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Impacts of vehicles with infrastructure and the environment – as measured by Footprint measuring systems

Editors

Rayner Mayer • Lily Poulikakos • Andy Lees

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Executive Summary

The continuing increase in traffic throughout Europe is creating significant impacts on the infrastructure, environment and resources. From a safety viewpoint, such traffic flows can affect the residual life of structures and dictate when maintenance has to be undertaken whilst the environmental impact is strongly influencing Europe's strategy to reduce greenhouse gas emissions.

In the first project report [22] the partners in the Footprint project described a methodology for measuring and quantifying such impacts for both road and rail modes in a transparent manner. This requires an array of sensors embedded within or alongside the track or pavement at appropriate locations so that vehicles can be monitored in service use. These sensors measure the parameters which characterise the interaction of a vehicle with its infrastructure such as dynamic loading, audible noise and ground borne vibration.

In this second Footprint report, the data from various Footprint measuring systems were analysed to determine the impact on the infrastructure and the environment that characterise these interactions. Data from laboratory tests are also described in order to help characterise suspensions and infrastructures. The data sets are compared with limit values that are prescribed by relevant legislation for both modes.

The concept of an environmentally friendly vehicle is considered and a proposal put forward how to set such limits for road as well as rail vehicles. Such a classification could be used for example to introduce a bonus/malus system of user charging as proposed by the European Commission for reducing noise emissions from the existing rail freight fleet.

Finally the impacts of road and rail traffic are considered from the viewpoint of the operator, infrastructure maintainer and society and the ranking reflects their specific concerns.

This kind of information can help to rank strategies which could be used to reduce environmental impact such as noise emissions and through continuing measurement to determine whether such strategies are successful

These recommendations in this report will help to support the initiatives set out in the European Commission's Green Transport package of 8 July 2008. If these recommendations are viewed favourably by Member States, then further work is required to develop and refine these concepts. This work should then be undertaken within a second phase of the Footprint project within the Eureka collaborative framework.

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Conclusions and recommendations

R1: *Footprint measurement systems can determine the nature and magnitude of the environmental impacts and how such impacts depend upon vehicle class and flow*

R2: *Footprint measurement systems can detect which vehicles have excessive noise emissions and what may be the origin of this impact whether by vehicle class, speed, type of infrastructure or lack of maintenance of the vehicle or its suspension system*

R3: *Footprint measurement systems can detect which vehicles exert forces in excess of legal limits and can provide information to operators and drivers about the nature of this excessive force such as inappropriate loading, condition of suspension system, wheel quality or tyre pressure*

R4: *The parameters which describe the impact of a vehicle on its surroundings, constitutes its environmental footprint. These are -*

- *gross vehicle mass*
- *axle load*
- *noise*
- *vibration*
- *environmental emissions*

R5: *An environmentally friendly vehicle possesses a small environmental footprint*

R6*: An environmentally friendly vehicle is defined as one whose impacts are significantly less than average for each vehicle class and impact*

R7: *Limits to be set for each environmental impact and vehicle class which can define the degree of environmental friendliness of the vehicle*

R8: *Such limits may be classified as average, environmentally friendly or environmentally harmful*

R9: *The threshold limits to set bonus and malus user charges, if so desired, can be determined by Footprint measuring systems*

R10: *Measurements of vehicles in-service can determine the effectiveness of charging regimes to promote more environmentally friendly vehicles*

R11: *If these recommendations are favourably received then a second phase of Footprint should be undertaken to develop and refine these concepts*

Contents

Executive summary

Authors

Conclusions and recommendations

Acknowledgements

Abbreviations and terminology

Chapter 1 Collecting data
1.1 Concept of environmental footprint
1.2 Sensor arrays and locations
1.3 Collecting, transmitting and sorting data
1.4 Vehicle classification(s)
1.5 Parameter identification which characterise interaction between vehicles, infrastructure and the environment
1.6 Methods of vehicle identification
1.7 Conclusions

Chapter 2 Characterising vehicle suspensions
2.1 Introduction
2.2 Types of suspensions and dampers
2.3 Laboratory characterisation
2.4 Natural frequency and dynamic damping ratio
2.5 Characteristic resonant frequencies
2.6 Road suspensions
2.7 Rail suspensions
2.8 Discussion
2.9 Conclusions

Chapter 3 Characterising infrastructures
3.1 Introduction
3.2 Infrastructure profiles and test vehicles
3.3 Infrastructure profile
3.4 Vehicle speed
3.5 Infrastructure friendly suspensions
3.6 Conclusions

Chapter 4 Influence of vehicle mass and wheel quality
4.1 Introduction
4.2 Quasi static loads (road)
4.3 Effect of tyre pressure
4.4 Quasi static loads (rail)
4.5 Dynamic loads and wheel quality
4.6 Effect of mass on vibrations
4.7 Summary and conclusions

Chapter 5 Effect of axle load
5.1 Introduction
5.2 Axle load (road)
5.3 Axle load (rail)
5.4 Axle load and noise emissions
5.5 Axle load and vibrations
5.6 Axle over-loading
5.7 Bonus/malus system
5.8 Conclusions

Chapter 6 Factors influencing rail noise emissions
6.1 Introduction
6.2 Locomotives
6.3 Rolling stock
6.4 Influence of braking
6.5 Influence of axles per train on pass-by noise
6.6 Influence of rail roughness on rolling noise generation
6.7 Rail vibration and rolling noise generation
6.8 Speed dependency of pass-by noise from railbound vehicles
6.9 Discussion
6.10 Conclusions

Chapter 7 Factors influencing road noise emissions
7.1 Introduction
7.2 Vehicle type
7.3 Road vehicle speed
7.4 Vehicle mass
7.5 Discussions
7.6 Conclusions

Chapter 8 Vehicle pollutant emissions
8.1 Exhaust gas emissions from diesel engines
8.2 Reducing pollutant emissions
8.3 Emission limits
8.4 Pollutant emissions from heavy duty vehicles
8.5 Influence of fuels on pollutant emissions
8.6 Other factors influencing pollutant emissions
8.7 Conclusions

Chapter 9 Setting limits for environmentally friendly vehicles
9.1 Introduction
9.2 Environmental noise
9.3 Vehicle mass, axle load and forces
9.4 Variation in impacts between vehicles
9.5 Setting the limits
9.6 Bonus/malus system for user charging
9.7 External costs
9.8 Overall conclusions

Chapter 10 Ranking the impacts by mode
10.1 Conveyance of freight
10.2 Infrastructure maintainer's concerns
10.3 Societal concerns
10.4 Comparison of modes (passenger)
10.5 Comparison of modes (freight)
10.6 Discussion and conclusions

References

Annex 1 Road vehicle legal load limits

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Abbreviations

ADSL	Asymmetric Digital Subscriber Line
ANPR	Automatic Number Plate Recognition
apl	axles per unit length
ASTM	American Society for Testing and Materials
AVI	Automatic Vehicle Identification
BQ	(track) Band Quality
CD	Compact Disc
COST	European Cooperation in the field of Scientific and Technical Research
DAQ	Data acquisition system
DIVINE	Dynamic Interaction between Vehicle and Infrastructure Experiment
DLC	Dynamic load coefficient
ECE	Economic Commission for Europe
EGR	Exhaust gas recirculation
EN	European Norm (standard)
EU	European Union
EUL	Enhanced UpLink
FMS	Footprint Measurement System
GPRS	General Packet Radio Service
GRP	Glass Reinforced Plastic
GSM	Global System for Mobile communications
GVW	Gross Vehicle Weight
HBEFA	Handbook of Emission Factors for Road Transport
HDV	Heavy Duty Vehicle
HSUPA	High Speed Uplink Packet Access
MMLS3	Model Mobile Load Simulator 3
PPV	Peak Particle Velocity
PSD	Power Spectral Density
PM_{10}	Particulates size less than 10µm
RFID	Radio Frequency Identification
SCR	Selective catalytic reduction
SIM	Subscriber Identity Module
SMPS	Scanning Mobility Particle Sizer
TCP/IP	Transmission Control Protocol/Internet Protocol
UHC	Unburned hydrocarbons
UIC	Union Internationale des Chemins de fer
UNECE	United Nations Economic Commission for Europe
USB	Universal Serial Bus
VOSA	Vehicle and Operator Services Agency

WHO	World Health Organisation
WIM	Weigh-In-Motion
XML	Extensible Markup Language (data file)

Chapter 1 Collecting data

1.1 Concept of environmental footprint

Footprint is a European collaborative R & D project within the EUREKA framework whose global aim is to relate the environmental footprint of a vehicle to the lifetime cost of maintaining the infrastructure and the environment. One of its principal objectives was to develop the measurement techniques for measuring the environmental footprint in service usage which will then allow these impacts to be related to economic costs in order to justify the basis for usage charging.

The origins of this project lie in the work undertaken within the OECD project DIVINE [8] and COST 323 [5] both of which were primarily concerned about the dynamic loading of a vehicle on its pavement. What the Footprint project has achieved is to carry these concepts across to rail and to add two other manifestations of this interaction namely noise and vibration. With ever increasing amounts of traffic these have become of increasing concern particularly for those living alongside road or railway lines.

Footprint proposes the concept of a vehicle's **environmental footprint** which is related to its environmental and infrastructure impact. The size of the footprint is related to its impact and its external (social/environmental) cost. Small vehicles will not necessarily have a small footprint nor will large vehicles have necessarily a larger footprint. However, within any group of vehicles there should be an incentive for vehicle types with a low footprint and a penalty for vehicles with a large footprint. This would be in accord with the polluter pays principle as set out in the EU Transport White Paper [9].

These measurements were being evolved at the same time for both road and rail modes. This not only allows data to be compared, but also to articulate dialogue about the most suitable methods for reducing the environmental impacts of various types of transport modes. The guidelines [22] for these techniques have now been designed and Footprint is now looking at how these data can be collected and analysed to help rank strategies which could be used to reduce environmental impact such as noise emissions.

Such measurements will also allow the impacts of various classes of vehicles to be defined from which it should be possible to evolve definitions of **environmentally friendly** road or rail vehicles. These data can also be used to identify and reward operators who operate such classes of vehicles.

The environmental footprint will comprise –

- gross vehicle mass
- axle load
- noise
- vibration
- environmental emissions

The concept can be broadened to include other impacts.

1.2 Sensor arrays and locations

Road – arrays

Footprint has adopted portions of the COST 323 and ASTM standards that are relevant to the project. As a result it has been recommended in the guideline document [22] that, for road measurement, a Footprint site should be based around the fundamental design for a high speed weigh-in-motion (WIM) site.

The layout of these sites can vary dependent on the type of equipment, or manufacturers' product being employed for the purpose. At present there are four sites equipped for Footprint data collection from roads, three in the UK and one in Switzerland. The two countries employ different types of arrays and manufacturers' products but both are accurate in capturing WIM and Footprint Measuring Systems (FMS) data.

A layout schematic for the road system in the UK is given in Figure 1.1 and for Switzerland in Figure 1.2.

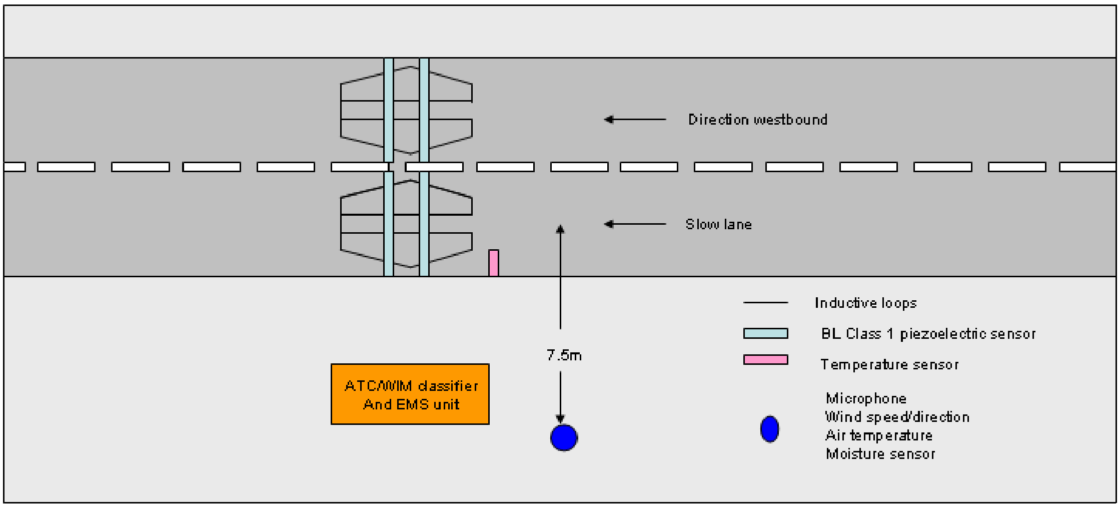


Figure 1.1: Layout for a road FMS on the A303 near Wincanton, UK

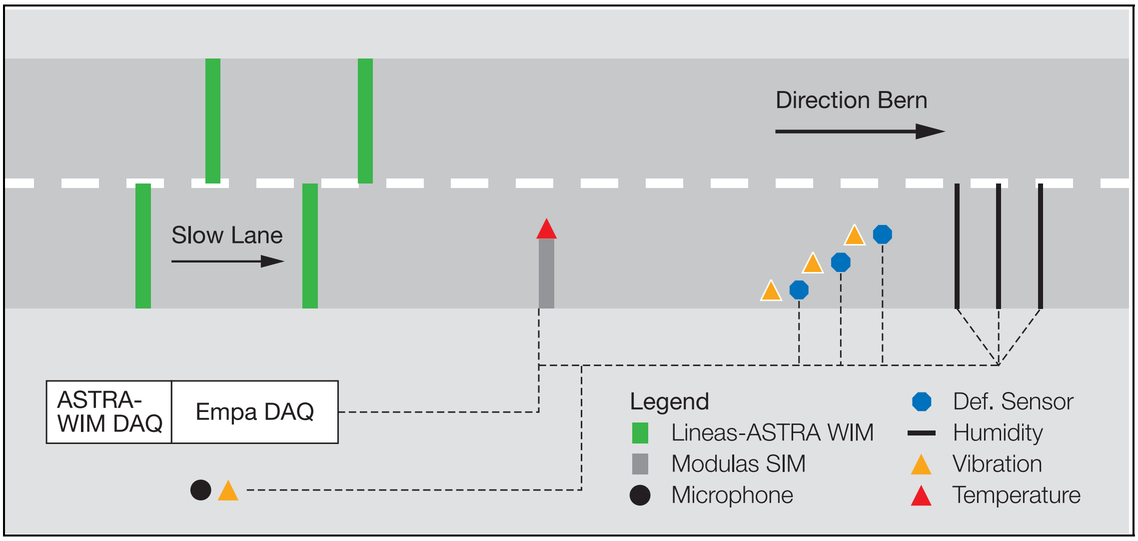


Figure 1.2: Layout for a road FMS on the A1 near Lenzburg Switzerland

Road – locations

The location for a road based FMS has to be chosen with a high degree of care and needs to consider a number of parameters before a site can be installed. In general, a good road based Footprint site should have the following:

- A smooth, flat pavement that is in good condition and that has sufficient strength to adequately support WIM axle sensors
- Vehicles travelling at constant speeds over the sensors wherever possible
- Access to power and communications (*although these can be supplied from solar panels, wind turbines and through various GSM forms of communications*)
- Sufficient space adjacent to the carriageway to install outstation equipment
- Free from extraneous vibration and noise reflective structures
- Safe working environment

In addition there should also be sufficient traffic flow at the site to justify the installation of the measuring equipment.

A layout schematic for the rail system in NL is given in Figure 1.3.

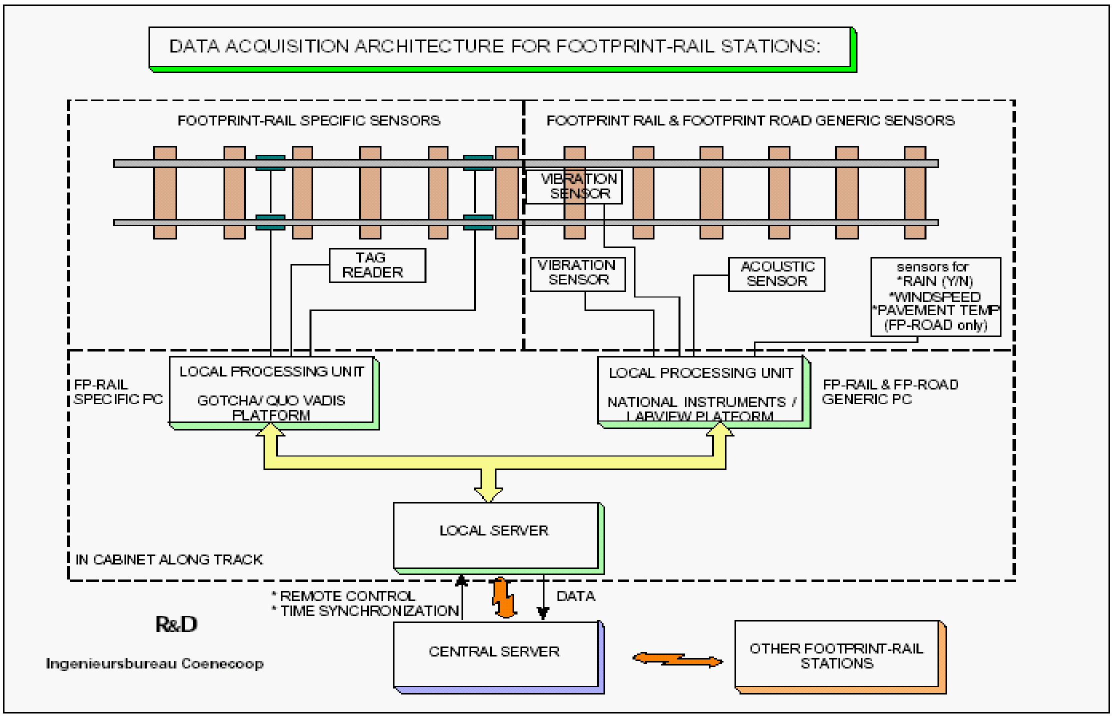


Figure 1.3: Layout for a Rail FMS in the Netherlands

Rail – arrays

One of the most important parameters characterising the vehicle/track interaction is the quasi-static and dynamic load exerted by the vehicle on the track. Unlike vehicle/pavement interactions where the rubber acts as a primary suspension and spreads the load, the presence of a steel wheel on a steel track creates high forces with different wavelength over a small contact area.

