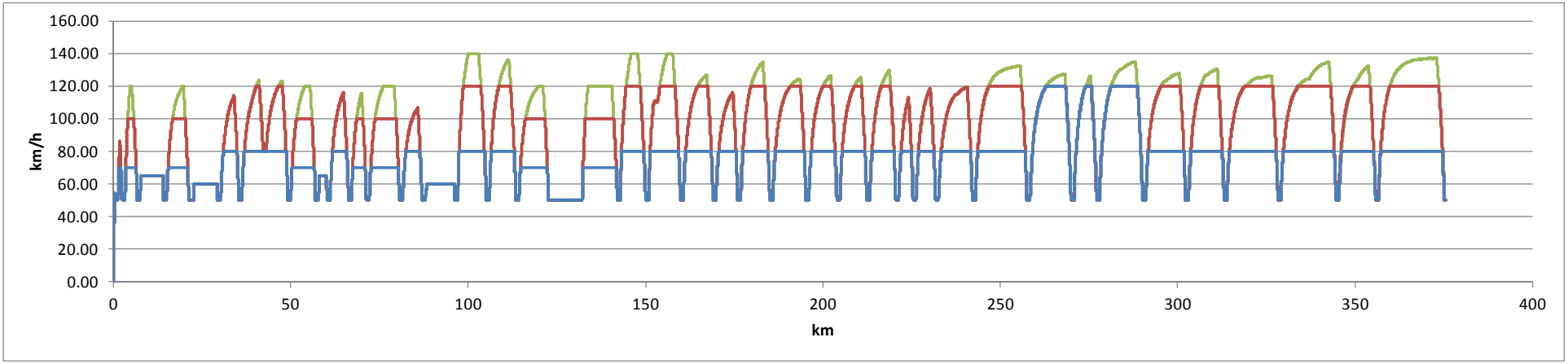


Figure 6.10: Speed diagram comparing the three simulations

All simulations have been run starting at the same time (8 a.m.); in this way the duration of simulations can be easily compared.

6.4.2.3 Simulation outputs and conclusions

Outputs of the simulations consist in different diagrams and text files.

The following figures show diagrams of accelerations, for runs at different speeds; the last diagram (Figure 6.14) compares accelerations for the different speeds along the line.

Acceleration has been set to a maximum value of 0.4 m/s^2, which is already a quite high figure for a freight train. As shown in the graphs below, the value of 0.4 m/s^2 is reached only in some sections of the line; this is mainly due to the quite small distance between stations (where speed reduction is required due to signalling/safety reasons).

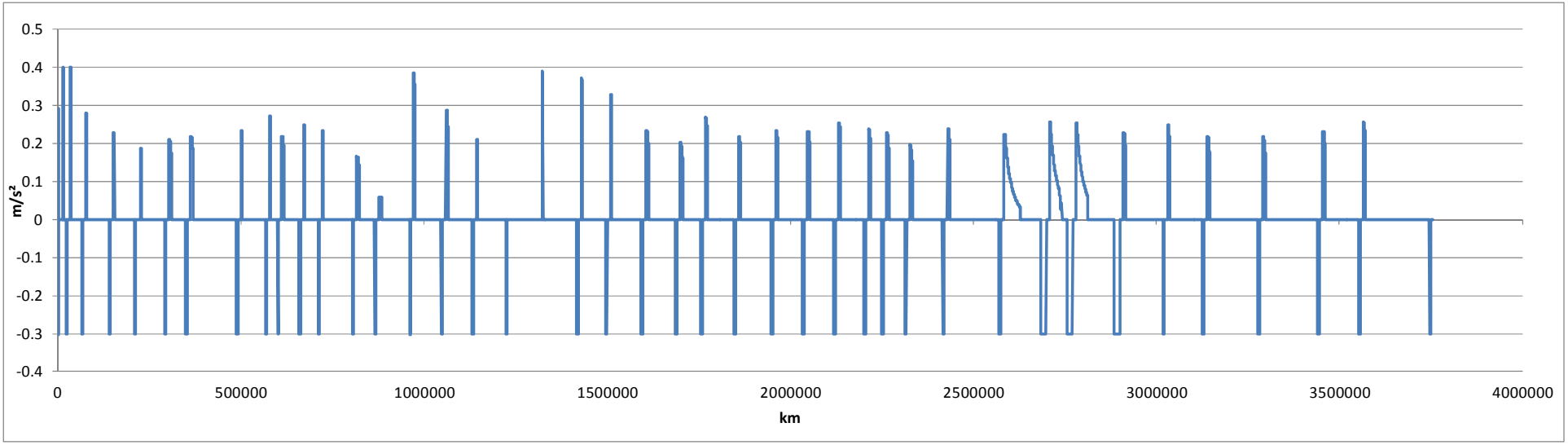


Figure 6.11: Acceleration diagram with actual speed limits

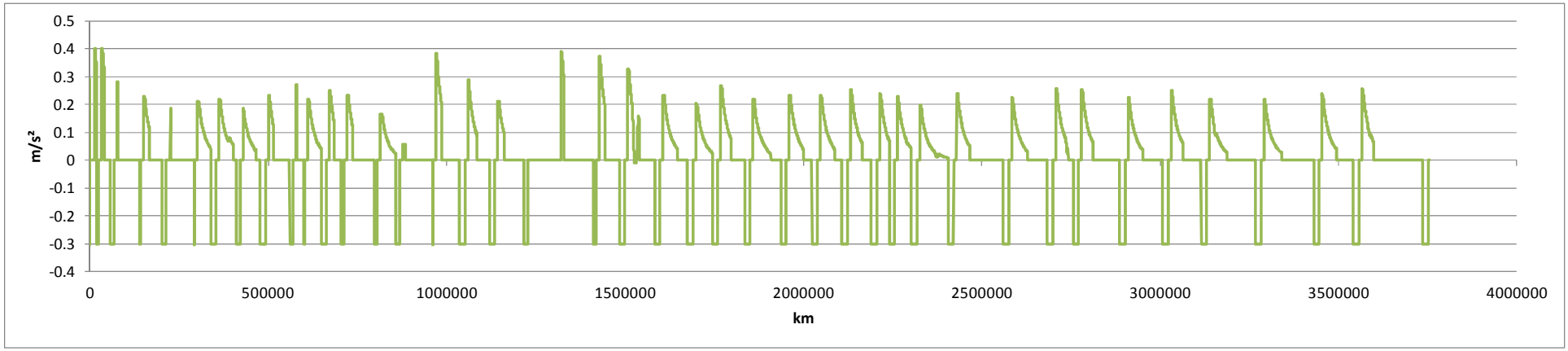


Figure 6.12: Acceleration diagram with maximum speed of 120 km/h

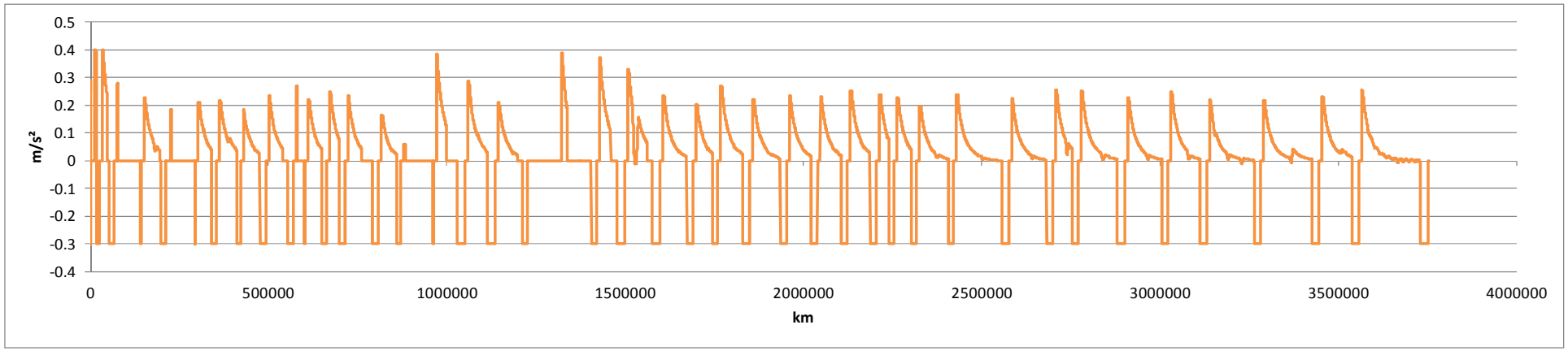


Figure 6.13: Acceleration diagram with maximum speed of 140 km/h

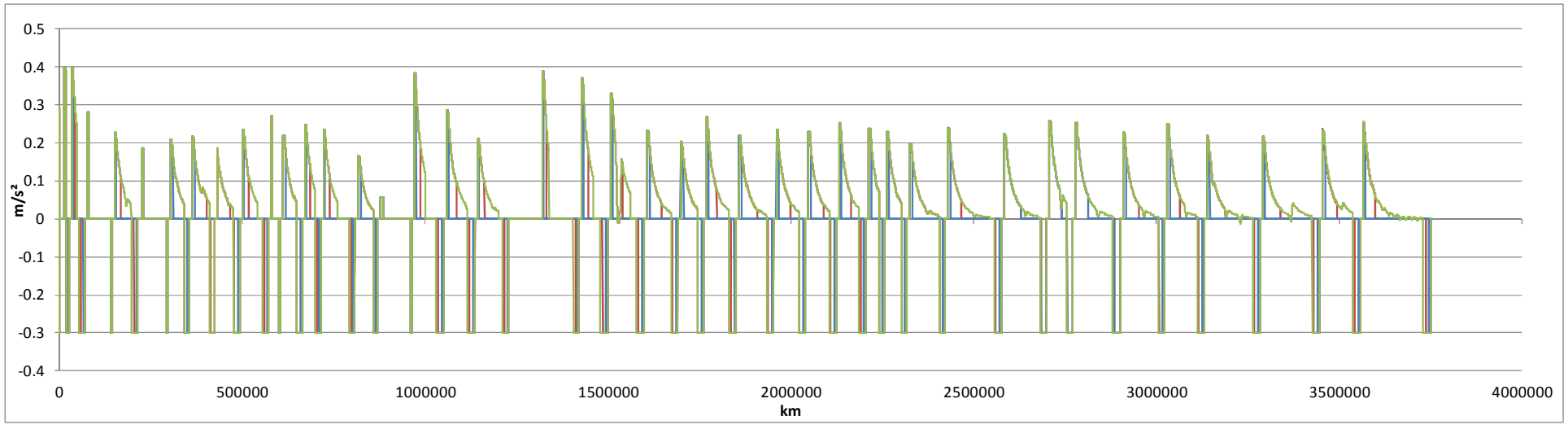


Figure 6.14: Acceleration diagram comparing the three simulations

Simulations using trains running at different speeds show that by increasing line-speed to 120 km/h the train arrives at the destination about one hour before trains running at the actual speed limit. By using 140 km/h the time “gained” is about 10 minutes compared to the train running at 120 km/h. This is mainly because the speed of 120 km/h is reached only in some small sections, due to the speed restrictions caused by stations close one to each other.