Like road weigh-in-motion, the primary loading direction is in the vertical direction which comprises the static loading due to gravitational loading of the vehicle mass and the dynamic component due to the irregularities at the track and wheel quality.

Rail – sensors and trackside measuring equipment

The sensors in the measuring system should be able to:

- detect wheel rail interaction forces and wheel defects.
- measure over the complete wheel circumference of passing wheels with a diameter of 320 – 1800 mm.
- measure between 30 and 300 km/hr.
- measure axle loads between 1.5 and 40 tonnes.
- galvanic separated from any connection to trackside equipment and or the track power supply.
- not require any signalling devices or other equipment in the track.
- not require any change or special construction in the track and it is not allowed to drill holes in the rail or to change the sleeper distance.
- not influence the running behaviour of the vehicle.
- stay in place in case of track tamping and track grinding works; no special maintenance equipment for track tamping and track grinding works should be needed.

Figure 1.4: Strain gauge based measurement system

The measurement system should:

- produce clear results which can be observed without special processing equipment in standard file formats.
- be placed in a secure cabinet, off the track bed; power supplies should be isolated from that of the signalling supply with adequate protection provided against lightning strikes to prevent damage to equipment, sensors or power supplies.
- be able to be connected to a RFID tag reader to identify passing rolling stock; alternatively to a train information system to obtain the train/vehicle information from a central data server.
- recognise individual vehicle types based on a specific axle and bogie configuration.
- be under constant surveillance of a central management system in order to provide information about system diagnostics as well as access control.
- provide transmission equipment for links with a central data server. The data transmission protocol is typically TCP/IP and the file type XML. UIC conform data formats shall be supported.

Rail – locations

As with roads, rail sites need to be chosen with care and require good track quality to get the best performance with a minimum number of sensors. The following conditions should ideally be met with to obtain the highest degree of data quality.

- Superstructure condition – the track needs to be well aligned and free from corrugations and there should be no significant rail defects or loose sleepers. The sleepers need to be well ballasted with all rail attachments and bedding plates attached.
- Track construction – the site should have no switches, crossings, electrical insulation joints or butt welds. Concrete sleepers give more reproducible results than wooden sleepers.
- Position along the track – the measurement location should allow a train speed typically between 40 and 160 km/h. There should be a distance of at least 100m from structural works like culverts and bridges and 1000m from signals with a homogeneous ballast bed. Any track curvature should have a radius greater than 1500m and train separation to be at least 1000m to enable data from the preceding train to be processed in real time.

1.3 Collecting, transmitting and sorting data

The data collected by Footprint outstations initially need to be retained as a number of variables, at site before they can be retrieved. These are discussed in greater detail in the guideline document [22] and later on in this chapter in section 1.5.

The quantities of data stored can vary from site to site dependent on the flow and the frequency of retrieval. A useful guideline for storage may be obtained from the UK road vehicle site at Plymouth where an average flow of vehicles reaches approximately 55,000 a day. Using this example and the binary format the data are stored in, it can be assumed a file of this size takes up around 0.8 Mbytes per day.

Data storage can be a major issue and it is necessary to decide on which format it should be held in. Again using the UK example above, it is advisable to store it in binary format as this requires less space and it is also quicker when it comes to retrieval. A change in format can always be carried out on subsequently processing the data.

Collection of data from the Footprint outstations can be carried out using three methods, manually, by telemetry or via the internet. The older but more time consuming method is manual collection which is reliant on an individual visiting the site and downloading the data onto an easily transportable medium such as a CD or USB memory stick. This is not only a time consuming method but it also has health and safety implications for an individual visiting site.

A faster and more efficient method of retrieval can be carried out using telemetry either through the standard telephone land line method or using the GSM network. The land line method allows a relatively fast retrieval speed at 19600 bps but the GSM network will currently only transmit at speeds up to 9600 bps. There are advantages and disadvantages with both methods. The land line system, whilst providing a more rapid transmission speed, does require a physical link between the outstation and the network. This can be a very expensive process compared to GSM, which although slower in its transmission is a lot cheaper. It can be worthwhile examining closely the cost effectiveness of each system before deciding on which method to employ.

Finally the third and the fastest method is via the internet. There are three methods of internet connection available to remote stations; ADSL, GPRS (General packet radio service), HSUPA (High speed upload packet access) and EUL (Enhanced uplink).

ADSL is currently the fastest method widely available. To set up this system it is ideal that the outstation is equipped with an ADSL connection which will allow the in-station to contact the site and download the data at high transfer speeds. This is by far the most efficient and potentially cost effective method of data retrieval. A schematic diagram of such a data acquisition system is shown below in Figure 1.5.

GPRS and HSUPA both operate over the GSM/3G networks. GPRS offers upload transfer rates of 19200 bps, twice that of GSM data. HSUPA may be available at speeds of up to 1150000 bps (typical 730 000 bps). Data are charged for by the amount uploaded/downloaded. As this is the case it is critical to ensure security of the link (either through private IP assignment, or through filtering of allowable incoming IP connections, or by making the outstation connect to the instation. Charges can quickly add up if non authorized connections start connecting to the outstations and request data.

A drawback to GPRS is the latency between transmissions of data. This can affect the transmission protocol used making it inefficient. Data download protocols should be designed around the default size of a TCP/IP packet (1500 bytes).

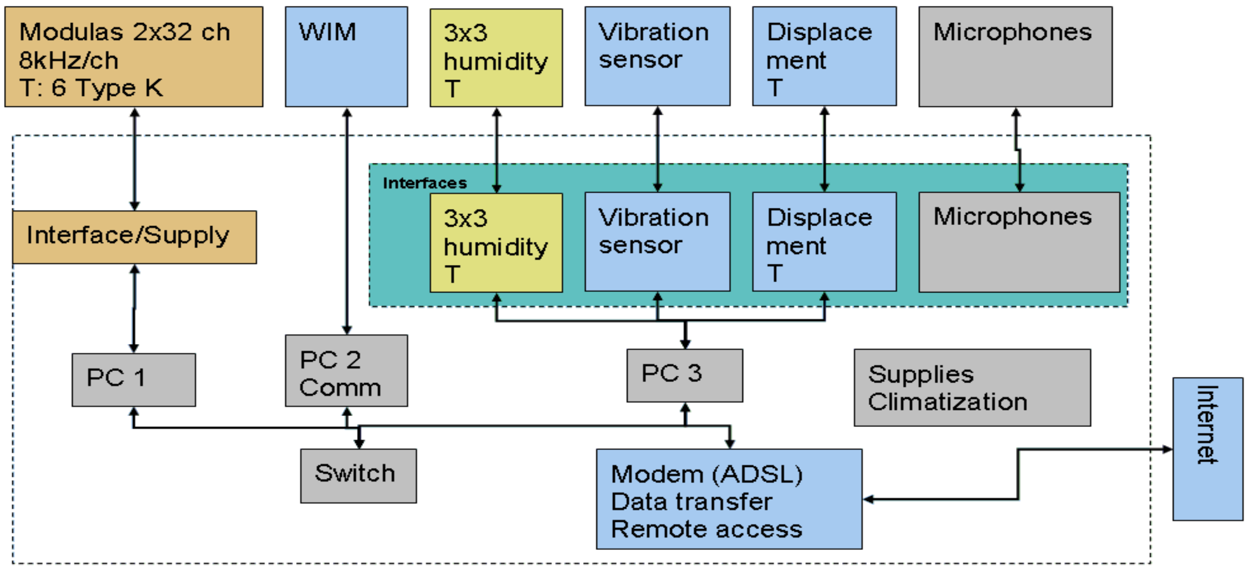


Figure 1.5: **Data acquisition system used in Switzerland**

One of the distinct advantages of internet or telemetry connection to an FMS is that the user is able to monitor the performance and “health” of the FMS remotely. A number of counter/classifiers, particularly road based systems, have the facility to provide users with diagnostic data relating to the operational state of the equipment at site. As a result, the user is alerted at an early stage to any defect that may have occurred and they can then arrange for a repair to take place as quickly as possible thus minimizing data loss.

After data retrieval has taken place, users need to decide on the format they wish to analyse the data in. Data conversion into an ASCII file is the ideal scenario as this can then be easily read by most data analysis software systems. However, in terms of storage, users may wish to hold the data in binary format as this requires considerably less disk space. The choice of format users wish to adopt is very much dependent on the analysis systems and software being employed and is an individual choice for that organization.

1.4 Vehicle classification(s)

The counting of axles and the determination of axle loads is an important means of separating passenger and freight traffic whether on road or rail. Such traffic flows are important for safety, traffic statistics, headway or separation between vehicles and for apportioning pavement and track wear and damage. This information will allow infrastructure maintainers to decide when to undertake maintenance whilst information about excessive axle loadings can be fed back to vehicle operators to schedule their maintenance.

A convenient means of classifying vehicles is therefore the number of axles, their spacing and loading. The use of such classes will also allow the external costs to be allocated for each vehicle type. If audible noise and ground borne vibration are also recorded then it becomes possible to measure noise as a function for example of axle load and spacing thus allowing the environmental noise impact of vehicles to be assessed.

Whilst various national schemes exist such as the UK 20 and Swiss 10 road classes, COST 323 Weigh in Motion [5] has derived such a classification scheme for use in road weigh-in-motion measuring systems throughout Europe and the relationship between the 3 schemes is illustrated in Table 1.1. Σ! 2486 Footprint has produced a similar draft classification scheme for rail [22]. These are shown in Figures 1.6 and 1.7.

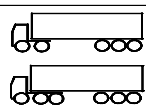
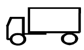
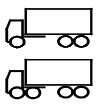
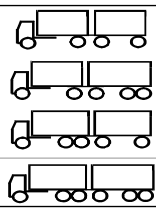
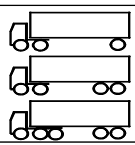
Classes	Silhouette	Classes	Silhouette
Class 1	Cars, vans (< 35 tonnes)	Class 5	
Class 2			
Class 3		Class 6	
Class 4			
		Class 7	Buses
		Class 8	Other

Figure 1.6: Classification of road vehicles by silhouette, COST 323 Weigh-in-motion (5)

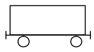
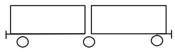
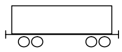
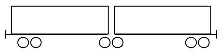
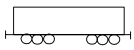
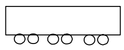
	**individual or up to 5 close coupled**
	**single axle articulated**
	**bogied**
	**bogie articulated e.g. 4'car' artic car carrier**
	**diesel, electric**
	**eurotunnel 3-bogied locomotives**

Figure 1.7: A classification of rail vehicles by silhouette, Footprint weigh-in-motion (22)

Such classifications enable environmental impacts to be allocated between vehicle types in each mode. They will not enable direct comparison between modes without additional data. A correlation between the three road vehicle classes is given in Table 1.1.

Table 1.1: Equivalence between Swiss 10 categories, UK DfT scheme and COST 323 vehicle classes.

vehicle type	COST 323 class	Swiss 10 category	UK DfT scheme
Articulated truck with 3 to 5 axles	Class 4	8 (Lastwagen)	51,52, 53 and 55
Articulated truck with 5 or 6 axles	Class 5	10 (Sattelzug)	54 and 56
Truck/trailer with 4 to 6 axles	Class 6	9 (Lastenzug)	41, 42, 43 and 44

1.5 Parameter identification which characterise interaction between vehicles, infrastructure and the environment

The classification of vehicles is an important aspect of collecting data which typifies vehicle flows and enables one to understand the influence of various vehicle types on the interaction of the vehicle with its infrastructure and the environment. However, to gain a better understanding on how these vehicles interact with the infrastructure it is necessary to collect information from a number of other variables associated with each vehicle.

These variables can best be summarised as follows:

- Vehicle class
- Speed

- Individual axle weight
- Gross vehicle weight
- Noise level
- Road and air temperature
- Wind speed and direction
- Humidity (wet or dry)
- Tyre pressure (road)
- Wheel quality (rail)

WIM data

The WIM data should log all vehicles above a certain weight. Axle load, total weight, number of vehicles and axles as well as the speed should be recorded. The WIM data can be used to identify single passages. All the other data can then be searched by time stamp according to this selected passage.

Vibration data

The vibration data require a minimum sample frequency of 2 kHz. A threshold value provides the possibility to reduce the amount of data, so only valid vibration data from a passage will be saved.

Noise data

The noise data require a sample frequency of 50 kHz and can be reduced after passage of the vehicle.

Pavement deformation data

The magnetostrictive sensors which measure the deformations within the pavement layers should be sampled at a frequency of 250-300 Hz. This is sufficient for speeds up to 100 km/h.

Temperature and humidity data

To correlate footprint data, temperature and humidity data are also required for each passage.

Tyre pressure

The system can measure the load distribution under the tyre by means of 64 piezo electric sensors. The raw data are stored in a binary file of 1 MB size (= 4096 points x 64 channels x 4 Byte) and can be subsequently reduced. A limit value defines the minimal force in a channel for a detection of a vehicle passage. If in a file the signals of all 64 channels are below this limit, the raw data will be deleted immediately. After a detection of a passage, a second limit value defines the noise level. All values below this limit will be deleted in order to reduce the measurement points to the relevant data of the vehicle passage. The size of this reduced array depends on the speed and the tyre size. The reduced data will then be saved with the exact time stamp name as a binary file, together with a log file containing the information of the active channels. The raw data can then be deleted.

Wheel quality

For rail vehicles, an array of deflection sensors attached to the rail or to the sleeper can measure the quality of wheels and distinguish various defect types such as out-of-roundness or flats which can be classified. By systematic numbering of the axles in the train set it is possible to identify the axle in need of maintenance. Such defects can result in excessive dynamic loading, noise and vibration so having a significant environmental impact as well as reducing the residual life of the rail

Normalisation

There will be a variation of all data about a mean value and so comparison between data within one class, between classes and sites becomes increasingly difficult. One way of doing this is to normalize the data to a set speed such as 80 km/h for road vehicles and this is illustrated in figures 7.2 to 7.4 for three vehicle classes.

1.6 Methods of vehicle identification

Vehicle identification methods currently consist of an identification plate at front and rear for road vehicles and a number affixed to the side of a railway wagon, coach or locomotive. Clearly optical recognition systems could be used to read the number and this forms the basis of the London congestion-charging scheme for example. A number of journey monitoring surveys such as Trafficmaster, in the UK, use only certain characters from a vehicles number plate to avoid any infringements of civil liberties which can be an issue when dealing with the passage of private motor vehicles.

With the advent of road and rail user charging schemes as set out in the EU White Paper on Transport [4] and the enactment of primary legislation, the need for automatic vehicle identification (AVI) has increased and systems other than optical recognition are being introduced.

An alternative method of identification is to use radio frequency beams to interrogate a tag mounted on the vehicle. It is also possible to reverse the procedure with the reader mounted on the vehicle and the tag mounted on the track as used by London underground.

The use of AVI is optional but very useful particularly for vehicles whose parameters exceed set limits. An example of this is the system deployed by the UK's Vehicle and Operators Services Agency (VOSA) VIPER system which combines real time WIM with ANPR cameras linked to a central database. When a vehicle passes over the WIM array, the number plate of the vehicle is checked automatically against the database and if the vehicle exceeds prescribed limits over and above its plated weight, then VOSA officers are immediately alerted and the vehicle is diverted off the road into a static weighbridge where the vehicle is examined in more detail.

1.7 Conclusions

The environmental footprint of a road or rail vehicle can be measured by an array of sensors embedded in the, or located adjacent to, the track or pavement. Similar techniques can be used for measuring the impacts of both types of vehicles. Measurement systems can be automated so that data can be recorded and analysed in real time. The impacts derived from these measurements are described in subsequent chapters as well as the possible use of the data to set environmental limits.

Chapter 2: Characterising vehicle suspensions

2.1 Introduction

As the physical characteristics of the vehicle suspension and the infrastructure influence their interaction, it is easier to characterise their impact in the laboratory than in service. Such knowledge enables one to interpret impacts measured in service as well as classify vehicles and infrastructures.

The primary role of the suspension is to maintain the vehicle height as constant as possible irrespective of any irregularities or undulations in the surface of the infrastructure. Thus the softer the suspension the more level is the ride and the *spring rate* K_s is used to characterise the suspension as measured in N/m. It is related to the *natural frequency* ν of the *sprung mass* m_s by

the equation

$$\nu = (K_s/m_s)^{0.5}$$

The second requirement is to minimise any vibrations associated with the interaction between the vehicle and the infrastructure. The suppression of such vibrations is characterised by the damping capability of the suspension. The *damping ratio* D_d is related to the logarithmic decay of the successive vibrations of natural frequency (amplitude d_0 and d_1) through the formula

$$D_d = (1/2\,\pi)\ \ln (d_1/d_0)$$

These vibrations can manifest themselves as either ground borne vibrations or audible noise.

A third characteristic of a suspension is its ability to absorb energy and filter any vibration originating at the wheel/infrastructure interface. The three primary methods of doing this is by Coulomb damping as in steel leaf suspensions, by hydraulic damping as used with air suspensions or by internal damping as in suspensions made from glass reinforced plastic. As these methods of energy absorption are so very different so too is the vehicle response and the noise emissions (as discussed in chapter 6).

In the following sections, measured data are compared for various types of suspensions and dampers.

2.2 Types of suspensions and dampers

Three types of vehicle have been studied on shaker rigs and are listed in Table 2.1 together with their suspension type.

Table 2.1: Vehicle types, suspension and static load per wheel

Vehicle type	suspension	Load per wheel Tare (kN)	Laden (kN)
Tri-axial road trailer	Single leaf GRP	n/a	37.5
Two axle wagon type HAA	Parabolic leaf assembly 5 leaf steel or 2 leaf GRP	34.5	Level 1: 56 Level 2: 77.5 Level 3: 97.5
Flat bed wagon	2 leaf parabolic GRP bogie type D826 Coil sprung bogie type Y25	21.5 23.2	46.0 51.1

The suspension design is highly dependent upon the characteristics of the suspension material and its damping properties. Of these materials only rubber and to a lesser extent glass reinforced plastic (GRP) have intrinsic damping properties. Thus it is possible to design suspensions which combine the properties of rubber and either steel or GRP [13]. For freight vehicles, friction damping is also used but it is neither reliable nor consistent and its use is restricted in road friendly suspensions to less than 50% [10]. A third option for supplying damping is to fit an external damper like a hydraulic damper, such as in air suspensions, which is the industry standard, and can be tuned to give the best ride on smooth roads or rails.

The various types of suspension that have been characterised are listed in Table 2.2 each of which have a different stiffness and a different source of damping

Table 2.2: suspension type and source of damping

Type of suspension	Source of damping
road	
3 leaf parabolic steel	Friction damping at ends of spring
1 leaf parabolic GRP	Intrinsic damping of GRP material and friction damping between self lubricating nylon wear ends and steel hangar bracket
Air bag	Hydraulic damper
rail	
8 leaf trapezoidal steel	Friction damping across entire leaf area
5 leaf parabolic steel	Friction damping at ends of spring
2 leaf parabolic GRP	Intrinsic damping of GRP materials and rubber damper beneath lower leaf
Coil spring	Friction damping between static and moving steel plates

2.3 Laboratory characterisation

Vehicle suspensions can be characterised quasi statically and dynamically in the laboratory. The quasi static method involves loading and unloading the vehicle suspension in a load test rig. The dynamic method involves a ¼ chassis rig [33]. For a vehicle shaker rig, a servo hydraulic actuator is fitted under most or all of the wheels (Figures 2.1, 2.2). The vehicle shaker rig method was developed by project DIVINE [8] and Eurosprings [13] for road vehicles and has now been adapted for rail vehicles by Skoda Vyzkum [3].

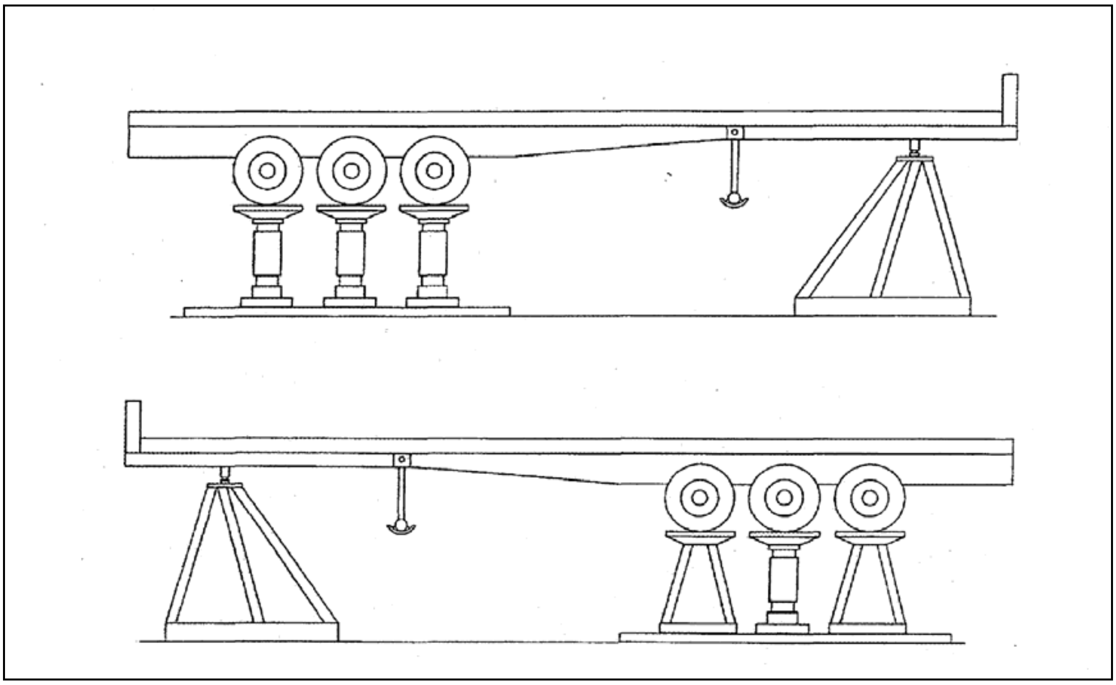


Figure 2.1: Trailer test rig [courtesy of Autokut, inc. Hungary]

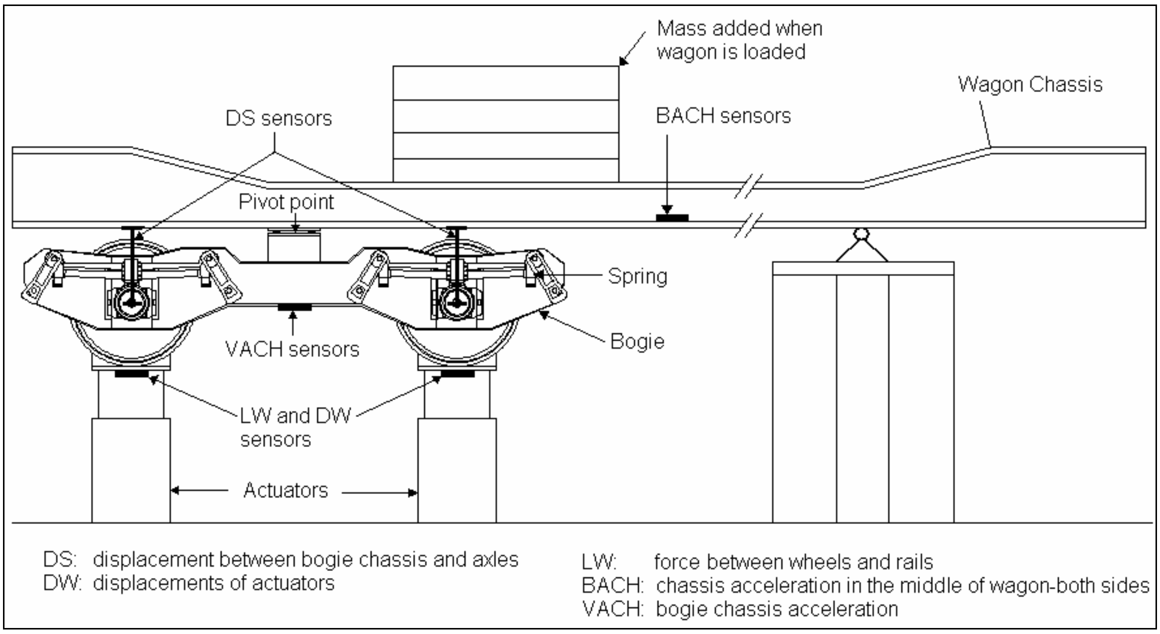


Figure 2.2: diagram of vehicle shaker rig with flat bed bogie wagon

Two methods have been evolved to characterise the suspensions -

- *Natural frequency and dynamic damping ratio* in which actuators (or vehicle) are dropped simultaneously a set distance
- *Characteristic resonant frequencies* in which the actuator frequency is swept slowly from 1 to 30 Hz with constant excitation amplitude. This enables individual resonance frequencies to be excited and their amplitude to be measured through Fourier transform analysis

2.4 Natural frequency and dynamic damping ratio

The effect of the drop test is illustrated for three types of suspension fitted to a bogie wagon fitted with 5 leaf parabolic steel, 2 leaf parabolic GRP (type D826)and coil sprung bogie (type Y25). Typical induced vibrations are shown in Figure 2.3.

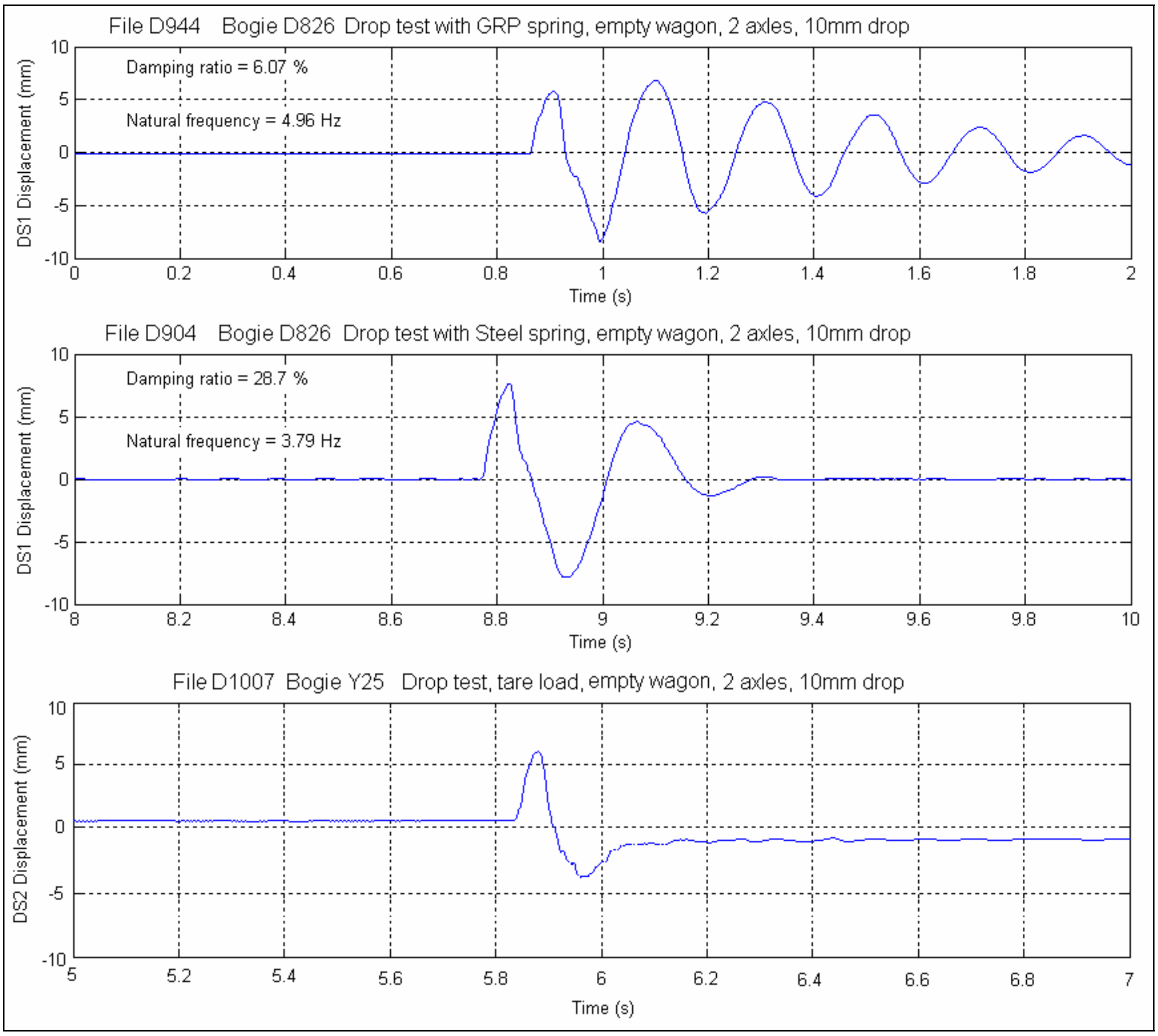


Figure 2.3: drop test of bogie wagons at tare load; measurements of displacement between bogie chassis and axles.

The effect of increasing the damping is clearly visible from a lightly damped GRP leaf bogie to an over damped coil sprung bogie. These measurements were made with a drop height of 10mm and the reliability and consistency of the damping can be checked by dropping from other heights.

Similar measurements have been recorded for suspension response of road vehicles.

2.5 Characteristic resonant frequencies

On sweeping the frequency from 1 to 30 Hz, the fundamental resonance peaks can be excited and are reproducible. The peaks can be identified by looking at that part of the vehicle that is excited at any one frequency whilst the location of the sprung mass peak will decrease in accordance with the equation in section 2.1.

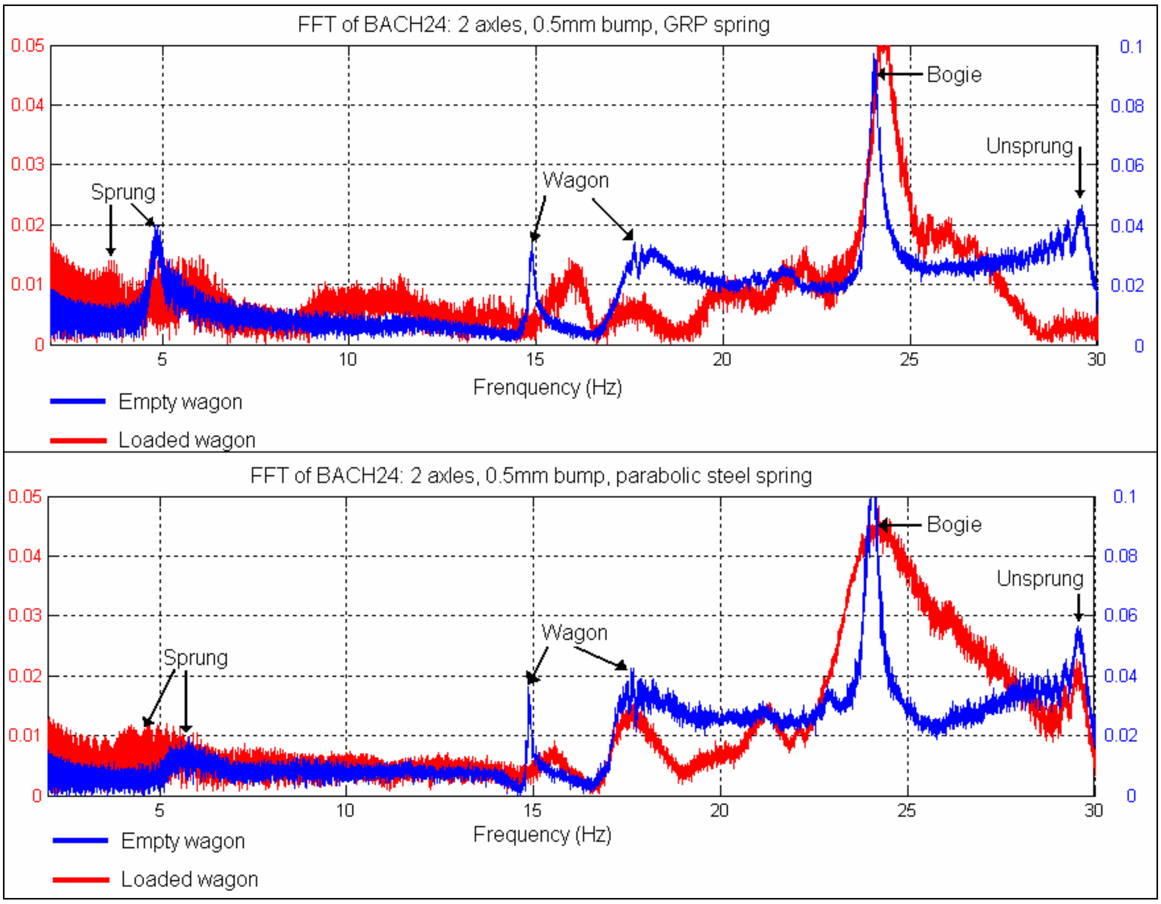


Figure 2.4: Transfer function of the chassis acceleration for a rail bogie wagon fitted with either parabolic GRP (2 leaf) or parabolic steel (5 leaves); bogie type D826; excitation amplitude 0.5mm, frequency sweep from 1 to 30 Hz; tare load and load of 120 kN added

From these sweeps, the location can be identified of the sprung mass, wagon, bogie and unsprung mass peaks whilst their amplitude can be determined from Fourier transform analysis.

Similar spectra are obtained for road vehicles.

2.6 Road suspensions

The characteristics of the 3 principal types of road suspension are listed in Table 2.3

Table 2.3 Comparison of road suspension characteristics for semi trailers, laden load

	Air suspension	**GRP leaf**	**Steel leaf**
Frequency response (Hz)			
Sprung mass	1.5	2.5	3.1
Unsprung mass	12	17	na
Peak response (kN)			
Sprung mass	4	4	30
Unsprung mass	2	2.5	3
Damping ratio (%)			
40 mm drop	11	7	7
80 mm drop	7	20	10
Dynamic load coefficient	0.05	0.05	nm

The air suspension has the lowest natural frequency and steel the highest so the ride would be much better on air than steel. This is the principal reason why 90% of all heavy road freight has switched to air suspension.