Figure 6.15 compares the three simulation results in terms of timetable.

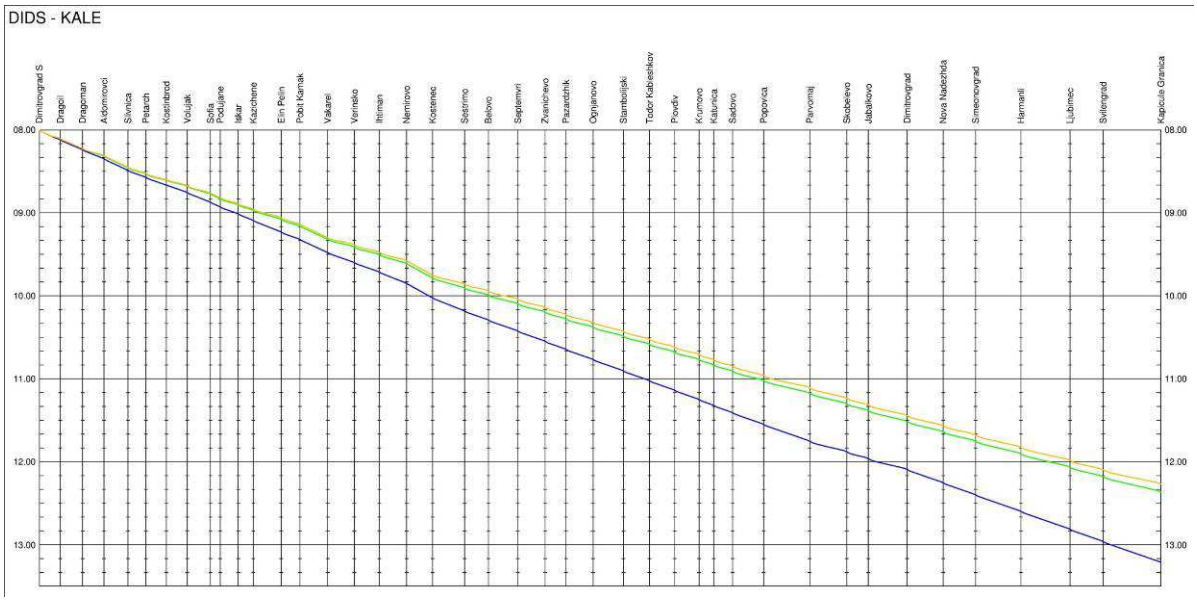


Figure 6.15: Train diagram

With the increase of speed to 120 km/h the time saved with respect to today’s situation allows the modification of the timetable, with the addition of at least 3 trains in the section. Of course simulations performed did not take into account possible presence of passenger trains in the same section (the route is a mixed traffic line).

The increase of speed to 120 km/h (and to 140 km/h) could only be reached if the limitations can be solved; most speed limits are due to bad technical conditions of the track, therefore interventions on the infrastructure side are needed to have trains running at higher speed than today.

In some circumstances, speed limits are due to railway crossings, switches, curves with small radius, and sections with high gradient; in these cases it is more difficult to bring improvements in order to increase speeds.

6.5 Vehicle green label

One of the requirements identified in Subtask 2.4.3 is relevant to the energy efficiency of the train.

A green label (as shown in the example of Figure 6.16) could be assigned to each vehicle, after having evaluated a score based on some parameters, such as:

- Unsprung mass (function of the design of a vehicle's suspension and the materials used in the construction of suspension components);
- Technology for wheels and subcomponents;
- Materials for bogie construction;

- CO_2 emissions.

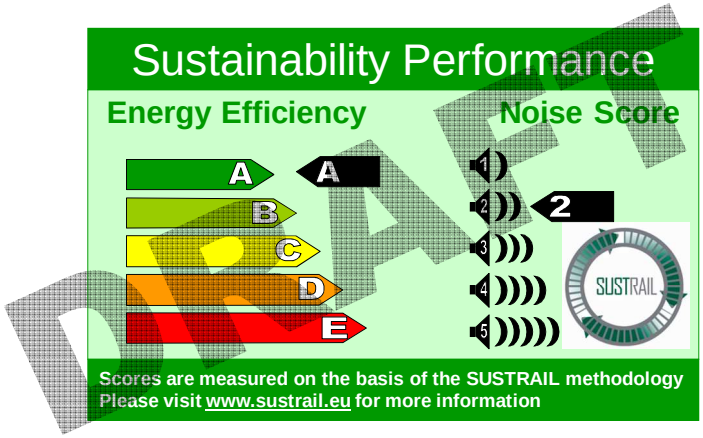


Figure 6.16: Vehicle Green Label - Example

The label could be renewed each year, following a check and the confirmation of the score assigned for each of the factors listed above.

Vehicles characterized by better performance, therefore getting the “green label”, should be entitled to reduced access charges for infrastructure.

Therefore this label could provide advantages to the railway operators in terms of access charge payment.

6.6 Traction and Braking

This section is associated with subtask **2.4.3 Acceleration and speed requirements**. The objective of this task is to evaluate duty requirements in terms of acceleration and braking while increasing speed of freight traffic.

6.6.1 Traction

A rail vehicle's tractive effort must be sufficient to overcome the vehicle's running resistance and provide desired acceleration. For freight locomotives it is often speed requirements and gradients along the line that that necessitates high tractive power, however, the overall performance must allow the train to fit in the traffic pattern for a given line [69].

The running resistance can be divided into four parts:

- Mechanical resistance (D_m)
- Aerodynamic resistance (D_a)
- Curve resistance (D_c)
- Gradient resistance (D_g)

Mechanical and aerodynamic resistance are generally determined via empirical methods. These models must be used with caution as they are valid under given conditions. Data presented in the following sections are results from research on typical trains and tracks in Sweden [70].

6.6.1.1 Mechanical resistance on tangent track (D_m)

The main sources of mechanical resistance are the following factors:

- Energy dissipation in wheel bearings
- Plastic deformation in the contact between wheel and rail
- Energy dissipation due to creepage
- Loss of energy in springs, dampers and friction surfaces within the vehicle
- Energy loss in transmission system

For locos and freight wagons the mechanical resistance on tangent track can be estimated using the following formula:

$$D_m = a \cdot \sum_{i=1}^{n_{ax}} (a_0 + a_Q \cdot Q_i) + \sum_{i=1}^{n_{ax}} (b_Q \cdot Q_i) \cdot v$$

where

$a \approx 1$,	for train in motion
$a \approx 2$,	initial resistance at start
$a_0 \approx 30$,	for locos
$a_0 \approx 65$,	for freight wagons
$a_Q \approx (0.4 - 0.7) \times 10^{-3}$,	for locos

$a_Q \approx (0.6 - 0.9) \times 10^{-3}$,	for freight wagons	
$b_Q \approx 0 - 2 \times 10^{-3}$,	for locos	[s/m]
n_{ax}	number of axles	
Q_i	axleload for axle number *i*	[N]

6.6.1.2 Aerodynamic resistance (D_a)

For speeds above approximately 100 km/h the aerodynamic resistance is often the predominant part of the total resistance; this resistance can be written as

$$D_a = \frac{\rho}{2} \cdot A \cdot C_D \cdot v^2 + (q + C_0 \cdot L_T) \cdot v$$

where

v	speed	[m/s]
ρ	air density	[kg/m^3]
A	cross section	[m^2]
$C_D = C_P + C_L \times L_T$	aerodynamic drag	[-]
q	total ventilation flow	[kg/s]
$C_0 = 0 - 0.6$	linear term, low value for trains without gaps between wagons	
L_T	length of train	[m]

Examples of aerodynamic drag as function of train length are shown in Figure 6.17.

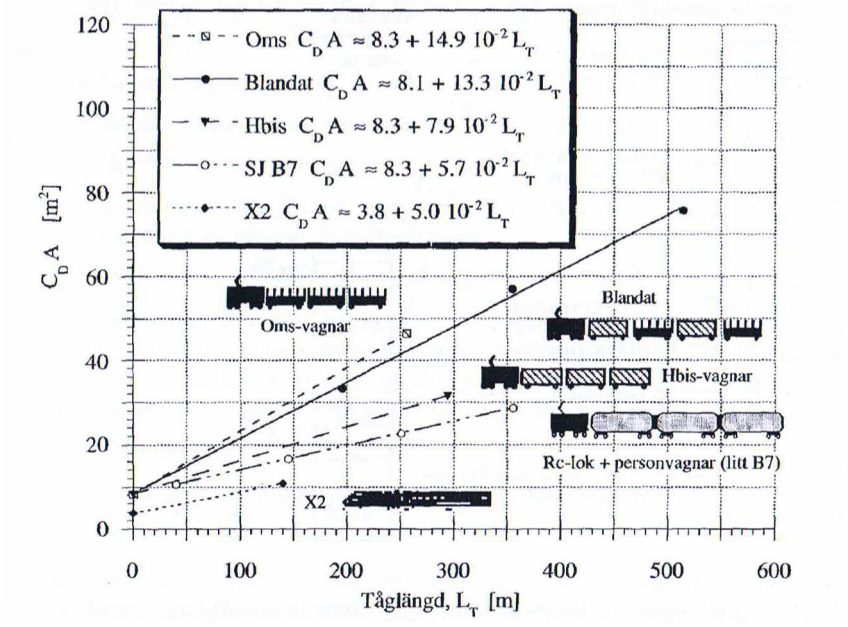


Figure 6.17: Aerodynamic drag as function of train length [70]

6.6.1.3 Curve resistance (D_c)

Ideally, the wheel-set will run smoothly through a curve due to the conical wheels that are connected via a rigid axle. This causes the outer wheel to travel the greater distance needed and the wheel-set to align itself radially.

In reality, however, due to unfavourable wheel and rail contact conditions and restrictions caused by the suspension system the friction forces increase resulting in greater running resistance in curves.

Andersson [74] proposed the following equation to calculate the curving resistance in curves with radius greater than 300 m.

$$D_c = \frac{6.5}{R-55} \cdot \left(1 - \frac{R^2}{R^2 + 30000} \cdot K_b\right) \cdot m_T$$

where

R	curve radius	[m]
m_T	mass of train	[kg]
$K_b = 0 – 1$	parameter for stiff or soft wheelset guidance	

Some examples:

$K_b \approx 0$	Rc loco
$K_b \approx 0.1$	Passenger coach with stiff MD bogies
$K_b \approx 0.8$	Passenger coach with soft ASEA bogies
$K_b \approx 0.9$	Two axle freight wagon with UIC double link suspension
$K_b \approx 0.8$	Freight wagon with Y25 bogie
$K_b \approx 0.9$	Freight wagon UIC link suspension bogie

6.6.1.4 Gradient resistance (D_g)

In railway contexts, the track's gradient S is often expressed per mille (‰) and the resistance is calculated as:

$$D_g = m_T \cdot g \cdot \frac{S}{1000}$$

where

m_T	Train weight	[kg]
g	Gravitational acceleration	[m/s^2]
S	Track gradient	[‰]

6.6.1.5 Total running resistance (D) and power demand

Total running resistance is given by the following equation

$$D = D_r + D_a + D_c + D_g$$

The needed tractive or braking force is expressed as

$$F = m_a \cdot a + D$$

where m_a is the train's equivalent dynamic mass and a is the acceleration.

The output power, P, is given by the following equation

$$P = F \cdot v$$

where v is the velocity.

6.6.2 Available tractive effort

The available tractive power is determined by two factors:

- The available adhesion, i.e. the coefficient of adhesion utilisation that can be obtained
- The tractive effort that the train's propulsion system can provide as function of speed

The possible adhesion utilisation may vary considerably depending on the contact conditions between wheel and rail and how well the vehicles tractive power can be regulated to utilize the available adhesion.

6.6.2.1 Adhesion

Adhesion is defined as the quotient between longitudinal and vertical wheel and rail contact forces, and can be regarded as the part of friction that can be used for traction or braking. The adhesion level will be lower or higher depending on whether there are substances between the wheel and rail, like water, oil or sand. If the rail is wet, the adhesion will be lower, and if for example there is sand, the adhesion will be higher. Examples of adhesion curves are shown in Figure 6.18.

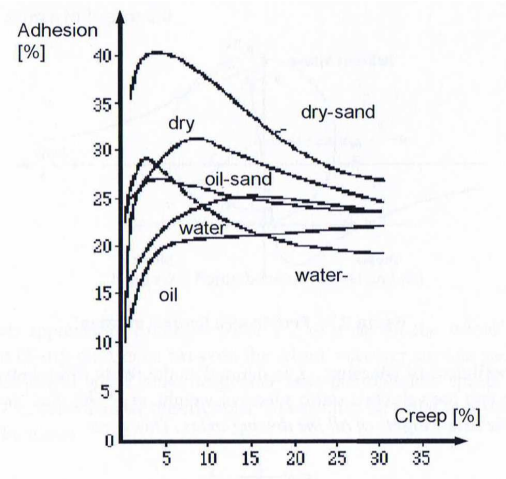


Figure 6.18: Examples of adhesion curves [71]

In dry wheel-rail contact conditions at speeds up to 70-100 km/h, the adhesion level is usually around 0.25-0.35. For wet or otherwise contaminated rails the adhesion is lower, however, the level can be restored, at least to the order of 0.25, by injecting sand in the wheel-rail interface.

6.6.2.2 Tractive effort

A vehicle's tractive power varies with its speed. A principal tractive effort diagram is shown in Figure 6.19 with the restrictions imposed by the motors characteristics. The solid lines represent the maximum tractive power that the propulsion system can generate. Some system, for instance electric motors, can usually be overloaded quite substantially for short periods without overheating. Internal combustion engines, i.e. diesel engines, do not normally have this ability. The dashed curve represents max continuously available tractive effort.

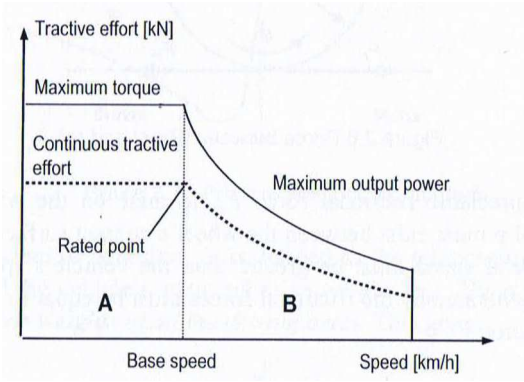


Figure 6.19: Typical tractive effort diagram [71]

In Table 6.1 some examples of data for European locomotives are shown.

The indicated power is the continuous power at the wheel rim. Hence, the power indicated for the diesel locos in this section is approximated to be only 80% of the diesel engine rating, due to auxiliary needs and losses in the electrical and mechanical transmission.

Table 6.1: Sample of data for European locomotives in service [72]

Type	Max tractive effort (kN)	Axle-arrangement	Power[1] (kW)	Weight (t)	Max speed (km/h)	Operator
Electric						
152	300	Bo′Bo′	6 400	86	140	Railion
182	300	Bo′Bo′	6 400	85	230	Railion
185	300	Bo′Bo′	5 600	84	140	Railion
EG 3100	400	Co′Co′	6 500	129	140	Railion Denmark
26 000	320*	Bo′Bo′	5 600	89	200	SNCF-Fret
27 000	350*	Bo′Bo′	4 200	89	140	SNCF-Fret
36 000	320*	Bo′Bo′	5 600	89	200	SNCF-Fret
Diesel						
232	294	Co′Co′	1 760	no info	120	Railion
294	231	Bo′Bo′	650	no info	40/80	Railion
66 000	167*	Bo′Bo′	820	no info	120	SNCF-Fret
72 000	362*	Co′Co′	2 120	no info	85	SNCF-Fret

1. Continuous power. On German locomotives, the maximum power is usually the same as the continuous.
* Information provided by www.railfaneurope.com (i.e. not SNCF).

6.6.3 Braking

6.6.3.1 Introduction

The train braking system is designed to ensure that the train's speed can be reduced or maintained on a slope, or that the train can be stopped within the allowable braking distance. The braking performance is mainly influenced by the braking power, train mass, rolling resistance, speed and available adhesion.

European freight wagons generally have pneumatically controlled and activated brake blocks. For some applications disk brakes are used. Examples of block and disk brakes are shown in Figure 6.20.

In this section the performance of these systems is discussed.



Figure 6.20: Tread and disk brakes.

6.6.3.2 Braking performance and limitations

Brake system for freight wagons must fulfil requirements in TSI [78]. Braking performance is determined both by the deceleration profile and the braked mass percentage (λ). The deceleration profile and equivalent build-up application time T_e are shown in Figure 6.21. There are four different standardized modes for brake application (G, P, R and EP). Equivalent build-up application time T_e for G and P braking modes are given in Table 6.2.

- **G braking mode**: brake mode used for freight trains with specified brake application time and brake release time.
- **P braking mode**: brake mode for passenger and freight trains with specified brake application respectively release time and brake mass percentage.
- **R braking mode**: brake mode for passenger trains and fast freight trains with brake application and release time as for braking mode P but with higher brake mass percentage.
- **EP brake (indirect Electro-pneumatic brake)**: assistance to indirect air brake by means of electrical train command and electro-pneumatic valves on the vehicles.

Demands on braking performance are shown in Table 6.2.

The braked mass marked on a wagon and the corresponding braked mass percentage λ, i.e. the quotient between braked mass and vehicle weight, indicates the braking power for this specific wagon when it is coupled in a 500 m long train that is operated in P braking mode.

The braked mass is determined via calculation or test. The procedure for this is described in Appendix S of TSI freight wagon and the relation between the calculated or tested stopping distance, S, and braked mass percentage, λ, is shown in Figure 6.21 [78].

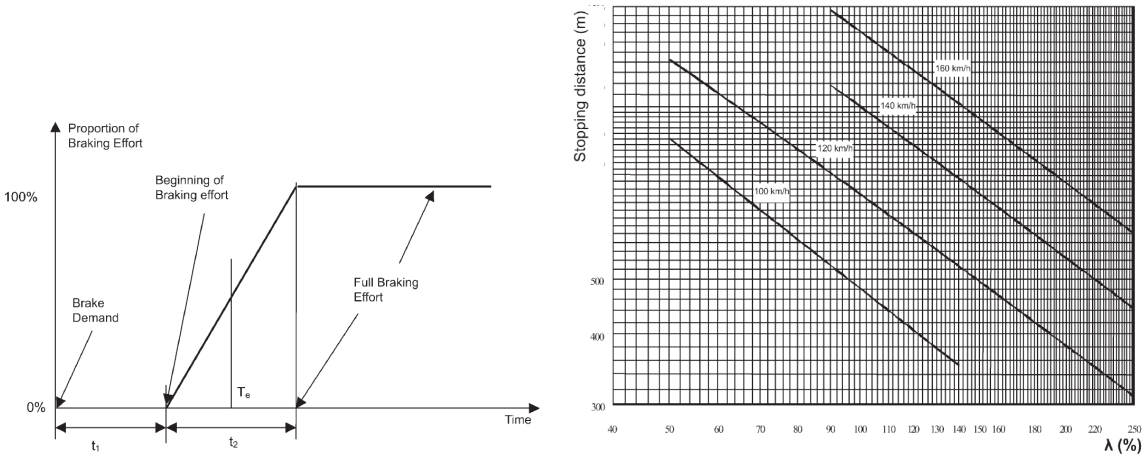


Figure 6.21: Deceleration profile, $T_e=t_1+t_2/2$, and stopping distance as function of braked mass percentage [78].

For block and disk brakes the performance is limited by the available adhesion. To reduce the risk of wheel flats low adhesion utilization is used for standard brake systems for freight wagons. For enhanced performance wheel slide protection (WSP) shall, according to TSI [78], be used for the following types of wagons;

- Wagons equipped with brake blocks made of cast iron or sintered material, for which the maximum mean utilization of adhesion (delta) is greater than 12% ($\lambda \geq$ 135%).
- Wagons equipped with disc brakes only, for which the maximum utilization of adhesion is greater than 11% and less than 12% ($125 < \lambda < 135\%$).
- Wagons with maximum operating speed ≥ 160 km/h.

Table 6.2: The minimum braking performance for different wagon types [78].