Though the values of the damping ratio are similar in magnitude, their origins are very different (table 2.1). Since friction damping is neither reliable nor consistent, it is not surprising that the sprung mass peak of the steel leaf suspension is so high – this will cause high strains in both the pavement and the vehicle which is why such suspensions are not deemed to be 'road friendly'.

2.7 Rail suspensions

The characteristics of 3 types of rail suspension are set out in Table 2.4.

The influence of friction damping can be clearly seen with the steel suspensions which have a high resonant frequency and the GRP suspension with more consistent and reproducible damping.

Table 2.4: Comparison of suspension characteristics for bogie wagons, laden load; a indicates axle wagon; b estimate as insufficient peaks to measure accurately

	Coil spring	GRP leaf	Steel leaf
Frequency response (Hz)			
Sprung mass	5.0	3.6	4.7
Unsprung mass	n/m	29	29
Peak response (kN)			
Sprung mass	14.8	9.7	9.5
Unsprung mass	25.2	30.4	28.6
Damping ratio (%)			
10 mm drop	100 (?)[b]	11	17[a](43)

2.8 Discussion

The data in Tables 2.3 and 2.4 show that road suspensions have a lower natural frequency than rail suspensions; this is primarily due to presence of the rubber tyre which acts as the primary suspension element. The **unsprung** mass is therefore lower for road than for rail vehicles and the resonant peak is correspondingly higher for rail vehicles (Tables 2.3 and 2.4). The significance of these parameters is that the ride should be better and the dynamic loading less for road than rail suspensions and a comparison of the data in Tables 2.3 and 2.4 supports this viewpoint.

Dynamic damping plays a critical role in the dynamic loading on the infrastructure. Too little damping and any induced vibration do not decay fast enough before the next vibration is induced by irregularities in the infrastructure. Too much damping prevents the wheel following the profile of the underlying infrastructure and also increases the frequency of the sprung mass peak.

The optimum value is determined by ride tests and may be prescribed by legislation. 'Road friendly' suspensions require 20% dynamic damping of which no more than 10% may arise from Coulomb (frictional) damping [10]. There is no agreed value for rail friendly suspensions but available evidence suggests that this might be a similar value. The limit value *will* be set by the ride quality that is acceptable. No legislative limits currently exist.

2.9 Conclusions

The parameters characterising vehicle suspensions can be defined in a similar manner for both road and rail. This suggests that environmentally friendly suspensions could be defined by European regulation for rail as well as road. Such definitions would help to implement some of the aspects of the Green Transport proposal put forward by the European Commission in July 2008 [4].

Chapter 3: Characterising infrastructures

3.1 Introduction

The alignment quality of the infrastructure has as much influence on the vehicle/infrastructure interaction as the suspension characteristics and vehicle parameters. Infrastructure quality will vary from motorway through primary to secondary routes and likewise does track quality. The suspension has to respond to all these varying alignments by keeping vehicle level and stable and not exerting excessive forces on either its contents or the infrastructure. Pavement characteristics directly influence the signal recorded by any WIM sensor as in most cases the road is supporting the sensor and therefore forms part of the measuring device. Therefore not only longitudinal evenness but also structural deterioration such as rutting can limit the accuracy of the measurements [5].

Whereas in chapter 2, vehicle suspensions were characterised in terms of their natural frequency and damping, for track quality the corresponding micro-scale parameter is deviation from a nominal mean of both the standard deviation (or dispersion) and the extreme maxima and minima.

The infrastructure profiles can be run through the servo-hydraulic actuators running in position control so the resulting accelerations (ride quality) and forces can be studied. Shaker rigs have been used at Autokut, Budapest and at Skoka Vyzkum, Plzen and are illustrated in Chapter 2.2

3.2 Infrastructure profiles and test vehicles

WIM site classes have been proposed by the COST 323 project [5]. The pavements have been classified as Class I (excellent), Class II (good), Class III (acceptable). These classes address requirements for rutting, deflection and evenness. In addition, particular requirements for bridges have also been addressed.

A number of standard profiles have been selected which are in common use. For pavements, Harris et al used [2] –

- Concrete road SL – worn cracked concrete road, Stella link, Texas
- HOUS – a mixed route of asphalt and concrete sections of medium quality in Houston
- LIAZ – bad quality stone road in Georgia

The data for the concrete road are given in Table 3.1.

Table 3.1: alignment data for concrete road, Texas

Alignment (mm)	Input Left	Displacement right
Minimum	-63	-54
Maximum	72	63
Dispersion	16.5	12.1

Track input data have been selected from 1 km sections of the UK freight acceptance route from Derby to Carnforth and four track band profiles have been used (Table 3.2).

Table 3.2: alignment data for 4 track quality bands

	BQ2		BQ4		BQ6		BQ9	
	Left	Right	Left	Right	Left	Right	Left	Right
Maximum (mm)	19.6	18.8	13.8	10.8	11.2	13.1	4.9	5.3
Minimum (mm)	-14.7	-15.3	-12.8	-12.5	-14.8	-16.5	-5.1	-5.2
Dispersion	4.0	3.9	3.2	3.4	3.1	3.5	1.3	1.4

Note that the permitted dispersion and extremes are much greater for road than rail profiles.

Both acceleration and dynamic wheel loads have been measured. To characterise the dynamic wheel loads for any profile, the dynamic load coefficient (DLC) is used and is defined as the standard deviation (or dispersion) of the dynamic wheel load divided by the static wheel load [8].

The three types of test vehicle and their suspensions are listed in Table 3.3, their suspension characteristics being listed in Tables 2.2 and 2.3.

Table 3.3: Vehicle types and suspension

Vehicle type	suspension	Load per wheel Tare (kN)	Test load (kN)
Tri-axial road trailer	Single leaf GRP suspension	n/a	37.5
Two axle wagon type HAA	Parabolic leaf suspensions 5 leaf steel or 2 leaf GRP	34.5	Level 1: 56 Level 2: 77.5 Level 3: 97.5
Flat bed wagon	2 leaf parabolic GRP sprung bogie type D826	21.5	46.0
	Coil sprung bogie type Y25	23.2	51.1

3.3 Infrastructure profile

For both road and rail modes, the dynamic wheel load increases linearly with displacement (figs 3.1, 3.2) for the range of profiles listed above. For a given displacement, the dynamic wheel load is much greater for rail than road reflecting the lower natural frequency of the road vehicle and the ability of the rubber tyre to act as a primary suspension element.

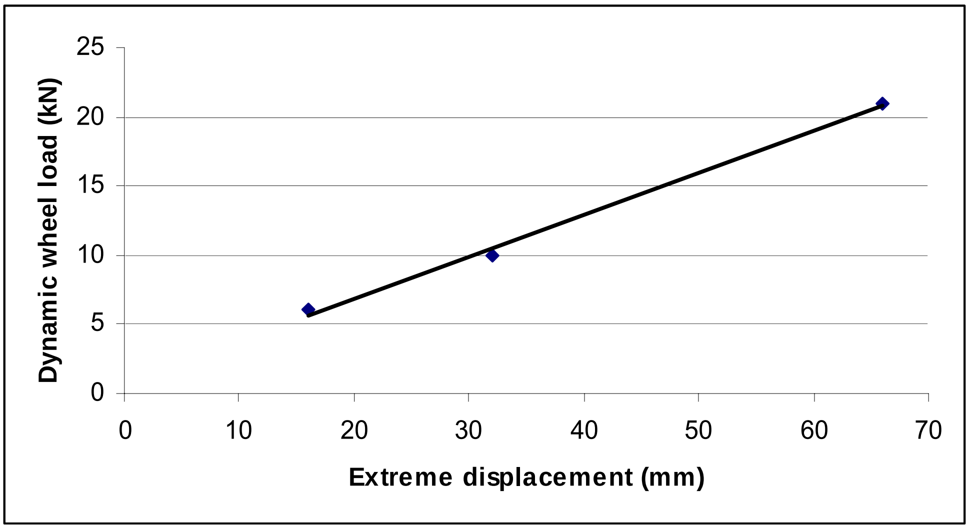


Figure 3.1: Effect of displacement on dynamic wheel load for GRP leaf sprung trailer on concrete road, Texas at 100 km/h

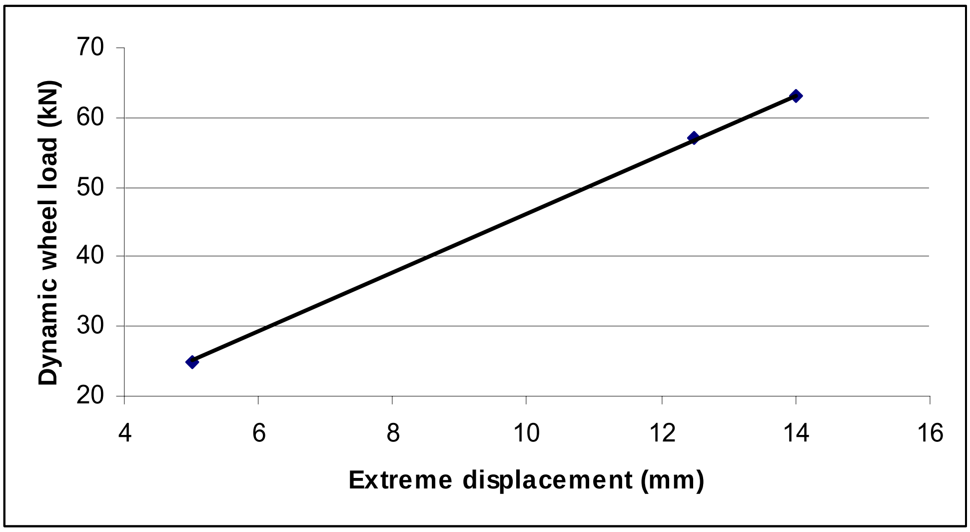


Figure 3.2: Effect of displacement on dynamic wheel load for GRP leaf sprung bogie wagon on track of varying quality (BQ4 to BQ9) at 76 km/h

There is also a linear relationship between the dispersion of the displacement and the dynamic load coefficient which is proportional to the dispersion of the dynamic wheel loads (fig 3.3, fig 3.4). As with the extreme displacement, the rail mode incurs much higher dynamic loads than the road mode for similar displacements for similar speeds. It is clear from these results that the better the alignment of the infrastructure, the lower is the dynamic load coefficient and extreme loads so influencing the design of both motorways and high speed track.

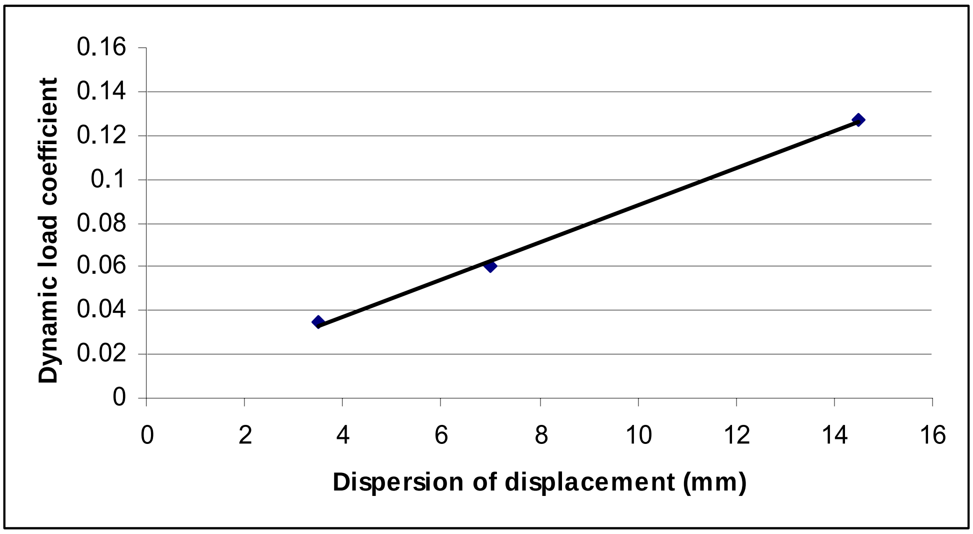


Figure 3.3: Effect of dispersion of displacement on dynamic load coefficient, concrete road, Texas, GRP parabolic leaf; vehicle speed 100 km/h; laden load

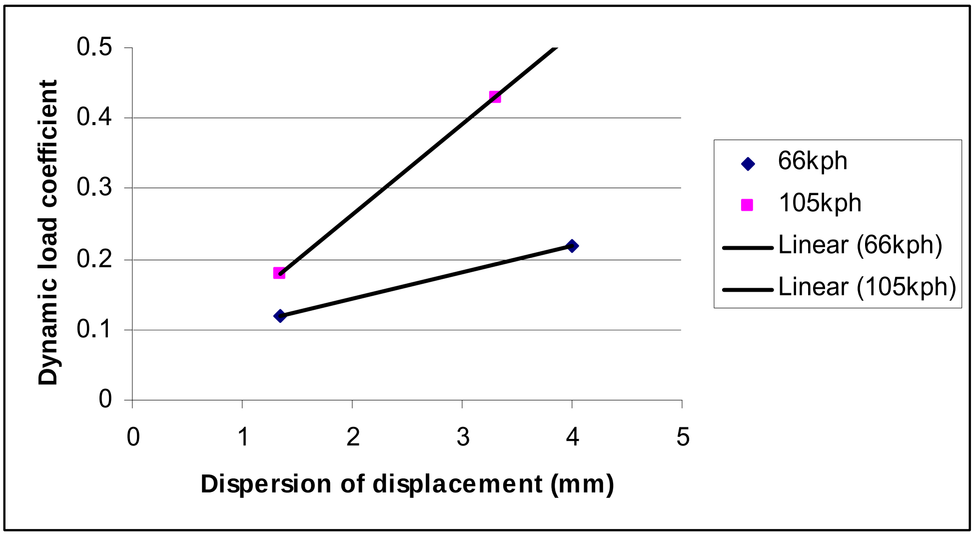


Figure 3.4: Effect of dispersion of displacement on dynamic load coefficient, bogie wagon, 2 leaf GRP parabolic suspension, tare load, vehicle speed 66 and 105 km/h

Static load

The dynamic wheel load increases linearly with static load for a given track alignment (fig 3.5).

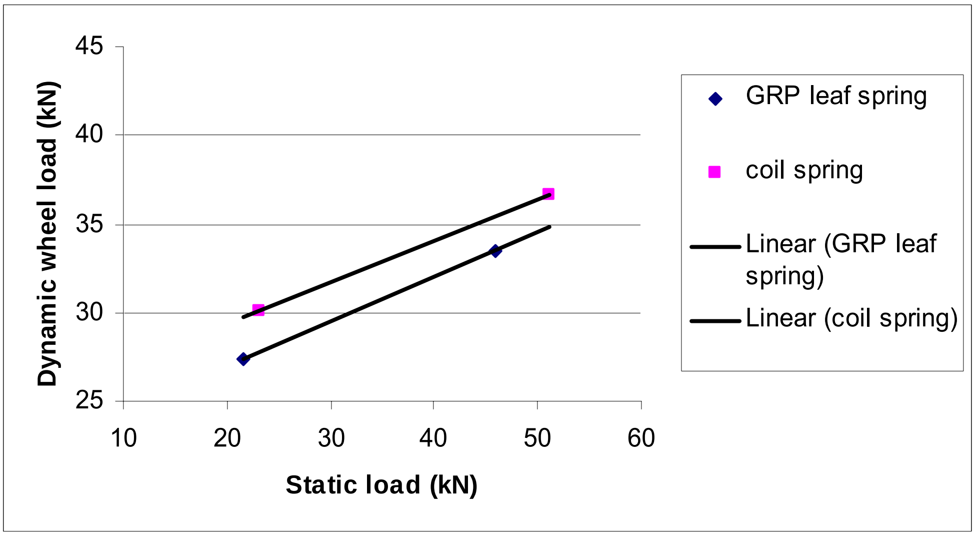


Figure 3.5: effect of static load on dynamic wheel load for BQ9, bogie wagons either GRP leaf or coil sprung, vehicle speed 160 km/h

This dependency is very different for heavy road vehicles because available evidence suggests that the dynamic wheel load increases as the 4th power of the axle load [3]. Thus vehicle overloading can create much higher forces on the pavement than on the track. Hence the ability of the track to carry much higher axle loads than the pavement even if the suspensions are ‘road friendly’.

3.4 Vehicle speed

The dynamic load coefficient increases with increasing vehicle speed as shown in figure 3.4 as well as fig 3.6. The smoother the track profile, the lower is the value of the dynamic load coefficient. This is the reason why higher speeds are allowed on motorways and high speed track, both of which are well aligned.