Braking Mode - T_e range (s)	**Wagon type**	**Command Equipment**	**Load**		**Requirement for running speed at 100 km/h**			**Requirement for running speed at 120 km/h**		
					Maxi	**Mini**		**Maxi**	**Mini**	
Braking mode "P" – $1.5 \leq T_e \leq 3$ s	All	All	Empty			**A** (7)	**B** (8)		**A**	**B**
				S	480	390	380	700	580	560
				λ (1)	100	125	130	100	125	130
				γ (1)	0.91	1.15	1.18	0.88	1.08	1.13
	"S1" (2)	Empty/load device	Intermediate load	**S**	810	390	380			
				λ	55	125	130			
				γ	0.51	1.15	1.18			
			Loaded (maximum =	**S**	700	480 (5)	480			
				λ	65	100	100			

			22.5 t/axle)	γ	0.60	0.91	0.91		
	"S2" (3)	Variable load relay	Loaded (maximum = 22.5 t/axle)	**S**	700	480 (5)	480		
				λ	65	100	100		
				γ	0.60	0.91	0.91		
	"SS" (4)	Variable load relay	Loaded (maximum = 22.5 t/axle)					**A**	**B**
							S	700 (6)	700
							λ	100	100
							γ	0.88	0.88
Braking mode "G" – 9≤T_e≤15 s				There shall be no separate assessment of the braking power of wagons in position G. A wagon's braked mass in position G shall be the same as braked mass in position P.					

(1) S is obtained according annex S. [m]

- "λ" = ((C/S)-D) according annex S. [%]
- "γ" = ((Speed (Km/h))/3.6)^2/(2x(S-((T_e)x(Speed (Km/h)/3.6)))) with T_e = 2 sec. [m/s^2]

(2) A wagon "S1" is a wagon with empty/load device.
(3) A wagon "S2" is a wagon with a variable load relay.
(4) A wagon "SS" shall be equipped with a variable load relay.
(5) The maximum mean retardation force admitted (for running speed at 100 km/h) is 18x0.91 = 16.5 kN/axle. This value comes from the maximum braking energy input permitted on a clasp braked wheel with a nominal new diameter in the range of [920 mm; 1 000 mm] during braking (the brake mass shall be limited to 18 tonnes). Wheels with a nominal new diameter (<920 mm) and/or push brakes shall be accepted in accordance with national rules.
(6) The maximum mean retardation force admitted (for running speed at 120 km/h) is 18x0.88 = 16 kN/axle. This value comes from the maximum braking energy input permitted on a clasp braked wheel with a nominal new diameter in the range of [920 mm; 1 000 mm] during braking (the brake mass shall be limited to 18 tonnes). Wheels with a nominal new diameter (<920 mm) and/or push brakes shall be accepted in accordance with national rules.
(7) Case A = composite blocks.
(8) Case B = all cases except for composite blocks.

Block braking imposes a thermal loading on the wheels [78, 79, 80, 81]. Combinations of axleload, speed and pre-signalling distance that give the same resulting thermal stress are shown in Figure 6.22. Example of a standard table used for signalling design is shown in Table 6.3. The longer pre-signalling distances that generally exist on rail networks for mixed traffic cannot be used for freight trains to increase speed or axleload as parts of the network, i.e. sidings, are designed given the higher braking performance of passenger vehicles, c.f. Table 6.3.

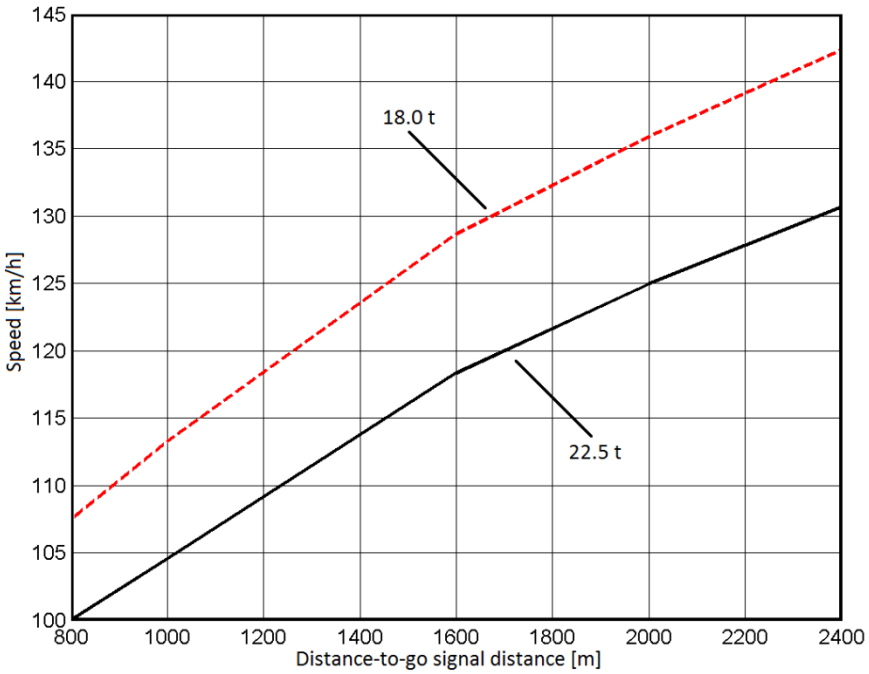


Figure 6.22: Speed as a function of pre signal distance for different loads [78].

Minimum deceleration [m/s²]											
Train speed limit [km/h]	Equivalent time of application [s]										
	3	4	5	6	7	8	9	10	11	12	13
40	0,43	0,43	0,43	0,43	0,43	0,43	0,43	0,43	0,45	0,48	0,50
50	0,43	0,43	0,43	0,43	0,43	0,43	0,43	0,43	0,45	0,48	0,50
60	0,46	0,46	0,46	0,46	0,46	0,47	0,48	0,48	0,49	0,50	0,51
70	0,48	0,48	0,48	0,48	0,48	0,49	0,50	0,51	0,52	0,52	0,53
80	0,59	0,59	0,59	0,59	0,59	0,61	0,62	0,63	0,65	0,66	0,68
90	0,61	0,61	0,61	0,61	0,61	0,62	0,64	0,65	0,66	0,68	0,69
100	0,64	0,64	0,64	0,64	0,64	0,65	0,66	0,67	0,68	0,70	0,71
110	0,66	0,66	0,66	0,66	0,66	0,67	0,68	0,70	0,71	0,72	0,74
120	0,66	0,66	0,67	0,68	0,69	0,70	0,71	0,72	0,74	0,75	0,76
130	0,73	0,75	0,76	0,77	0,79	0,80	0,82	0,83	0,85	0,87	0,89
140	0,83	0,84	0,86	0,88	0,90	0,92	0,94	0,96	0,98	1,02	1,06
150	0,89	0,91	0,92	0,94	0,96	0,99	1,01	1,03	1,07	1,12	–
160	0,91	0,93	0,94	0,96	0,98	1,00	1,03	1,05	1,07	1,12	–
170	0,97	0,99	1,01	1,03	1,05	1,07	1,10	1,12	–	–	–
180	1,03	1,05	1,07	1,09	1,12	1,14	–	–	–	–	–
190	1,03	1,05	1,07	1,09	1,12	1,14	–	–	–	–	–
200	1,03	1,05	1,07	1,09	1,12	1,14	–	–	–	–	–

Table 6.3: Deceleration, requirement for signal design [79].

6.6.4 Conclusions

In this chapter we have discussed traction and braking while increasing performance of freight traffic. Limiting factors for traction are available adhesion and tractive power to maintain high speed in gradients. Block braking is limited by thermal impact of the wheels. Increased pre-signalling distances may be used to enhance performance of freight trains, at least to some extent on dedicated freight routes.

It can be concluded that acceleration can be set for freight trains to a maximum value of 0.4 m/s^2, while deceleration requirements have been analysed and are detailed in Table 6.3, strictly depending on signalling constrains.

7. SUBTASK 2.4.4 – AERODYNAMICS REQUIREMENTS

7.1 Introduction

When a train moves it displaces air and causes air to flow around it, establishing regions of high and low pressure, eddies, resonance, and turbulence. The energy required compressing and moving air (the 'aerodynamic drag') reduces the energy available for traction; minimising the effect of the train on the air (if this can be done without significantly increasing the train's mass) will improve the efficiency of the train.

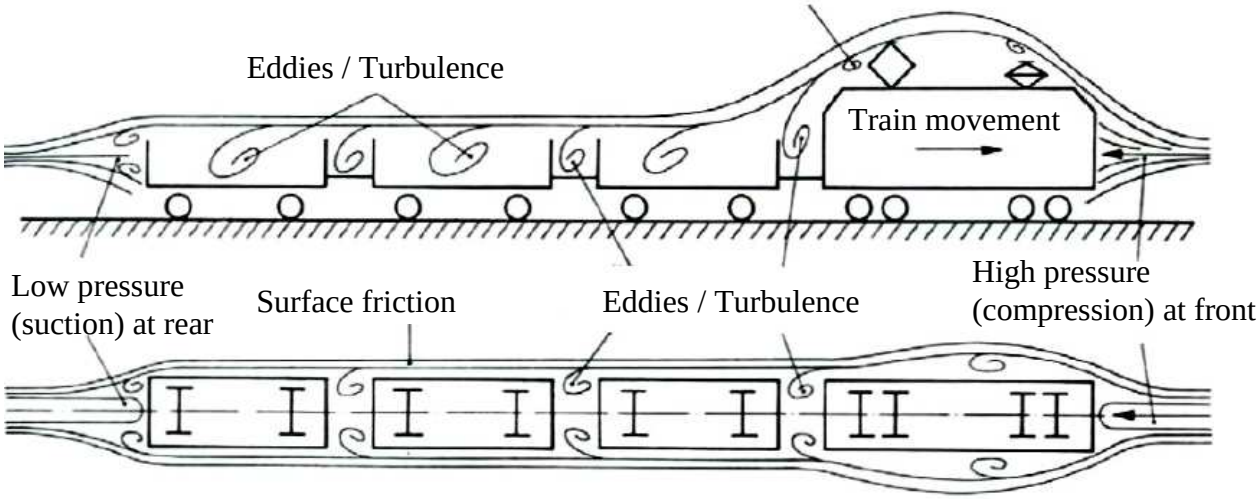


Figure 7.1: Schematic Air Flow Around Freight Train (After [45])

Methods of reducing aerodynamic drag and their effects are considered in Section 7.2.

Other aerodynamic effects are associated with the pressure differentials and wind induced by the train; these are mentioned in Section 7.3.

7.2 Aerodynamic drag

7.2.1 Context

Reducing the aerodynamic drag of freight vehicles has been recognised as an area that warrants attention as the payback times for some modifications are expected to be relatively short. The 'EVENT' project was commissioned by UIC [32] to provide an overview of energy efficient technologies; it recommended the optimisation of the aerodynamics of freight train configurations. Both this report and a comprehensive American study on reducing greenhouse gasses [52] recommended addressing the unfavourable profile of freight trains, unshielded space between vehicles, and lack of covers on empty wagons.

7.2.2 Significance

The resistance to motion (R_1) of a train travelling on a straight level track with no ambient wind is commonly approximated (in a 'top-down' analysis) by a quadratic equation in the train speed, V_{tr}:

$$R_1 = C_1 + C_2.V_{tr} + C_3.V_{tr}^2$$

Equation 2

"Where $C_1 + C_2.V_{tr}$ denotes both the mechanical resistance and the air momentum drag due to cooling air for the locomotives and air conditioning of the trailer cars; $C_3.V_{tr}^2$ denotes the aerodynamic resistance due to pressure drag and skin friction drag" [7]. **Equation 2** is also known as the Davis equation [11], though this equation had specific forms for C_1 and C_3. More detailed, 'bottom-up', analyses (summarised for example in [43], [44], [55], see also [9]) include the effects of acceleration, track slope, and wind speed and direction. They introduce additional quadratic terms in speed to determine the rolling resistance, but these terms' contribution is negligible in comparison with the aerodynamic term.

The constants in **Equation 2** depend both on the train and on the quality of the track, although the influence of the track is often not considered[1]. Methods for determining the values of the constants are described in [7] and [29]. Relevant values are available in various sources including [2], [27], [43], [44], and [9]; reference [27] claiming that "Through the methods collected and illustrated in this report, it should be possible to make a reasonable estimate of the driving resistance parameters for most kinds of trains encountered in operation" . **Equation 2** and its generalisations are the basis of many simulators of train dynamics that are used for time-tabling trains (see e.g. [12], [18], [43]).

It is clear that aerodynamic resistance, proportional to V_{tr}^2, will become more dominant at higher speeds (it is estimated to be about 80% of the total resistance at 300 kph [44]). Most train aerodynamics research has thus focussed on higher speeds, typically faster than 200 kph. The vehicles that operate at these speeds are passenger stock. These typically have lower aerodynamic drag than freight vehicles (smoother exteriors, smaller inter-vehicle gaps, streamlined ends), but it has been shown that relatively small changes can be economically justified[2] (e.g. enlarging inter-carriage covers on HST [36], further streamlining the Shinkansen [24], [21], bogie fairings [30]). Another aspect of high-speed operation is that the noise associated with turbulent airflow becomes unacceptable and this has been a major driver for streamlining of the pantograph [22], [24], [57].

Most freight trains operate slower than passenger trains, typically below 120 kph. At these speeds the aerodynamic resistance of passenger stock would be a smaller fraction of the total resistance to motion than at higher speeds (e.g. data in [43] shows that, for passenger stock, the aerodynamic resistance varies between 57% and 68% of the total resistance at 120 kph, rising to between 64% and 74% at 140 kph). However, aerodynamic features have not been considered in the design of freight trains so here the power required to overcome aerodynamic drag would be more significant if it were not for the larger mechanical resistance of freight trains. Stolz and Carrillo Zanuy [45], [9] studied container trains that were about 510m long, weighing 1200t, and travelling at up to 100 kph over a fairly curvy, hilly route. They predicted that about 33% of the train's energy would be used to overcome air resistance; at 120 kph this would increase to about 38% and at 140 kph 41%. On flatter or straighter routes the fraction of energy used in overcoming aerodynamic drag would be even higher. The study [27] concluded that above about 60 kph aerodynamic resistance was the largest contribution to the resistance to motion.

[1] The track's influence is in the energy absorbed by a vehicle's suspension when moving over track irregularities and in energy lost in the hysteresis of track substrate (theoretical analysis in [6], tests reported in [29], results in [2]).

[2] It has been suggested that the high cost of retro-fitting can mean that introducing changes to existing rolling stock cannot be economically justified [16].

7.2.2.1 Tunnels

The aerodynamic drag on a vehicle is generally larger when it is passing through a tunnel than in the open (see e.g. [43], [44]). This is due to the compression of a large quantity of air and the reflections of pressure waves from tunnel sides and ends. However, for freight vehicles the increase may not occur: there are no side-winds so the increased drag associated with them (see below) can be neglected; the relative velocity of the air experienced by the vehicles is significantly reduced as the passage of the train causes the air in the tunnel to move along the tunnel [5].

Whatever the effect, the proportion of its journey that a freight train spends in tunnels is small[3], so we propose that the effect of tunnels can be ignored.

7.2.2.2 Wind

The aerodynamic drag when there is a wind is found by using the train speed relative to the wind for V_{tr} in **Equation 2**. Conventionally this relative speed is calculated using a vector sum of wind velocity and train velocity [8]. Lukaszewicz [29] found that using a wind speed that varies with height above ground in the calculation gave results in far better agreement with test results than assuming the speed did not vary with height. His calculation assumed that the air within 0.2m of the ground was not moving and, above this height, a logarithmic speed variation was fitted to the measured wind speed at the appropriate height. This result implies that the aerodynamic drag of the bogies is less affected by ambient wind than the upper body.

The effect of side winds on aerodynamic drag has been measured in series of wind-tunnel tests in Germany [53], [37] and America [13], [15], [35]. The tests reported in [37] used a container wagon and found that the wind angle that gave the maximum drag (and the drag itself) varied with wind speed between 15° and 25° (larger angles and drag coefficients at higher speeds). The tests reported in [53] represented the variation of drag coefficients with angle as a Fourier series (the terms being cosines of even multiples of the wind angle, α, up to $\cos(10\alpha)$) and reported that the maximum drag occurred at an angle of between 10° and 40° depending on the vehicle type. The American study derived seventh order polynomials in the wind angle (reported in [2]). Additional results in [46] and [47] show that for coal hoppers the drag increases as wind angle increases up to a wind angle of 10°. The small maximum angle in these latter studies was calculated as the angle in the triangle defined by the mean American wind speed of 7 mph acting at right angles to a vehicle travelling at 40 mph.

A more serious effect of side-winds is to derail vehicles or dislodge containers from the vehicles that were carrying them [39]. In the UK a minimum container weight of 1.6 tonne is required when containers are not locked to be vehicle body, but rest on (UIC) spigots that are designed to lock containers if they slide in the presence of strong winds ([41]). If gusts of over 113kph or a four-hour period of gusts between 96 and 111 kph are forecast all vehicles are restricted to 80kph operation, while a forecast of a gust with a speed of 145 kph or over would result in all services being suspended in the affected area [33].

7.2.3 Analysis

The aerodynamic resistance (the $C_3.V_{tr}^2$ of **Equation 2**) is commonly written as

$C_D(\frac{1}{2}\rho A V_{tr}^2)$

[3] Less than 3.2% of the route of any country in the EU is in tunnels apart from 6.5% of the Italian railway [31] and these are predominantly high-speed lines. Only 1.2% of the UK's SustRail routes are in tunnels [48].

Equation 3

where C_D is the aerodynamic drag coefficient, ρ is the density of air (standard value is 1.225 kg/m³ ([23], [8]), but depends on pressure, temperature, and humidity), A is the (effective) area of the front of the train (about 10m²). Note that the 'top down' approach neglects any other quadratic contributions to the resistance to motion. The aerodynamic drag coefficient (or the multiple of this and the effective area, C_D.A, called the 'drag area') is considered to be the sum of separate terms that represent different contributions to the drag. For example:

In [43] C_D is the sum of: a multiple of total length; a contribution from each wheelset; a contribution from each inter-vehicle gap; and the leading and trailing vehicles' contributions.

In [29] C_D.A is the sum of a constant (the leading and trailing vehicles' contributions) and a multiple of the train length. The multiple was found to depend on the proportion of the vehicles that were covered as opposed to 'open', reducing by almost half if all were covered.

For intermodal freight trains there are so many possible variations of container dimensions, vehicle types, and loading options that each vehicle may have different aerodynamic properties. The aerodynamic drag needs to be separated into contributions from each vehicle in the train ([53], [55]). This approach has been used to estimate the effect of changing types of vehicles [9] and to interpret results of wind-tunnel and computational fluid dynamics (CFD) experiments.

7.2.4 Options for reducing drag

Three categories are considered: streamlining vehicles, arrangement of containers on intermodal wagons, and speed. Note that reductions in drag are generally calculated at constant speed and with no cross wind. The percentage reduction in the force resisting movement of a whole train will be smaller as both the drag of locomotives and the mechanical resistance will be largely unchanged by the measures.

7.2.4.1 Streamlining vehicles

These design changes will have associated costs and benefits that will need to be assessed to determine whether they should be considered further in SUSTRAIL. The first five can be retro-fitted, while the last two are fundamental design changes.

1. **Smooth Sides and Top**: The drag that can be attributed to turbulence caused by the strengthening ribs on the exterior of freight wagons was studied in [35]. It was found that a reduction of up to 23% in drag was achievable. Similar streamlining options for SUSTRAIL vehicles include adding a flat cover on the deck of intermodal wagons (the openings that contribute to drag are evident in the bottom right image of Figure 7.2).

2. **Bogie Fairings**: Covers on freight vehicle bogies have been designed to reduce the noise associated with the operation of brakes [10]. The MetaRail project (see Figure 7.2) included adding covers over bogies of a rake of intermodal vehicles and running tests with them. For high-speed passenger stock the reduction in drag associated with covering the bogies was found (both experimentally and in full-scale trials) to be about 10% [30].



Figure 7.2: Bogie Shrouds from MetaRail [56] (these shrouds were scrapped in 2001)

3. **Smooth Underframe**: Bogie skirts reduce drag by improving air-flow under the vehicle (see Figure 7.3). This innovation is used for the fastest high-speed trains [34]. It has been suggested that having a smooth underframe (covering equipment with a smooth cover) could save up to 7.5% of the air resistance ([32]), though tests on high-speed trains ([14] reported in [38]) suggest that higher savings may be achievable.

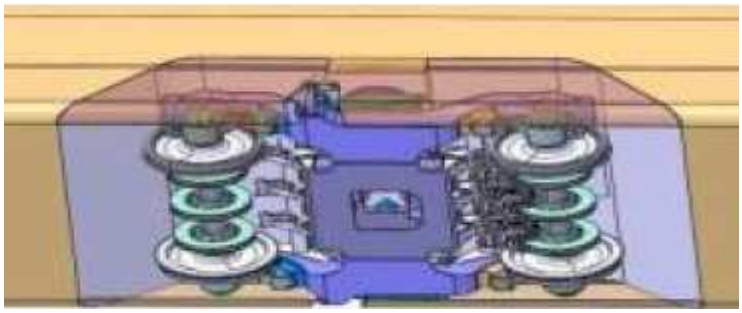


Figure 7.3: Bogie Skirt from Bombardier [34]

4. **Covering Hoppers**: The aerodynamic drag associated with open hopper wagons can be reduced by adding covers; extensive tests are reported in [54]. Calculations in [27] show that at high speeds it can be cheaper to pull laden wagons than uncovered empty ones! The drag can be significantly reduced even by adding vertical baffles within the vehicles [46]. Having tilted instead of vertical ends to covers has been shown to be

even more efficient [47]. However, the savings on average European journeys, calculated in [28], may be only about 3%.