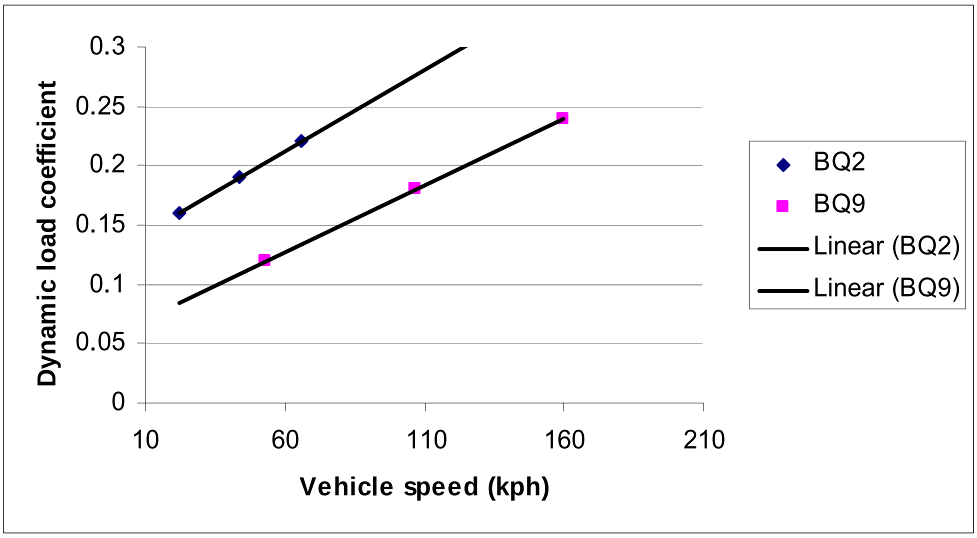


Figure 3.6: effect of vehicle speed (km/h) on dynamic load coefficient for BQ2 and BQ9 track quality; bogie wagon 2 leaf GRP parabolic; tare load

3.5 Infrastructure friendly suspensions

“Road friendly” suspensions are those which exert low dynamic wheel loads. They are defined by EU legislation in terms of the vehicle’s natural frequency and dynamic damping of the sprung mass and can be measured by the EU drop test which requires dropping the vehicle off a ramp 80mm high or pulling down the vehicle 80mm and releasing [10]. It is based around the properties of air suspension and does not allow other suspensions like GRP leaf to qualify as their natural frequency is higher than the 2.0 Hz limit even though their dynamic load coefficient is equal to that of air suspensions on good roads [5]. An improved definition would require either the natural frequency to be less than 2.0 Hz or else the dynamic load coefficient to be <0.10 for ‘well laid’ roads.

No European definition exists yet for rail suspensions and so the weight and vehicle excise duty concessions granted for road vehicles fitted with ‘road friendly’ suspensions cannot be applied to rail vehicles. A suitable limit could be based on the dynamic load coefficient for a vehicle travelling at 100 kph on continuous track (track quality band BQ9).

3.7 Conclusions

The infrastructure profile dominates the interaction with the vehicle as the suspension design has to respond to whatever quality of infrastructure it meets. The better the profile, the lower is the dynamic wheel load so investment in infrastructure is a critical parameter in terms of minimising the interaction. Better profiles will also permit higher speeds or higher axle loads so increasing the carrying capacity.

Chapter 4 Influence of vehicle mass and wheel quality

4.1 Introduction

The vehicle mass exerts static (or quasi static) forces on the infrastructure. Undulations in the track or pavement, or irregularities in wheel quality, result in dynamic forces being super-imposed on the static load. The infrastructure has to be able to resist both sets of forces for ever increasing amounts of traffic over long time periods as maintenance can only be undertaken by disrupting the traffic flows.

For road vehicles, these loads can be measured by weigh-in-motion (WIM) sensors which measure the dynamic forces exerted through the tyre of a moving vehicle and estimate the corresponding static tyre loads. As outlined before [22], the WIM sensor array used to measure loads can also provide information on

- gross vehicle mass
- mass per axle, number and spacing of axles
- vehicle speed
- direction of travel
- lane of operation

Tyre pressure and the resulting contact forces play an important role in the transfer of loads from the vehicle to the infrastructure. Improperly pumped tyres induce high strains in the pavement causing more damage and making them environmentally unfriendly. The contact forces can be measured in various ways. At the Swiss FMS at Lenzburg they are measured through the use of the Kistler modulas sensor [23, 24, 25].

For rail vehicles, the influence of the steel wheel running on a steel track is more complex because the load is being transferred to the rail over a small contact area so the forces are much higher. The track itself is mounted on pads and sleepers which in turn are mounted on ballast so this structure has its own dynamic response to a moving load. The track guides the wheel which results in forces in the lateral direction (Y) from instability running on straight track and turning forces and rolling on curves. These forces are very important in curves of small radius (250-400 m) and in switches.

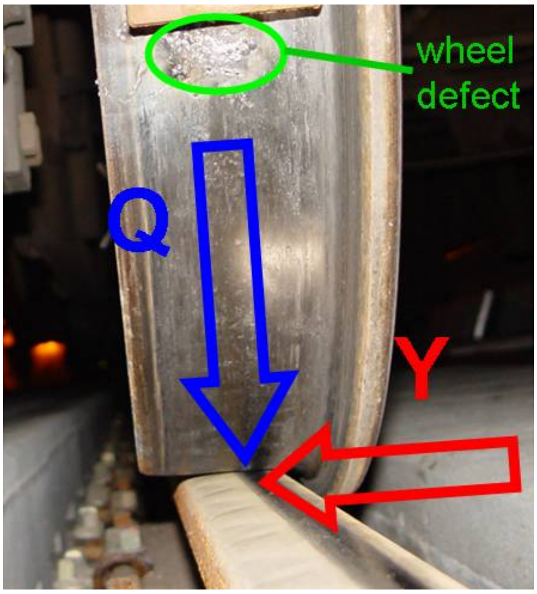


Figure 4.1: Lateral and vertical forces exert by the wheel

Figure 4.1 shows the vertical (Q) and lateral (Y) forces that are transmitted through the rail to the sleeper and via the ballast or concrete slab to the surface and sub-surface layers. A typical wheel defect in the wheel is also shown.

The result of these forces is illustrated in Figure 4.2.

Figure 4.2: From top left clockwise – cracks in pavement; wear and rolling contact fatigue; rutting due to vehicles travelling in the same location; repairs to pavement

4.2 Quasi static loads (road)

Both the gross vehicle mass (GVM) and the axle load are important when considering pavement damage. The limit values are prescribed by legislation for the EU and Switzerland which are gradually moving towards similar limits. The legal limits are listed for the UK and CH in annex 1.

A sample of recorded WIM data (Figure 4. 3) at the road FMS in Switzerland registers about 5500 vehicles over 3 tonnes per weekday out of which about 10% have axle loads greater than 10 tonnes and could be damaging to the pavement. The number of vehicles per day depends on the day (weekday or weekend) and season and year. For example in January 2007 on weekdays this site had 500 vehicles per day less. The GVM limit in Switzerland is 40 tonnes.

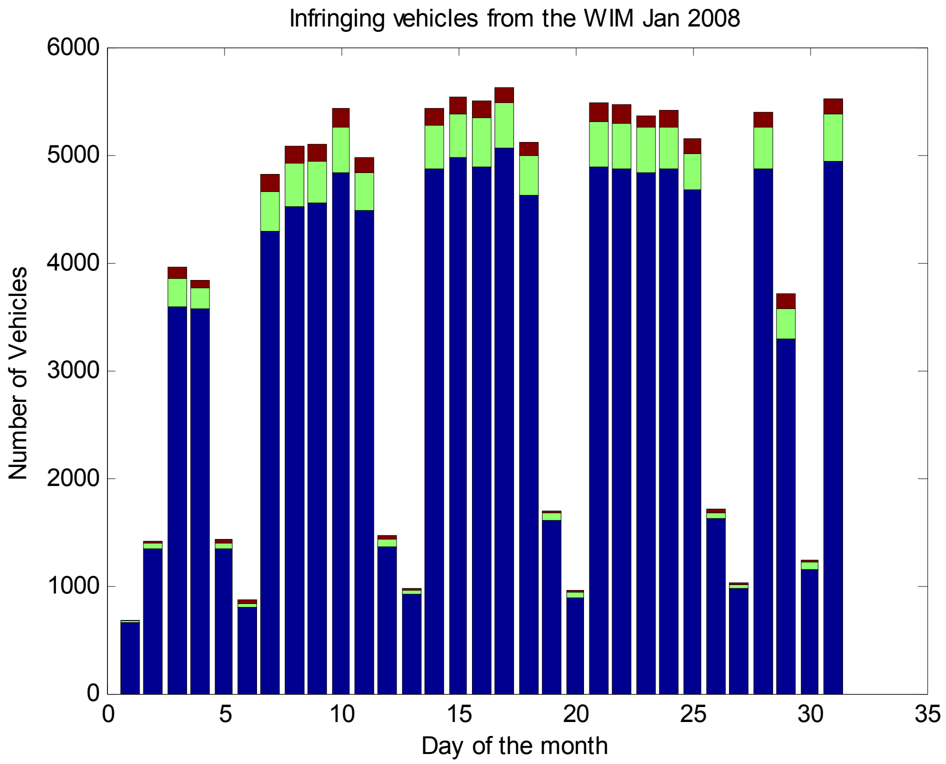


Figure 4.3: Number of vehicles greater than 3 tonnes per day in January 2008, Lenzburg, CH

The number of vehicles that could be above the legal limit for an individual axle is disturbing and will impact the life of the pavement. What is not known is whether the operators are aware of this possible exceedance or whether the vehicle has simply been filled on volume, which in turn has resulted in the weight limits being exceeded. This could be prevented by weighing at the place of loading as many goods are sold on this basis

The number of vehicles greater than three tonnes per day for a typical urban and rural area in the UK are shown in Figures 4.4 and 4.5.

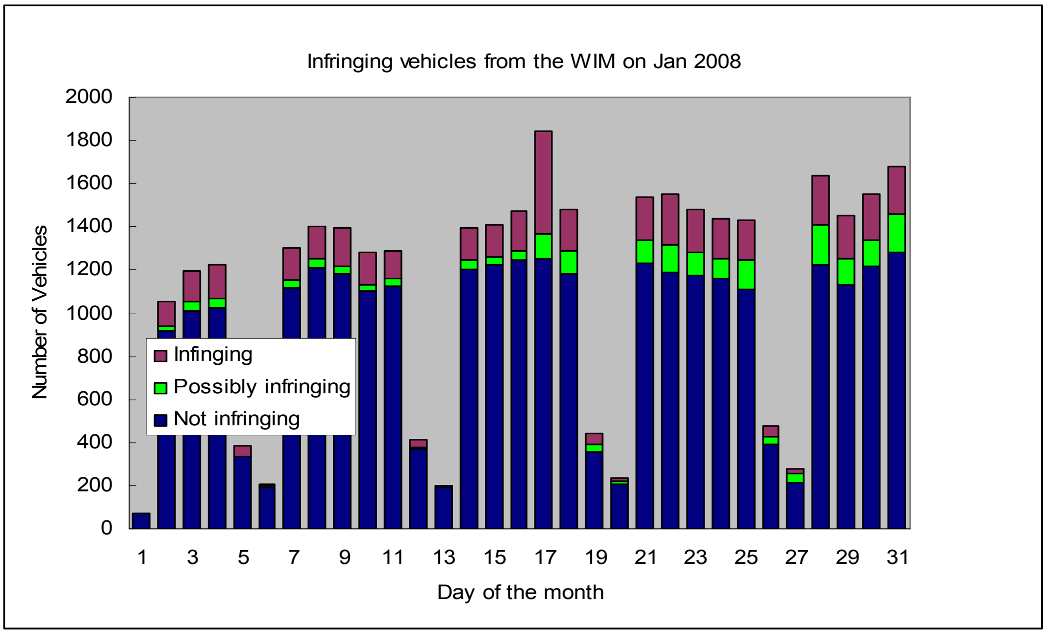


Figure 4.4: Number of vehicles greater than 3 tonnes per day in January 2008, Plymouth, UK a typical urban area

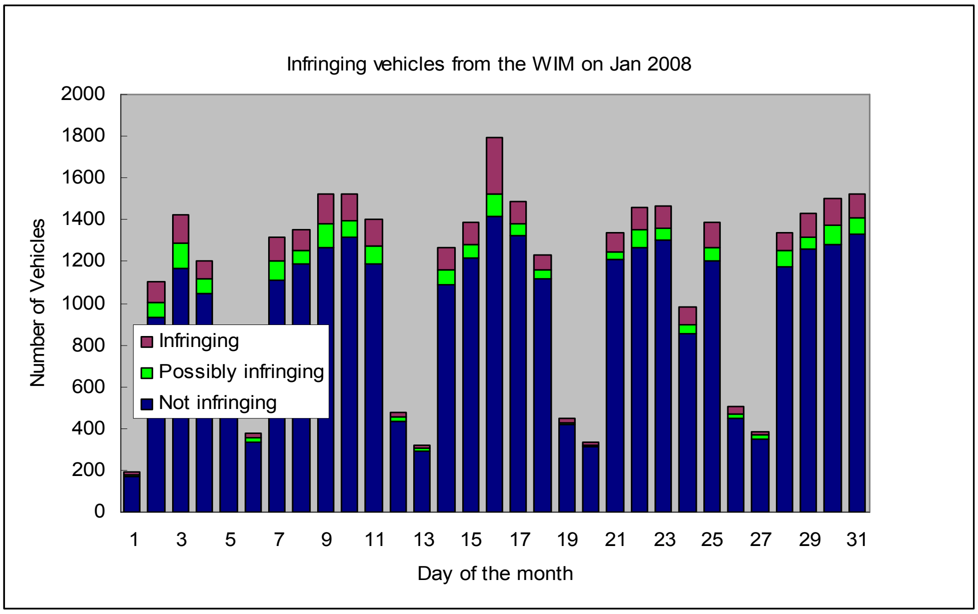


Figure 4.5: Number of vehicles greater than 3 tonnes per day in January 2008, Sparkford, UK a typical rural area

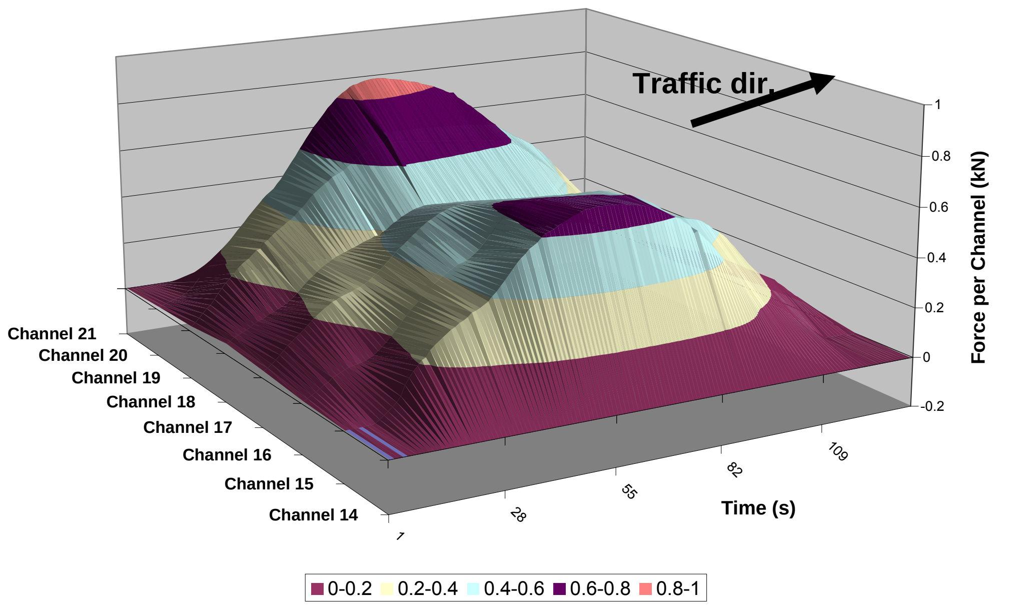
For both the Swiss and UK sites, there appears to be a similar number of vehicles that are or may be infringing the legal load limits for an individual axle, which is surprising. A method of alerting the operator should be devised possibly using number plate recognition which would allow the operator to make checks on his vehicle or loading procedure.

In the UK, at a number of carefully selected strategic locations, VOSA operate a WIM system linked to automatic number plate recognition (ANPR) cameras. These systems are used for pre-selection and are able to identify infringing vehicles which then alert VOSA officers positioned further along the route enabling them to identify the infringing vehicle and direct the vehicle into a static weigh station where the appropriate enforcement can be made.

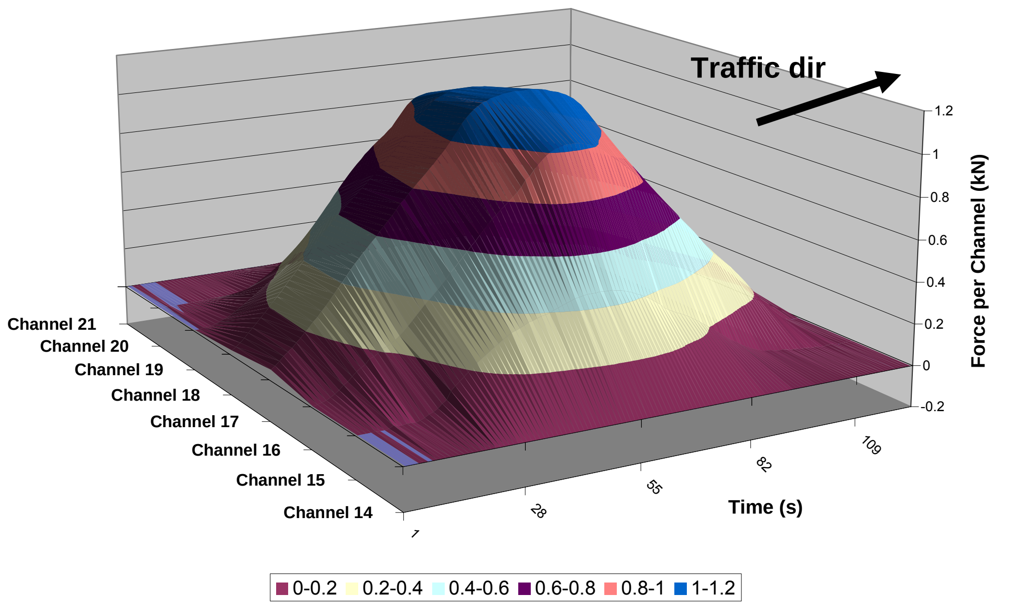
4.3 Effect of tyre pressure

The rubber tyre distributes the force across its contact area to the pavement. The magnitude of the forces and the size of the area will depend upon the tyre pressure. Such stress-in-motion data have been measured using a prototype sensor at the Lenzburg site. These data are then analysed using a finite element model of the pavement to determine the stress distribution [24, 25]. Figure 4.6 shows that tyre pressure does affect the contact stress distribution as seen in the 3D representation of force distribution in the footprints of MMLS3 tyres at 2 bar with “m” shape distribution and 6 bar “n” shape distribution. Additionally, it was shown that for all but the heaviest tyres, the shape of the contact stress distribution, which is affected by the tyre pressure, had a significant effect on the stresses and strains in the pavement [24, 25].

It is a practice amongst some operators to over inflate their tyres to increase tyre life but this can have an adverse effect on the life of the pavement as the forces are concentrated over a smaller area and the contribution of the tyre to the stiffness of the vehicle suspension is increased.



(a) Tyre Pressure= 2 bar, Wheel Load= 2.1 kN, Speed= 9km/h



(a) Tyre Pressure= 6 bar, Wheel Load= 2.1 kN, Speed= 9km/h

Figure 4.6: 3D representation of force distribution in the footprints of road traffic simulator MMLS3 tyres at 2 bar with "m" shape distribution (top) and 6 bar "n" shape distribution (bottom), traffic direction is perpendicular to the channels [24, 25]

In order to determine the impact of mass, various theories have been developed. The current approach in the scientific community is that the impact depends not only on the amount of load, although this is an important factor, but on how this load is transferred to the pavement. The sample in Figure 4.7 shows that similar wheel loads can have quite different impacts. In order to minimise impact in addition to limiting allowable loads, it is important in the case of road vehicles to have properly pumped tyres and in the case of rail vehicles to have properly shaped wheels.

In considering the effect of mass it is important to also consider the type of infrastructure as the same vehicle can have a small impact on the primary motorways but a higher impact on the secondary roads. The effect of infrastructure is further discussed in chapter 5.

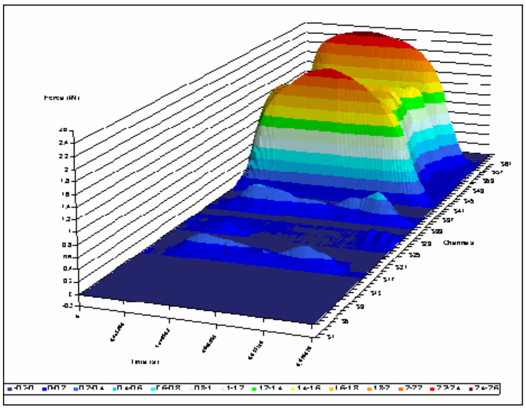
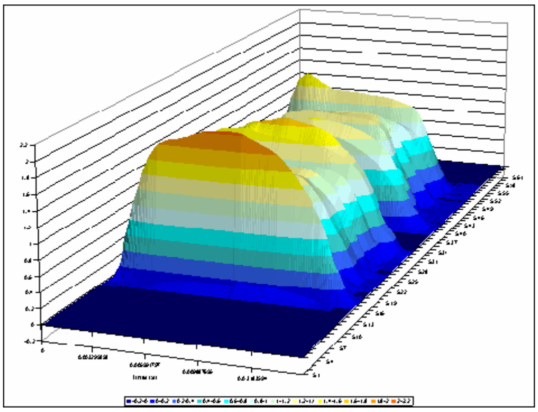
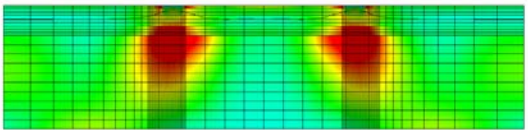
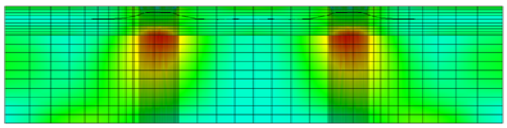
	
Run 67 In-situ measurement of double tyre with one flat tyre Load=72.4 kN, Temp=21°C, Speed=22 m/s	Run 70 In-situ measurement of properly inflated double tyres Load=83.9 kN, Temp=24°C,Speed=22 m/s
	
Strains in Asphalt:-375 με , +299 με	Strains in Asphalt:-216 με , +175 με

Figure 4.7: In-situ measurement of force distribution for two tyres (above) and the resulting impact (below)

4.4 Quasi static loads (rail)

Data from two Quo Vadis measuring sites are shown in Figure 4.8 over a period of 6 days in –August 2009; the data in red are from Zevenhuizen, NL which carries only passenger trains. (Gouda -> The Hague) and the data in blue from Rotterdam Europort which is mainly freight trains going eastwards from Europort. Though none of these trains exceed the maximum train mass based on the number of axles and an axle load limit of 225 kN, it is clear from this data set that there is a small number of axles that exceed the legal limits. Similarly, Figure 4.9 and 4.10 show the data measured in Austria through the "Argos" rail site. Axle loads are discussed further in chapter 5.

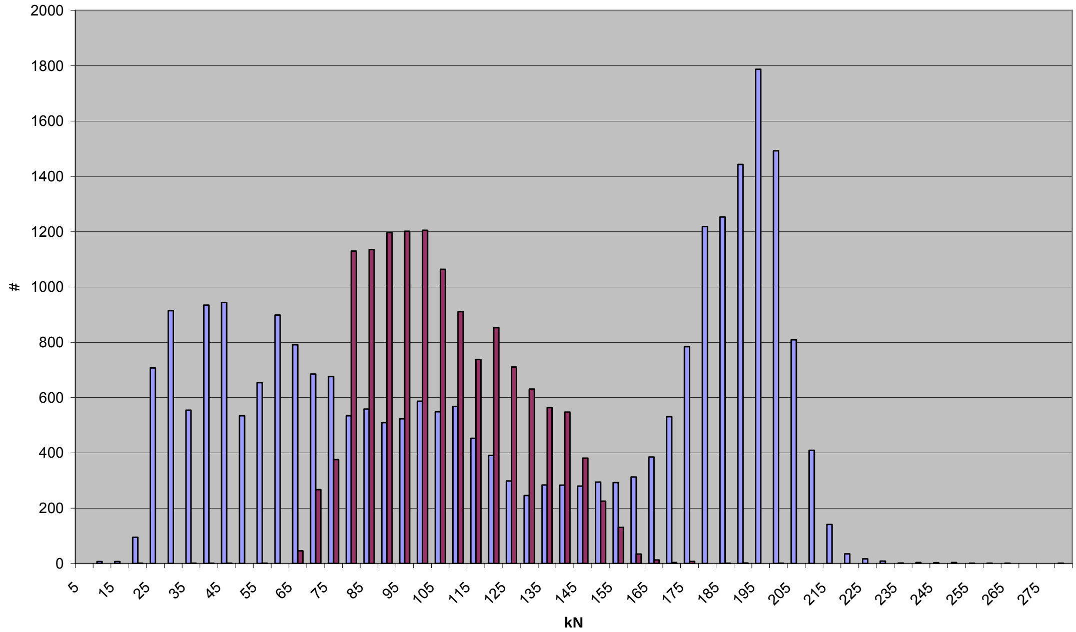


Figure 4.8: Histogram showing characteristic axle loads for two typical rail sites (NL). Data in red primarily from passenger traffic; in blue from a site with predominantly freight traffic

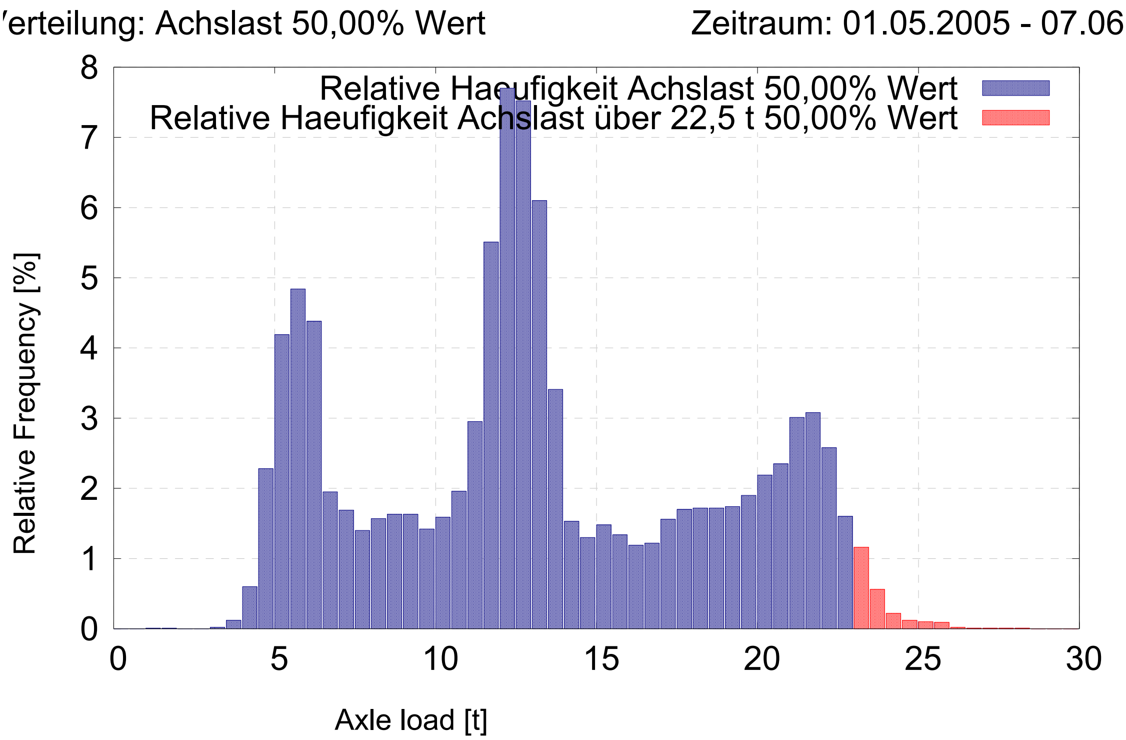


Figure 4.9: Railway - histogram showing relative frequency of axle loads, red axle load over 22,5t, measured in Austria through "Argos" rail site

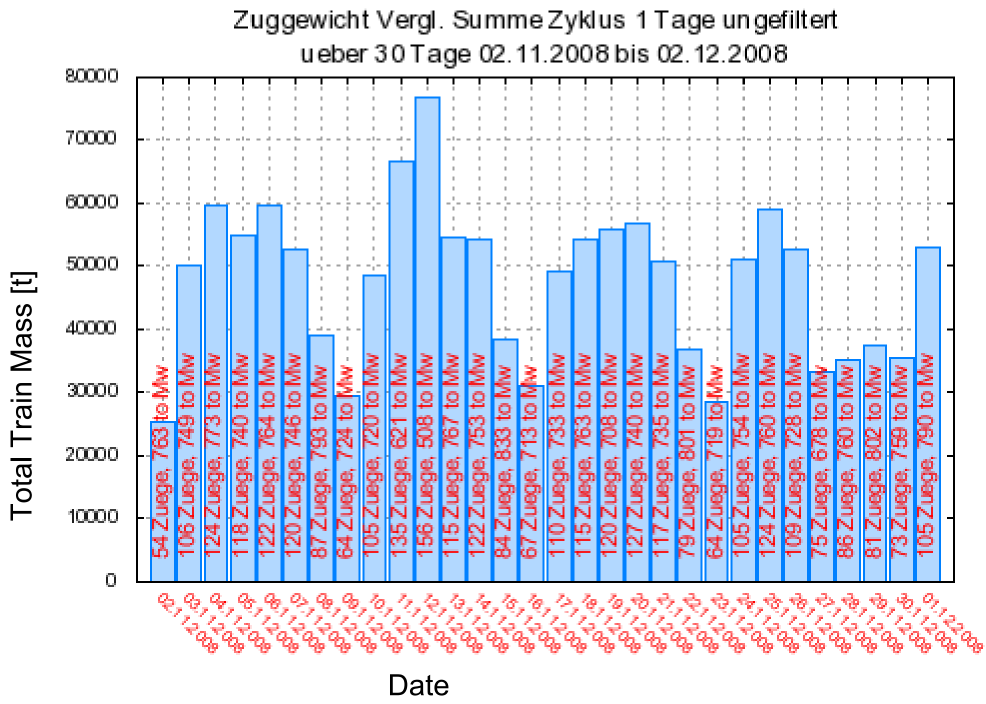


Figure 4.10: Railway - total daily train mass and number of trains, measured in Austria through "Argos" rail site

4.5 Dynamic loads and wheel quality

For rail vehicles, the output of the load monitoring sensors is recorded for each train passage [22]. The signal from each sensor is then analysed for each wheel to identify the static load and dynamic forces. Such systems are capable of analysing the weights of wheels, axles, vehicle and train. An example of a typical sensor signal for two passing wheels is shown in fig 4.11, one with no defect and the other with a wheel flat. Figure 4.12 shows an example from Austria with static and dynamic loads of wheels with defect and no defect.

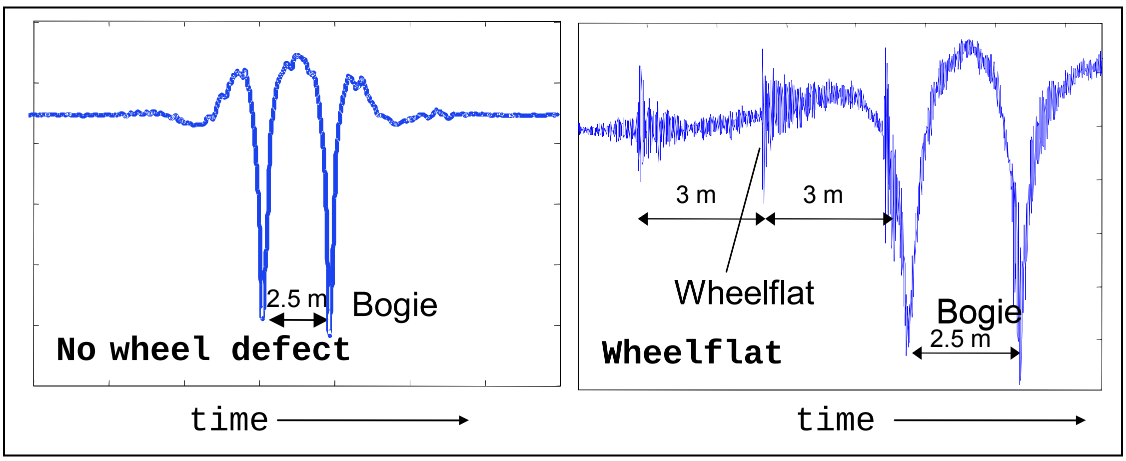


Figure 4.11: Output sensor signal showing no defect (left) and a wheel flat (right) from the rail FMS in the Netherlands [22]

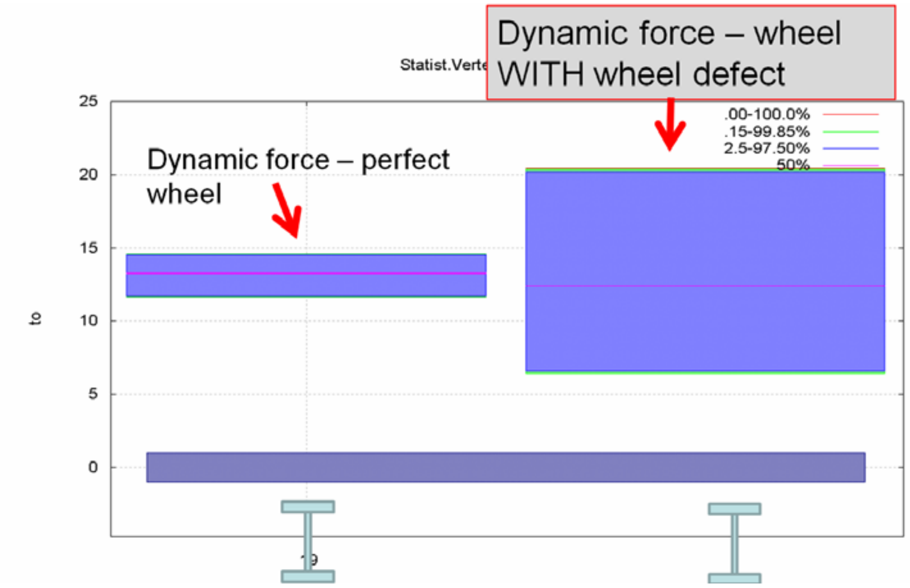


Figure 4.12: left axle: dynamic force in tonnes (blue band) and static force (red line) of an wheel without wheel defects; right axle dynamic force of an axle with wheel defect (flat with 70mm, measured in Austria through "Argos" rail site

Thus for rail vehicles, such measuring systems can produce information about the quality of wheels for specific axles and distinguish various types of defects such as out of roundness or wheel flats.

Depending upon the magnitude of the dynamic load, it is possible to allocate a defect class [22]. If the dynamic load exceeds a preset level, then an alarm can be triggered in the control cabin which can in turn be used to alert the driver. All alarm settings can be individually set for different track and for different types of rolling stock.

Examples of wheel defects from the Argos FMS are shown in Figure 4.13 and 4.14.

As the train set is an assembly of vehicles not all of which, or none, may be tagged, it is essential that the axle with an excessive load or defect is identified by a systematic numbering of the axles starting with the first axle of the train.

Wheel defects (out of roundness and wheel shape irregularities) are the main cause of noise emission and vibrations. The most cost efficient way is to reduce these emissions at the source by reducing the number of wheel defects through proactive maintenance giving the possibility of savings in both noise reduction and the prevention of track damage.

If additional sensors are installed above the minimum required to determine wheel quality and sufficient data are recorded it is then also possible to determine the whole wheel shape. This allows the wheel defects to be classified as shown in Figure 4.15 and so enables the maintenance engineers to schedule their maintenance regimes.