5. **Streamlining the load**:
    a. The drag that can be attributed to the angular features on the sides of shipping containers was reported in [19] (mentioned in [35]). It was found that a smooth exterior to containers can reduce drag by 10%.
    b. There are patented 'bolt-on' fairings for the ends of containers, and curtains between containers, see e.g. [20].
6. **Lengthening Vehicle**: The Vel-Wagon project [9] considered changing the length of an intermodal vehicle to better accommodate the expected mix of container sizes expected on certain European routes. They found that an eighty-foot vehicle could provide a 14% reduction in aerodynamic resistance compared to a standard sixty-foot one.
7. **Reducing Inter-Vehicle Gaps**: The large gaps associated with buffers contribute to the aerodynamic losses. For this reason close-coupled wagons have been developed; "EcoFret" and "MegaFret" wagons that have respectively two and three sixty-foot decks with buffers only at the outboard ends. Experiments reported in [54] reveal a reduction of about 10% in drag coefficient as the gap between hopper cars was reduced from 1.87m to 0.65m.

7.2.4.2 Arrangement of containers on intermodal wagons

A number of loading algorithms have been proposed to reduce energy consumption by optimising the position of containers along a train; for a review see [40]. The objective is to provide advice to terminal operators on the best ordering of containers along a train. However, commercial constraints on operation can mean that containers arrive at the terminal too late to be placed in the optimum positions on the train.

It has been shown that reducing the gap between containers reduces the drag; the trailing container becomes better shielded by the first. Lai [26] states that if the gap exceeds 72" (1.83m) the trailing container does not benefit from being shielded (though the gap between vehicles including buffers is typically of about this size). Some of his data is given in Figure 7.4. Similar data is available in [35] for vehicles carrying two containers, one on top of the other; this arrangement is common in America.

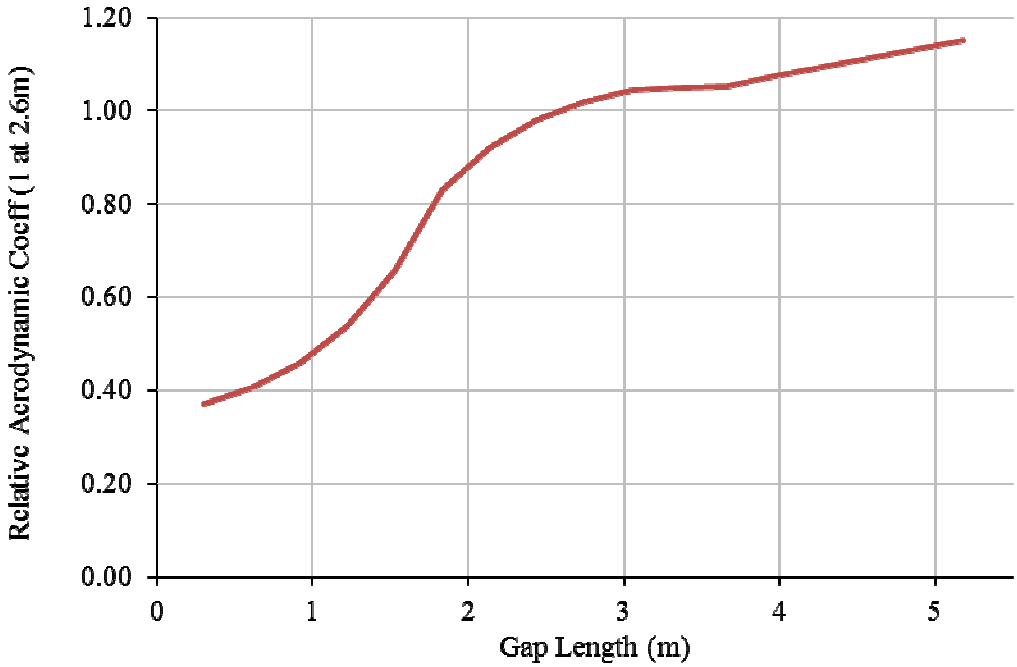


Figure 7.4: Effect of Gap Length on Relative Aerodynamic Coefficient (after [25])

It is clear using results from [53] (see e.g. [27]) that all containers should be as close together as possible and close to the locomotive. Ideally, no vehicle (or container on a vehicle) would have a larger cross-section than the one in front of it.

The effect of distance from front of train is considered in [25]; wind-tunnel results show that a gap at the front of a train will be associated with a larger drag than one of the same size further back (see Figure 7.5: Effect of Distance Along Vehicle (after [25])

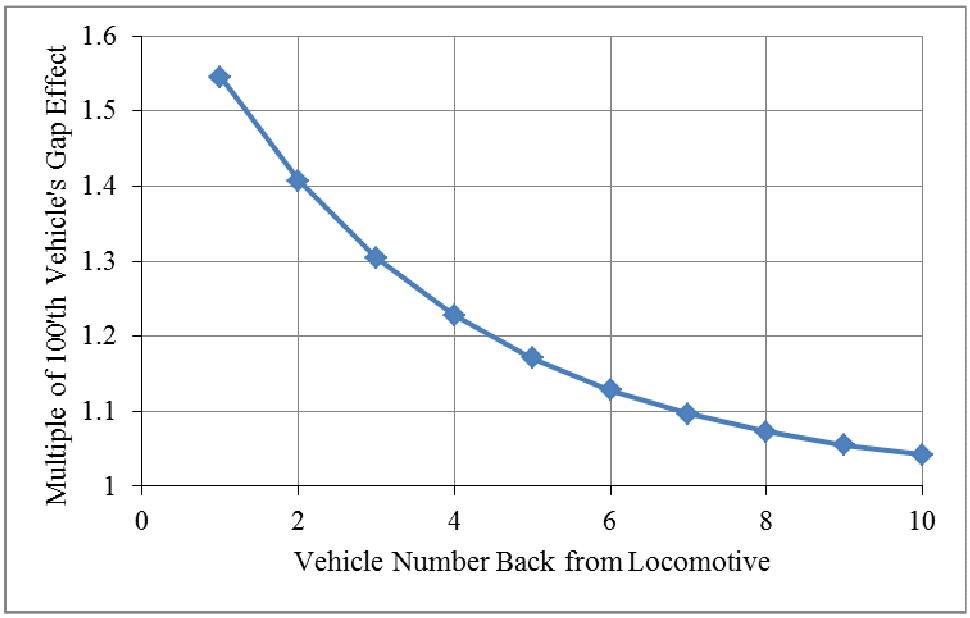


Figure 7.5: Effect of Distance Along Vehicle (after [25])

Adding empty containers to multimodal flat cars was analysed in [27]. They used the data from [53] and found that it would theoretically be more economical to carry an extra one or two empty (2.3 tonne) twenty-foot containers to fill the deck of a sixty-foot vehicle than to overcome the drag that would be caused by the additional flat faces of a load in two or one twenty-foot containers. The calculations were undertaken at constant speeds and neglected the extra time and cost for loading and logistics issues. However, the break-even speed was below 36 kph with a saving of between 8% and 30% in resistance to motion at 100 kph.

7.2.4.3 Speed

The aerodynamic drag increases with the square of the speed, so the slower that a vehicle travels the less energy it will consume. The issue of economical driving is receiving considerable attention [32], [29]. The simplest approach would be to allow freight to travel at a low constant speed, but with a mixed-traffic railway travelling at full speed between halts in passing loops is required to allow passenger vehicles to maintain timetables.

7.3 Other aerodynamic effects

Other aerodynamic effects are mentioned here. The UK's Railway Safety and Standards Board has published a review of recent work in these areas [3] with comprehensive bibliographies.

7.3.1 Safety in cross-winds

This was mentioned above. There have been numerous examples worldwide of trains derailing or containers becoming detached due to high winds. A recent analysis [17] has revealed that the complex shape of an intermodal freight train compared to a passenger train gives rise to complex turbulence. This paper also concludes that the side-force on double-stacked containers can be less than that on a single-stacked container, but [1] states the latter may be underestimated.

7.3.2 Force due to passing-by of two trains

When one train passes another it generates a pressure pulse that will affect the latter train. In the UK the design force is 1.44 kPa [42]. This effect is particularly significant in tunnels [38]. The effect on freight vehicles being passed by high-speed trains is discussed in [3].

7.3.3 Winds induced by train

Trains passing through stations cause gusts of wind that can affect the safety of passengers on platforms; this safety issue is covered by European Technical Standards for Interoperability (TSI, [51], [50]). A limit on the speed of the wind induced by the passage of a train measured at a height of 1.2 m above a platform at a distance of 3m from track centre is specified. For passenger trains travelling faster than 160 kph ([51]), and for high-speed trains at their maximum speed (or at 200 kph if this is lower) ([50]) the limit is 15.5m/s; no corresponding restriction is currently quoted for freight. This issue is discussed in [3] with more detail in [49].

A particular concern for freight is the low-pressure behind a container or other bluff body that acts to drag people and objects toward the track (a list of such incidents is included in [49]). It was found that the wind speed of 10.3m/s (measured at 1.5m from the platform edge) associated with a freight train moving at 120 kph is comparable to that for a passenger train travelling at 225 kph. The highest slipstream gust speeds reported in [4] (measurements were

made for a wide range of conventional and high-speed rolling stock at platforms throughout Europe) were for freight trains and could exceed 20 m/s.

7.3.4 Aerodynamic noise

The report for noise (Section 8, Subtask 2.4.5 below) indicates that at the speeds considered (100 kph – 140 kph) the aerodynamic noise does not predominate.

7.4 Conclusions

The aerodynamics of freight trains has been considered, primarily from the perspective of the associated drag. A series of options to improve the aerodynamics have been listed and these need to be considered further as part of SUSTRAIL WP 3 “The freight train of the future”.

For intermodal wagons, operational factors (vehicle choice and loading regime) can have significant and immediate benefits.

8. SUBTASK 2.4.5 – NOISE REQUIREMENTS

Over twenty million people in Europe are affected by rail noise. Noise pollution is of increasing importance in railway operation as EU legislation raises awareness of this issue.