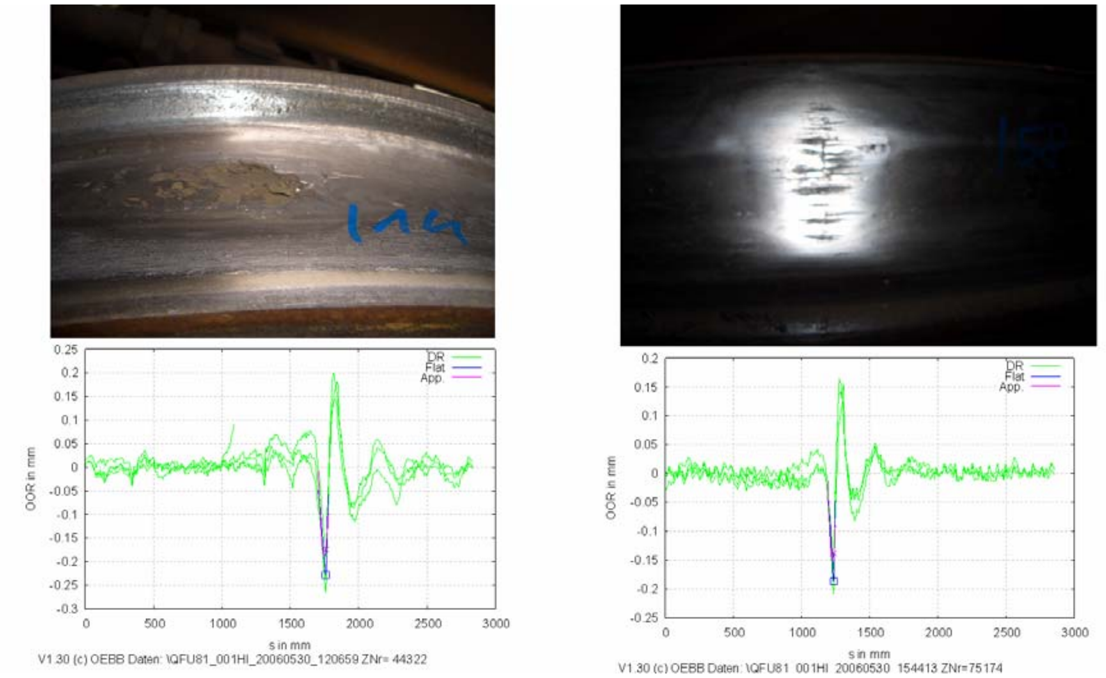


Figure 4.13: different wheel defects and measured out of roundness, measured in Austria through "Argos" rail site

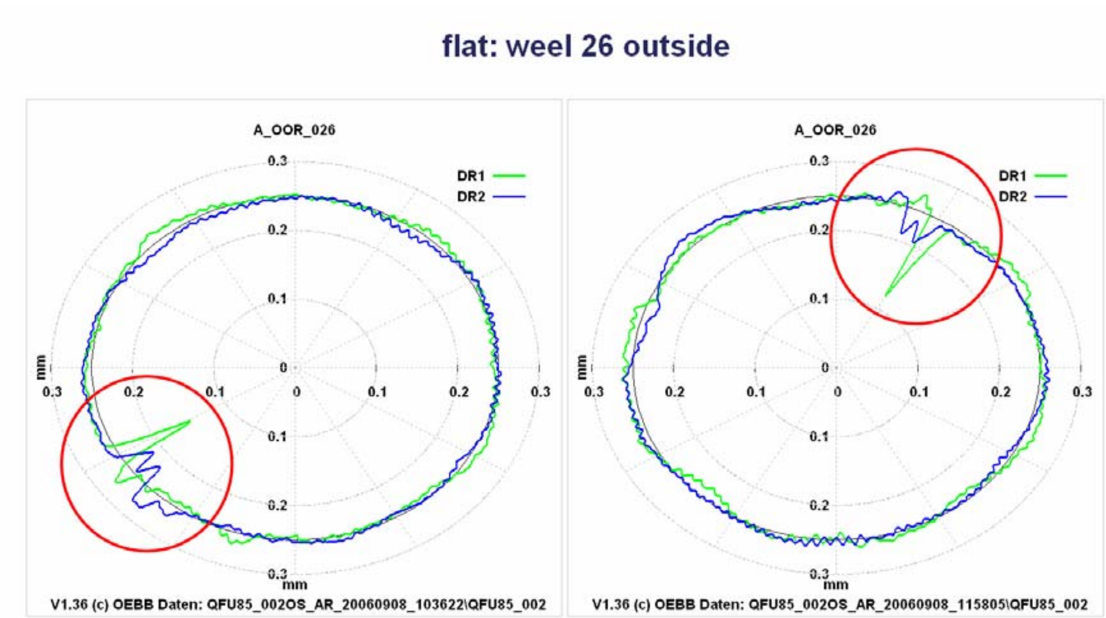


Figure 4.14: repeatability of measured out of roundness, same wheel measured twice at the "Argos" rail site

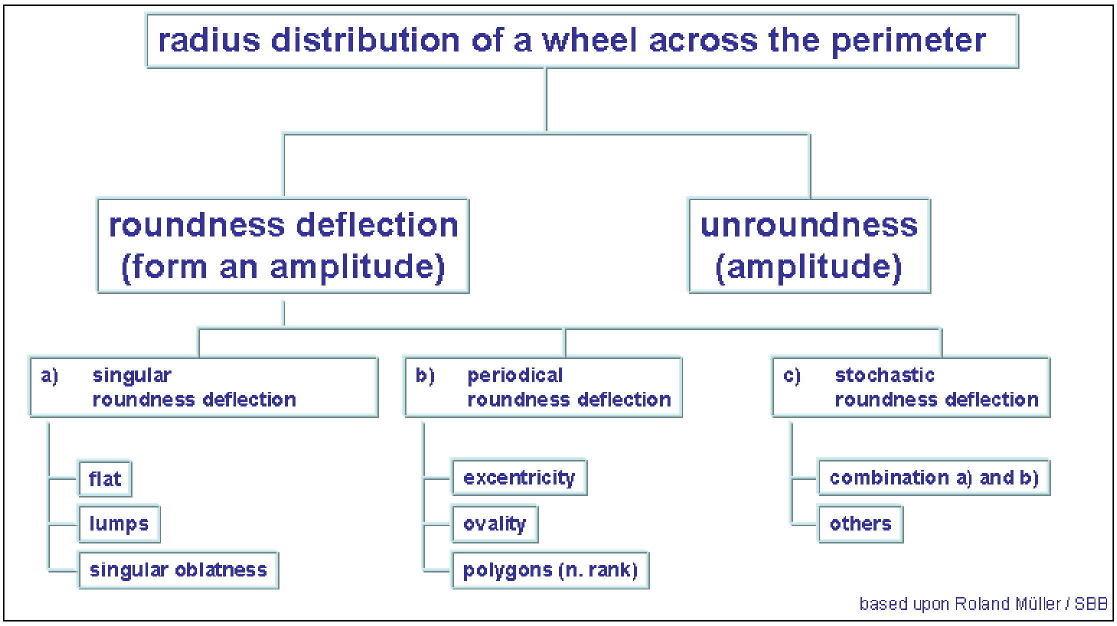


Figure 4.15: classification of wheel defects

4.6 Effect of mass on vibrations

Sample data from the Swiss road FMS at Lenzburg (Figure 4.16) show that with increasing gross vehicle weight there is an increase in the level of ground borne vibrations. However the data also show that ground borne vibrations are below levels that could be considered disturbing for humans or damaging for buildings at this particular site. This may however not be true for less well constructed pavements.

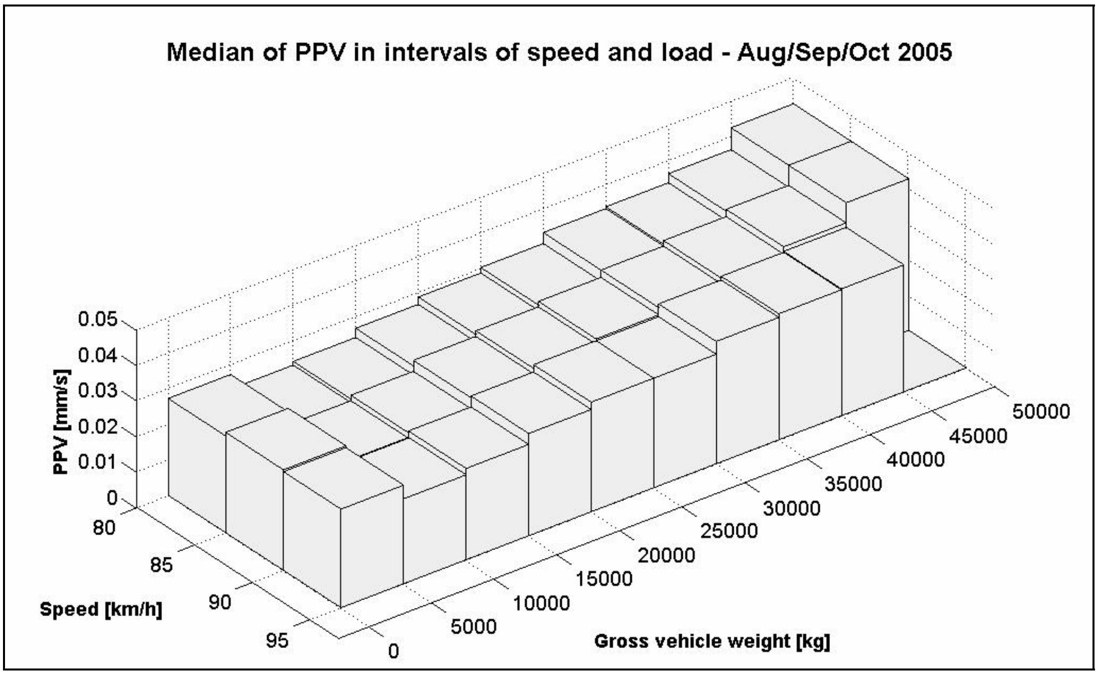


Figure 4.16: Correlation between particle peak velocity (PPV) to GVW and vehicle speed from the road FMS in Switzerland [24]

The measured velocity of ground borne vibrations from a rail FMS in CZ, is shown for individual axles of a train set in Figure 4.17 (RMS value) and in Figure 4.18 (PPV value).

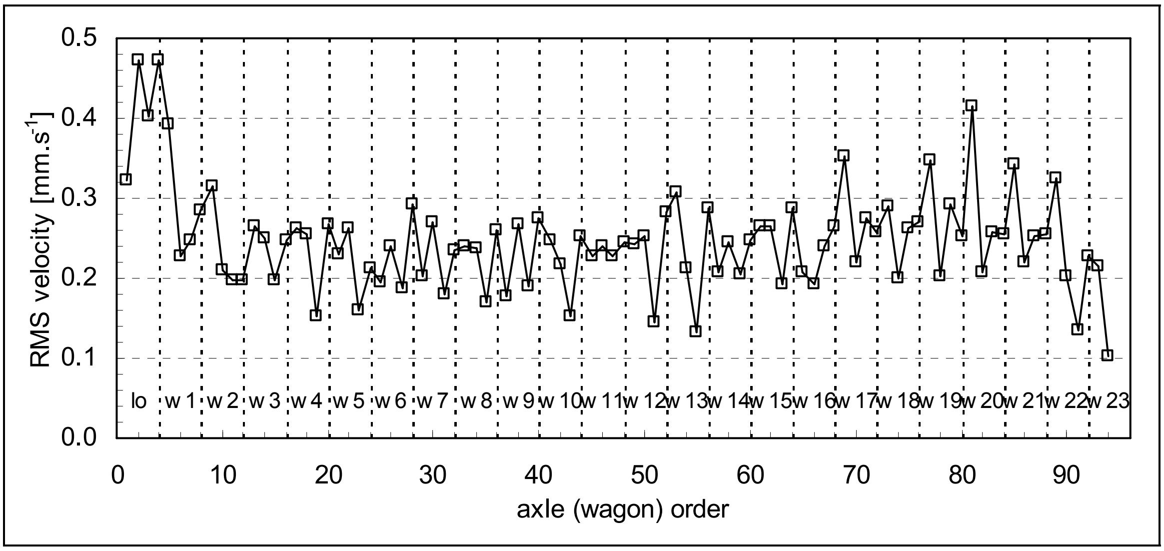


Figure 4.17: Distribution of RMS velocity of ground borne vibration from passing freight train from the rail FMS in CZ

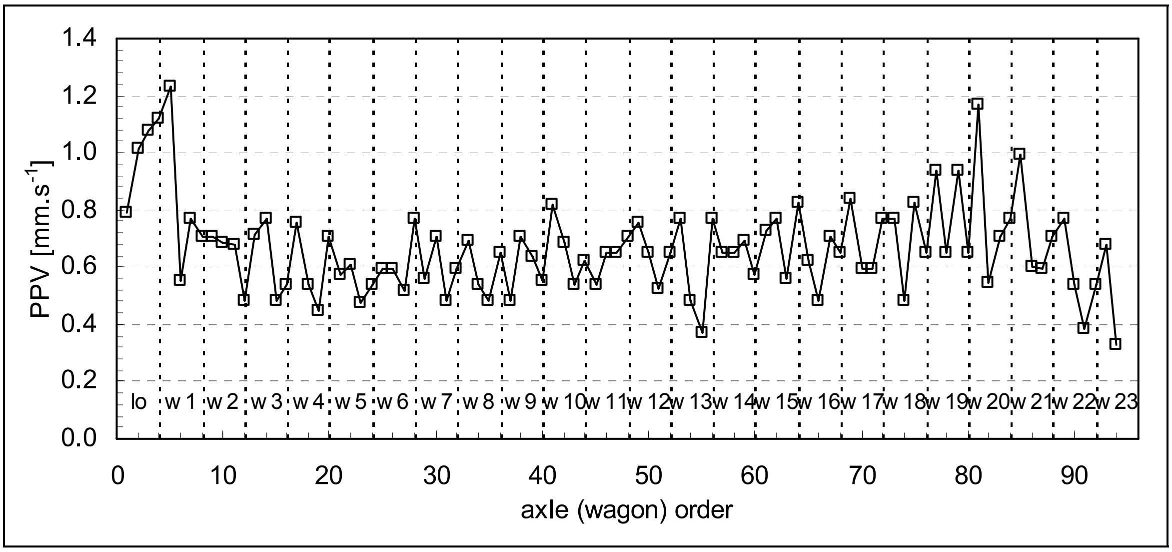


Figure 4.18: Distribution of PPV of ground borne vibration from passing freight train from the rail FMS in CZ

These data show that the vibration levels are high for the leading and for one other axle. The leading axles are always likely to have a high vibration level as the axles are steered by the rail; however the high vibration level of the one other axle (19w) suggests that that this wheel set is in need of attention and maintenance.

4.7 Conclusions

The allowable axle loads on the heavily trafficked road and rail network are similar throughout Europe with rail allowing typically a maximum of 22.5 tonnes and road 11.5 tonnes on the drive axle. Elsewhere the allowable limits depends on grouping of axles and number of tyres (refer annex 1).

The results from the footprint measurement systems (FMS) in various European countries presented here show that with rail freight gross vehicle loads are normally below these limits whereas for road freight, some vehicles surpass these allowable values. This can be due to the fact that it is easier to monitor rail vehicles than road vehicles and due to the fact that there are not as many different vehicle owners on the rail as on the road. However, wheel quality and tyre pressure should also be considered as they exert additional forces which will have a detrimental effect on the infrastructure.

Ground borne vibrations measured at the FMS sites are higher from rail vehicles than those produced by road vehicles which are below levels that can be detected by humans or damaging to infrastructure. However, it should be noted that the measurements for vibration on roads have all been carried out on pavements built to the highest design specification. It is possible that vibration could have a significant impact on less well designed pavements or bridges.

Chapter 5 Effect of axle loads

5.1 Introduction

The great advantage of weigh-in-motion measurements is that they enable individual axle loads as well as gross vehicle mass to be determined. The **higher** the axle load, the **higher** are the static and dynamic forces exerted on the track or pavement (refer chapter 3 and 4). Higher forces will lead to more damage to the infrastructure, higher levels of vibration and noise emissions and higher levels of environmental and societal costs.

5.2 Axle load (road)

A typical distribution from the Swiss FMS on the A1 motorway at Lenzburg between Zürich and Berne is shown in Figure 5.1. The lower peak around 1.5 tonnes is due to unladen and light trucks and the higher peak around 6 tonnes to laden and heavy trucks whilst the tail beyond the peak is due to the heaviest trucks and those that are exceeding the weight limits. Such data enable pavement and bridge designers to develop and check the loadings exerted on their structures and so determine the residual life. Such distributions can also be used to monitor long term and establish trends in vehicle usage and loading.