Using EU legislation and other existing guidelines for railway operation, the duty requirements for future vehicle and track systems will be specified. Sources of noise to be considered will include rail-wheel interface, brakes, engine, and aerodynamic noise.

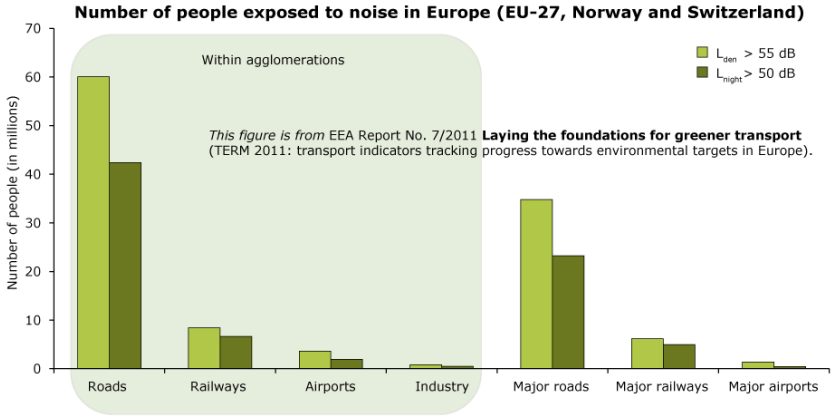


Figure 8.1: Number of people in Europe exposed to high noise levels, within and outside agglomerations (urban environments); breakdown by transport mode

8.1 Legislation

8.1.1 European Noise Directive (END)

Directive 2002/49/EC 'relating to the assessment and management of environmental noise', also known as the European Noise Directive, requires Member States to provide noise maps and plans for reducing noise levels:

> *(q) 'noise mapping' shall mean the presentation of data on an existing or predicted noise situation in terms of a noise indicator, indicating breaches of any relevant limit value in force, the number of people affected in a certain area, or the number of dwellings exposed to certain values of a noise indicator in a certain area;*

For railways, the initial requirements are to study agglomerations and major railways, where:

> *(k) 'agglomeration' shall mean part of a territory, delimited by the Member State, having a population in excess of 100 000 persons and a population density such that the Member State considers it to be an urbanised area;*
>
> *(o) 'major railway' shall mean a railway, designated by the Member State, which has more than 30 000 train passages per year;*

The first stage of the mapping required only agglomerations with over 250,000 people and railways with more than 60,000 train passages per year.

Noise disturbance is to be assessed according to time of day, divided into day-evening-night where, typically, day is 7 a.m. – 7 p.m., evening is 7 p.m. – 11 p.m., and night is 11 p.m. – 7 a.m. A-weighted (i.e., adjusted for human perception and response to frequencies) long-term averages for noise measurements and/or predictions are required for each of the three time periods (L_{day}, $L_{evening}$ and L_{night}), and a combined noise measure for the whole 24-hour day (L_{den}) is defined which includes the greater sensitivity to noise during the evening and night:

$$L_{den} = 10\log\left(\frac{1}{2}10^{\frac{L_{day}}{10}} + \frac{1}{6}10^{\frac{L_{evening}+5}{10}} + \frac{1}{3}10^{\frac{L_{night}+10}{10}}\right)$$

Special consideration needs to be given to schools, hospitals, etc., and areas such as natural parks:

> *(m) 'quiet area in open country' shall mean an area, delimited by the competent authority, that is undisturbed by noise from traffic, industry or recreational activities;*

These noise maps are to be used for identification of Important Areas, i.e., areas where a large number of people are affected by high noise levels, and for identifying within these the First Priorities for noise mitigation.

An example of noise mapping and identification of important areas is given in Figure 8.2 for central London. In England, First Priority Locations are identified as places where $L_{Aeq,18h}$ (this noise indicator covers the period between 6 a.m. and midnight) exceeds 73 dB(A).

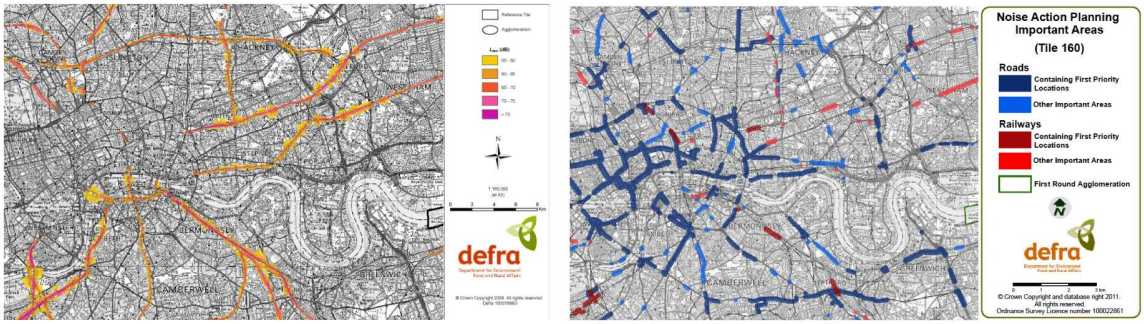


Figure 8.2: Railway noise in central London. Left: Noise map showing noise levels along major railways. Right: Important Areas marked in blue for roads and red for railways

The European Topic Centre on Spatial Information and Analysis (ETC-SIA) and the European Environment Agency (EEA)[4] have been responsible for collecting END data from Member States and providing an online interface (Figure 8.3), the Noise Observation and Information Service for Europe (NOISE)[5].

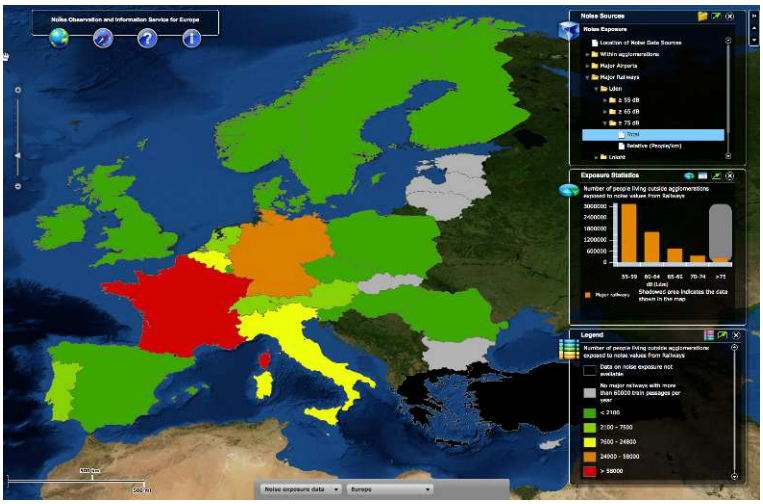


Figure 8.3: Noise Observation and Information Service for Europe: Number of people living outside agglomerations exposed to noise levels over 75 dB(A), by Member State.

8.1.2 The First Railway Package

The First Railway Package is a collection of European directives that together define the roles of railway undertakings, infrastructure managers, capacity allocation and access charges; and establishes rail regulators in the Member States:

Directive 2001/12/EC

[4] http://www.eea.europa.eu/themes/noise

[5] http://noise.eionet.europa.eu/

amending Council Directive 91/440/EEC on the development of the Community's railways

Directive 2001/13/EC

amending Council Directive 95/18/EC on the licensing of railway undertakings

Directive 2001/14/EC

on the allocation of railway infrastructure capacity and the levying of charges for the use of railway infrastructure and safety certification

Currently there is no explicit mention of noise or any requirement to include differentiation of access charges according to noise levels. However, there is a proposal, published as COM(2010) 475 on 17/09/2010, to recast the First Railway Package by merging and elaborating on Directives 2001/12/EC, 2001/13/EC and 2001/14/EC, and the draft version of the new legislation allows differential track access charges according to noise levels, with reference to TSI Noise. In addition, following the first reading in the European Parliament on 16/11/2011, the draft was revised to allow compensation for retrofitting vehicles with low-noise technology. (On 3rd July 2012, the European Parliament approved a compromise text in which the application of noise differentiated track access charging is optional[6].)

Recast of the First Railway Package, Article 31(5):

Infrastructure charges shall be modified to take account of the cost of noise effects caused by the operation of the train in accordance with Annex VIII, point 2. Such modification of infrastructure charges shall allow for compensation for investments in retrofitting rail vehicles with the most economically viable low-noise braking technology available. Member States shall ensure that the introduction of such differentiated charges shall not have any adverse effect on the financial equilibrium of the infrastructure manager. The rules for European co-funding shall be modified so as to allow for the co-funding for retrofitting rolling stock to reduce noise emissions as it is already the case for ERTMS.

Recast of First Railway Package, Annex VIII, pt. 2:

Noise-differentiated infrastructure charges referred to in Article 31(5) shall meet the following requirements:

(a) The charge shall be differentiated to reflect the composition of a train of vehicles respecting limit values for noise set by Commission Decision 2006/66/EC (TSI Noise).

(b) Priority shall be given to freight wagons.

(c) Differentiation according to the noise emission levels of freight wagons shall allow the payback of investments within a reasonable period for retrofitting wagons with the most economically viable low-noise braking technology available.

(d) Further elements to differentiate charges may be considered such as:

i) time of day, in particular night-time for noise emissions
ii) train composition with an impact on the level of noise emissions;
iii) sensitivity of the area affected by local emissions;
iv) further classes for noise emissions significantly lower than the one referred to under point (a).

Currently, there is no reference to 2008/232/CE, the TSI for high-speed rolling stock, which applies to vehicles with maximum speed over 190 km/h. The noise limits specified in the 2006/66/EC TSI Noise agree with the limits in the recent 2011/229/EC; the next revision of TSI Noise, due 2013, will merge high-speed and conventional rail.

8.1.3 Technical Specification for Interoperability

Directive 2006/66/EC (TSI Noise)

concerning the technical specifications of interoperability relating to the subsystem 'rolling stock – noise' of the trans-European conventional rail system

Directive 2011/229/EC was a 'limited revision' of the TSI Noise, and there is no change in limit values from the 2006 TSI Noise. Work on a full revision started in 2011 (due 2013), and will look at lowering pass-by noise limits, and at squeal, brake noise limits, and infrastructure.

The indicator for pass-by noise is the A-weighted equivalent continuous sound pressure level $L_{pAeq,Tp}$ measured over the pass-by time at a distance of 7.5 m from the centre of the track, 1.2 m above top of rail. (Measurement of noise is in accordance with EN/ISO 3095.)

[6] 'Recast of the First Railway Package: the Parliament's plenary endorses the agreement with the Council,' http://www.cer.be/media/2337_120703_Recast_EP_Council.pdf.

Freight wagons: 82-87 dB(A)
Locomotives & coaches: 80-85 dB(A)

These limits apply to new and upgraded rolling stock.

8.2 Noise sources and mitigation

The STAIRRS project did a cost-benefit analysis of noise abatement measures, and this is shown in Figure 8.4. This looked at both vehicle and infrastructure measures; retrofitting freight vehicles with quiet brakes provides a clear benefit in noise reduction at a low cost compared with infrastructure measures.

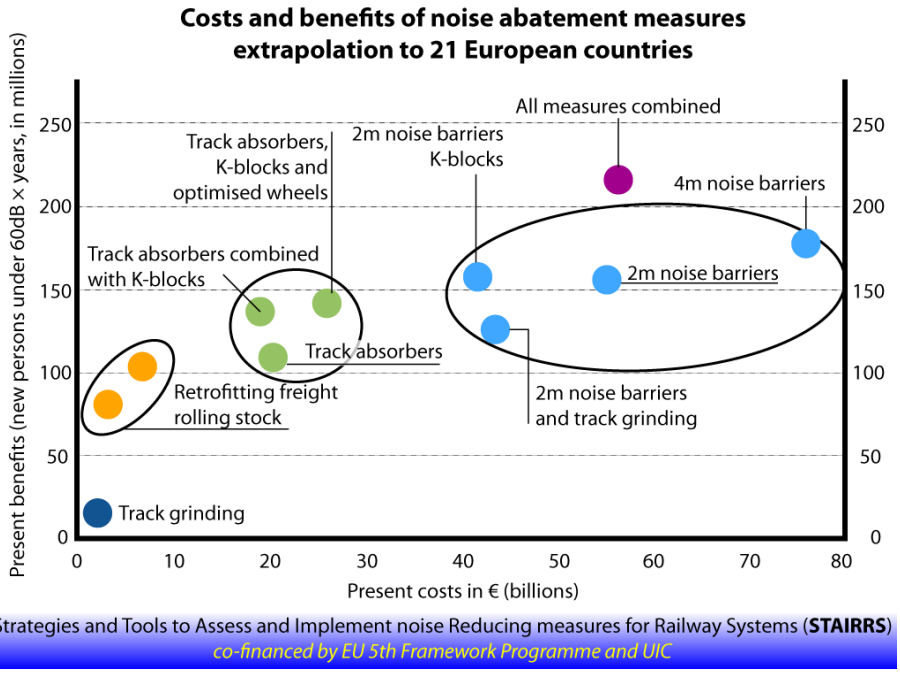


Figure 8.4: STAIRRS project cost-benefit analysis

8.2.1 Composite brake blocks

The introduction of noise-related track access charges (NRTAC) has been studied by UIC. These are the only track access charges linked to specific vehicles and routes and will require new tracking systems. NRTAC trials have taken place in Switzerland and the Netherlands, and Germany will be introducing a system in 2012 where a bonus is given to wagons newly retrofitted with low-noise equipment.

The introduction of composite brake blocks is generally seen as key to reducing freight noise levels. The majority of freight wagons in service use cast-iron tread brakes, but an alternative system, composite K-blocks, are homologated and available for retrofitting – where this is technically feasible. A newer alternative, composite LL-blocks, is cheaper and easier to retrofit, but is still in testing. Retrofitting costs are €1000-€5000 per wagon for LL-blocks, compared to €3000-€10000 per wagon for K-blocks[7].

In terms of life cycle costs (LCC), once brake block and wheelset maintenance are factored in, K-blocks are expensive compared to cast iron brake blocks, and LL-blocks are still an unknown. Composite brake blocks damage the wheels, causing problems with the equivalent conicity; sintered LL-blocks (56-68 Euro/block) behave especially poorly, but the organic LL-blocks are comparable to organic K-blocks (28-33 Euro/block).

Cast-iron brake blocks also produce a lot of iron dust, which makes vehicles dirty quickly, and can embed in composite brake blocks and increase the wheel profile wear rate. Composite brake blocks perform poorly in some weather conditions, and are not permitted in Finland, for example.

[7] See 'Implementation of noise-related track access charges,' the annex to 'UIC Status report and background information on noise-related track access charges,' but published separately. Both are available for download from the UIC website, http://www.uic.org/.

UIC is in charge of technical tests and certification required for approval of LL-blocks by the European Railway Agency (ERA). ERA plans also to establish a Working Party to set out specifications for brake blocks, and requirements for approval of composite brake blocks; this will feed into a revised TSI WAG[8].
In the EuropeTrain project[9], a UIC-led consortium is operating a real train fitted with a variety of brake blocks and monitoring technologies. As of 5th May, 2012, the train has completed 13 runs (163,000 km), taking it through several countries (from Italy to Sweden, and from France to Slovakia and Poland) and covering a wide variety of terrains and climates. Interim results indicate that block wear varies strongly with topography/climate, and that, so far, wagons which have developed a high equivalent conicity still comply with safety limits[10].

8.2.2 Principal Sources of Noise

Cast-iron brake blocks are a direct noise source during braking where brake squeal can be a major noise source. However, this tends to be a problem at specific locations only, on approach to stations and shunting yards. The main focus on replacing cast-iron brake blocks has to do with increased wheel roughness, which not only increases the rolling noise significantly but also increases wheel-rail interaction forces and consequent degradation of vehicle and track.
Briefly, the main sources of noise are:

- Rolling Noise
    - Wheel and rail surface roughness
        - Severe cases: out-of-round wheels & corrugated rails
    - Brake squeal (cast iron tread brakes are a major cause…)
    - Curve squeal
    - Vehicle suspension
- Aerodynamic Noise
    - Nose & leading bogie; pantograph (noise barriers generally don't block pantograph noise)
- Traction Equipment
    - Engines, Fans
- Structural Noise
    - Groundborne shock wave – 'boom' (the critical speed depends on soil / ground type)
    - Bridge re-radiation, especially steel bridges
    - S&C and jointed track

Broadly, the impact of noise sources depends on vehicle speed. Noise from traction and cooling systems dominate at low speeds (less than 30 km/h), and aerodynamic noise becomes the major source at high speeds (above 300 km/h). In the middle range, rolling noise is the dominant source, and this covers the range of operational speeds of freight wagons (see Figure 8.5).

[8] Piotr Rapacz, 'EU Rail Noise Policy – perspective of DG MOVE,' 7th UIC Noise Workshop, Paris, 8th November 2011.

[9] http://EuropeTrain.uic.org/

[10] Dr Stefan Dörsch, 'Conclusion of the first interim report (B 126 RP 43) and Project Status Report,' 7th UIC Noise Workshop, Paris, 8th November 2011.

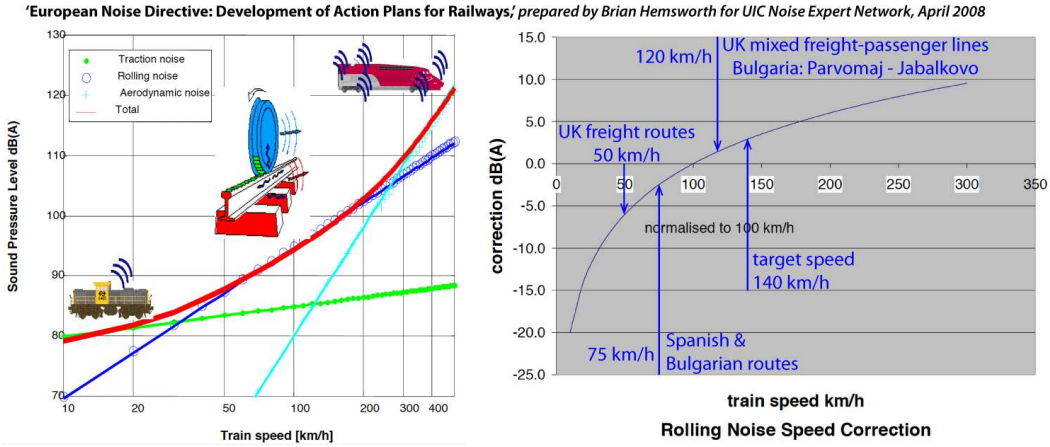


Figure 8.5: Dominant noise sources (left) and rolling noise correction (right) – dependence on vehicle speed.

8.2.3 The SUSTRAIL Wagon

For the range of operating speeds of the SUSTRAIL wagon, rolling noise will be dominant. One of the aims of the project is to increase the running speed from 120 km/h to 140 km/h (or higher), and this will increase the rolling noise. With the increasing pressure to decrease noise levels, this is a liability, and part of the SUSTRAIL solution, therefore, should be to introduce technological innovations that reduce noise emission. An obvious approach is to fit, or retrofit, the wagon with composite tread brakes or perhaps even disc brakes. A careful LCC calculation needs to be made, and this should include the impact of noise-differentiated track access charges and any incentives offered for retrofitting wagons with low-noise technologies.

9. CONCLUSIONS

Across D2.4 the requirements for the SUSTRAIL freight vehicles have been provided taking into account specific features:

- Suspension and running gear;
- Brakes;
- Accelerations and speed requirements;
- Aerodynamic requirements;
- Noise requirements

With reference to “suspension and running gear” it is suggested that they should provide for a reduction in damage to the track (rail wear and surface damage, track vertical settlement and lateral stability) and to the vehicle (wheel wear, component damage and load integrity) while maintaining a safe operation level against derailment and track lateral shift.

With reference to the brake characteristics it is highlighted that freight vehicles could benefit from a combined wheel-slide and brake control system.

Analysis of accelerations and speed requirements on the Bulgarian route showed that higher time savings can be obtained by increasing the line-speed up to 120 km/h for some track sections with respect to today’s situation whilst lower benefit can be achieved by increasing these speeds from 120 km/h to 140 km/h, mainly due to speed limits imposed by railway crossing, switches and curves with high radius and sections with high gradient. A vehicle with better acceleration and braking characteristics would be able to benefit more from the higher line speed (140 km/h).

Aerodynamics investigations, primarily from the perspective of the associated drag, pointed out a series of options to improve the aerodynamics of the freight vehicle and highlighted, for intermodal wagons, the relevant effect of operational factors (vehicle choice and loading regime).

Finally with reference to noise mitigation, for the range of operating speeds of the SUSTRAIL wagon, rolling noise will be the dominant source. Since it is clear that increasing the running speed from 120 km/h to 140 km/h (or higher), will increase the rolling noise, a possible approach is to fit, or retrofit, the wagon with composite tread brakes or perhaps even disc brakes.

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