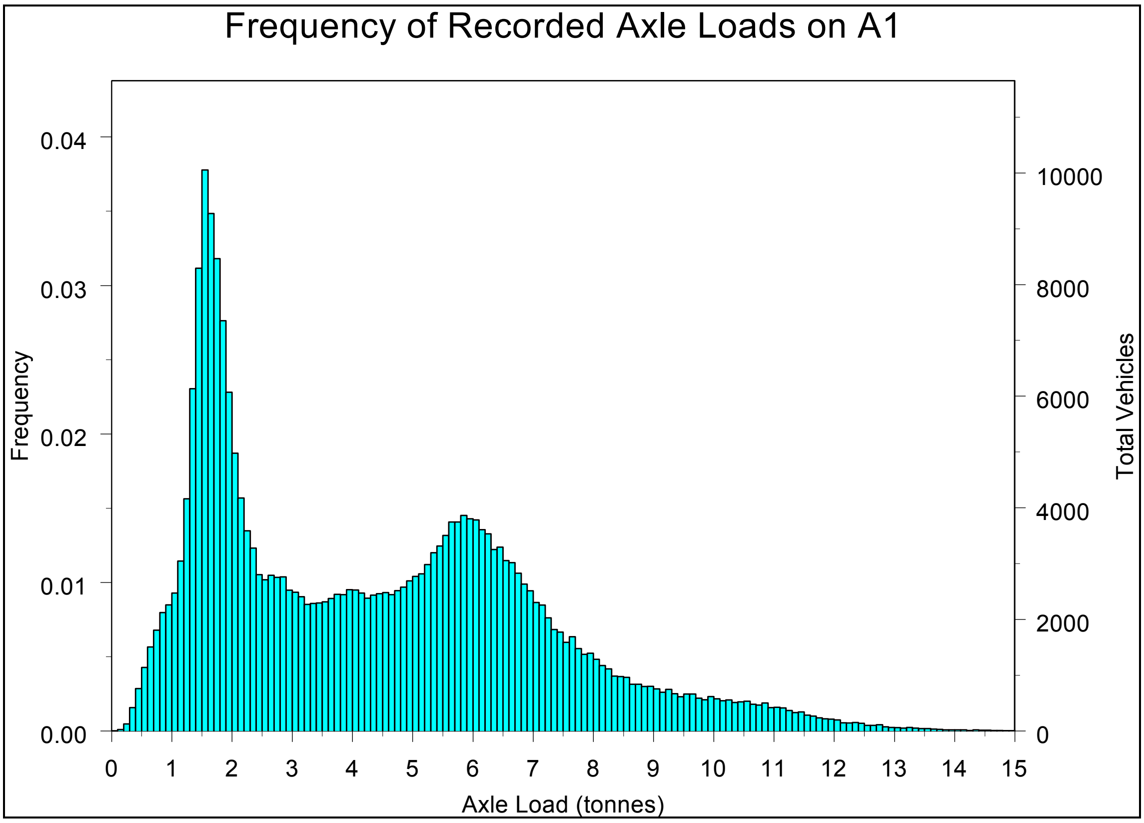


Figure 5.1: Frequency distribution of recorded axle loads on Lenzburg site, September 2005 (23)

What is of concern is the significant proportion of vehicles with axle loads that exceed 10 tonnes. This is illustrated in more detail in Figure 5.2 for articulated freight trucks, (Swiss class 10, COST class 5, chapter 1.4) which have the highest number of axles over 10 tonnes and so cause the most damage to the pavement.

The only categories that allow such high axle loads is the rear axle of two axle trucks of 18 tonne mass (class 2) and the drive axle of the tractor unit if all suspensions are road friendly (class 5). The maximum permitted axle load for these configurations is 11.5 tonnes and it can be seen from Figure 5.1 that axle loads above this limit have been detected.

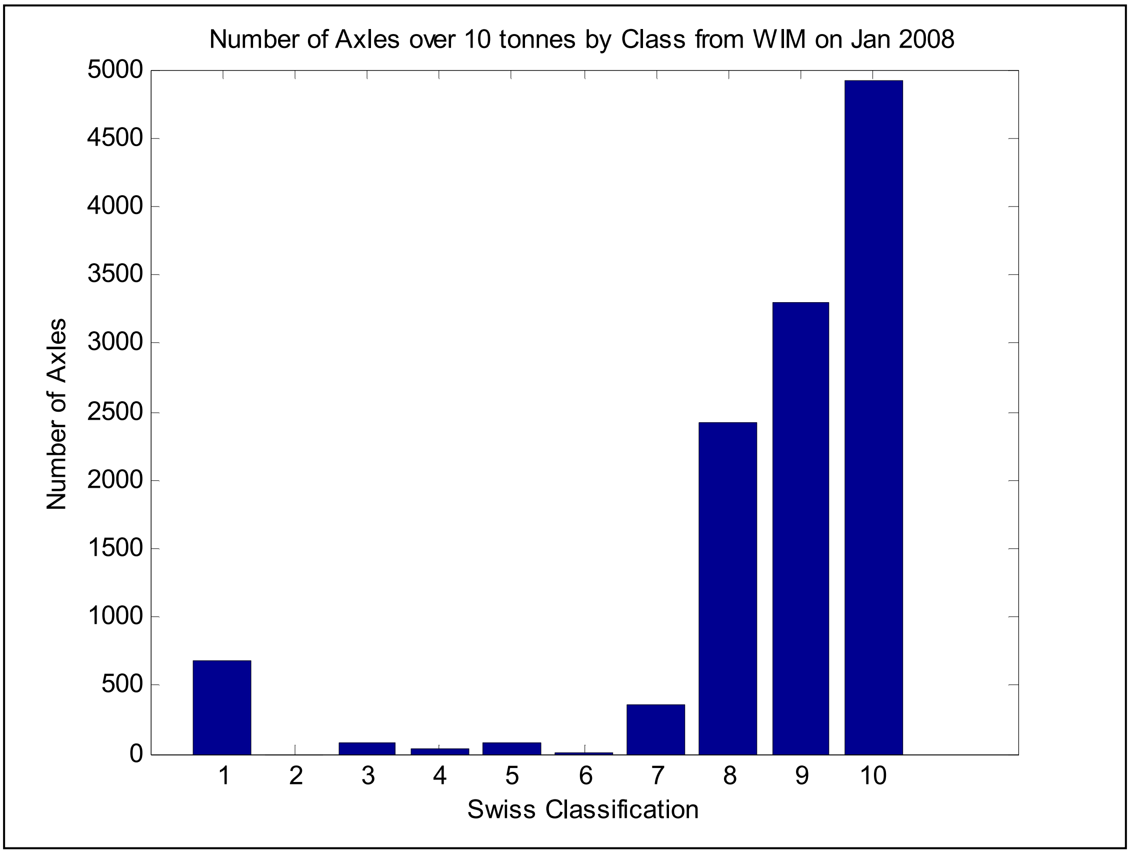


Figure 5.2: Number of axles over 10 tonnes by vehicle class, Lenzburg site January 2008 (Empa)

5.3 Axle load (rail)

The distribution of axle loads for rail vehicles is shown in Figure 5.3 aggregated across the various ProRail measurement sites [6].

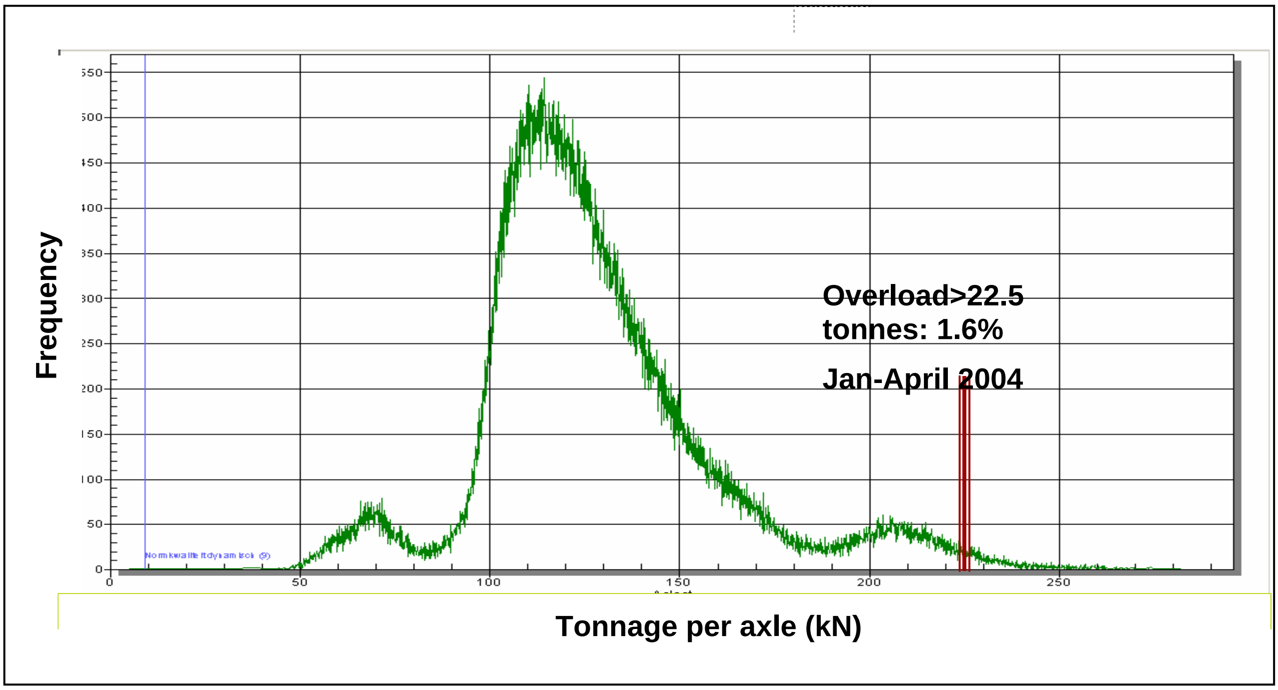


Figure 5.3: Axle loads in the Netherlands

The large peak is associated with passenger trains with an average axle load of around 12 tonnes. The smaller peak, around 7 tonnes, is associated with unladen freight vehicles and the third peak, around 21 tonnes, with laden freight vehicles. As with road vehicles, a significant proportion of axles were above the EU/UIC limit of 22.5 tonnes (225 kN).

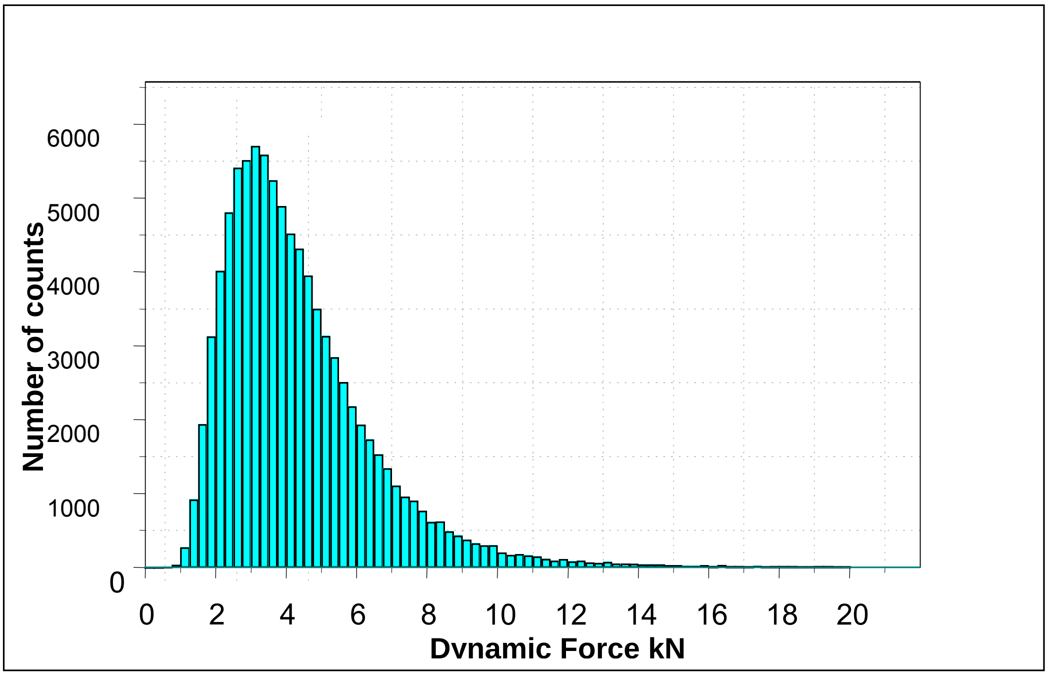
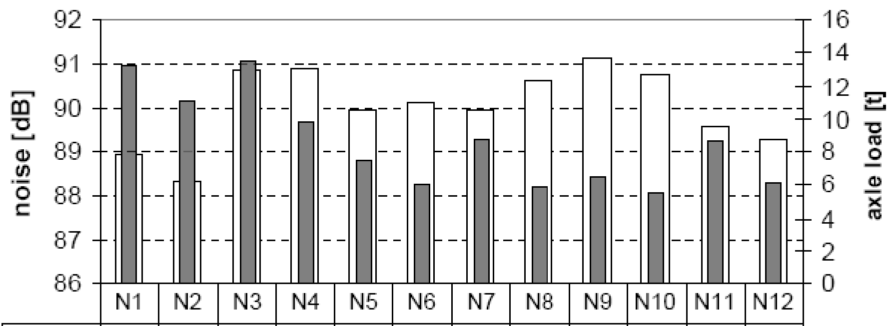


Figure 5.4: Measurement of dynamic forces by wheel for 90,000 wheels

The distribution of dynamic forces is shown in Figure 5.4 for 90,000 wheels. As previously, there is a significant proportion with a dynamic force in excess of 8 kN per wheel. Some of these wheels may be out of round and require wheel turning (refer chapter 4.5) and for other axles the suspension system may be in need of maintenance.

5.4 Axle load and noise emissions

The relationship between axle load and noise has been measured near Plzen, Czech Republic [3]. The data for a three coach passenger train are illustrated in Figure 5.5 which shows a significant variation amongst the axles; this is likely to be due to variations in wheel quality.



	N1	N2	N3	N4	N5	N6	N7	N8	N9	N10	N11	N12
□ noise	89.0	88.3	90.8	90.9	89.9	90.1	90.0	90.6	91.1	90.8	89.6	89.3
■ axle [t]	13.3	11.1	13.4	9.8	7.4	6.0	8.7	6.0	6.4	5.5	8.6	6.2

Figure 5.5: Load and noise measurements from each passing axle

The relationship between axle load and axle noise from one day's measurements is shown in Figure 5.6. Although there is considerable scatter amongst the data, there is some correlation between axle load and noise emissions.

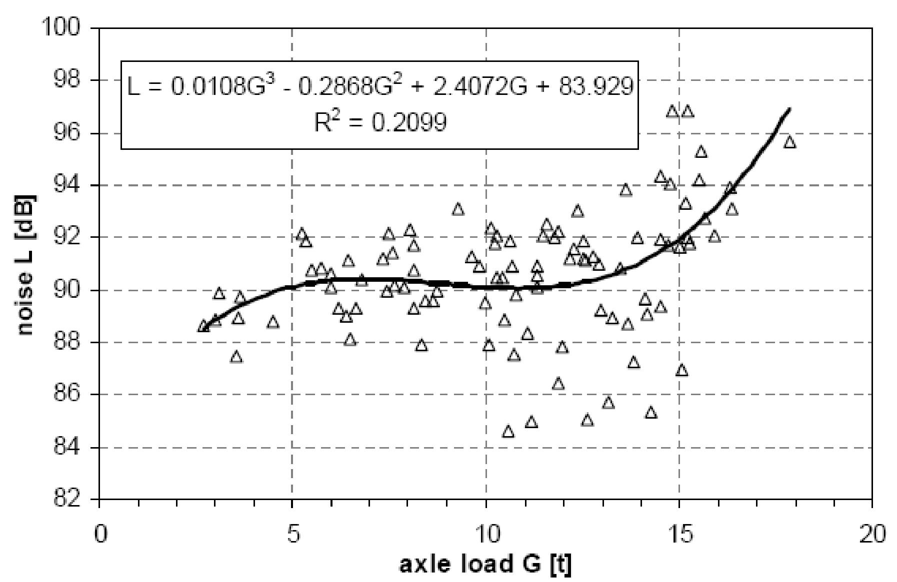


Figure 5.6: Relationship between axle load and noise

5.5 Axle load and vibration

The relation between audible noise as well as RMS velocity vs. axle load from the rail FMS in Plzen is given in Figure 5.7. As shown, no direct relationship between axle load and ground borne vibrations could be established.

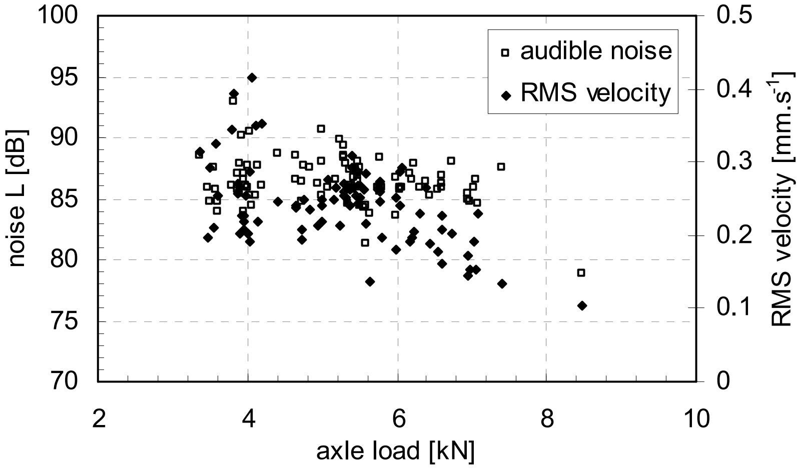


Figure 5.7: Relation between noise and RMS velocity vs. axle load of passing freight train

5.6 Axle over-loading

The gross vehicle mass affects primarily the overall static load which the structure has to be able to resist and is of particular importance in bridge design. The axle load primarily affects the dynamic loading which for road vehicles increases as the 4^{th} power of the axle load [8]. It is therefore important that both road and rail vehicles are loaded and maintained in such a way as to *not* exceed load limits. Reasons for overloading as observed in the data sets include –

- excessive loading which can be checked by weighing individual cargoes or the whole vehicle
- unbalanced loads which can be prevented by weighing individual loads or ensuring that bulk loads are equally loaded
- inadequate load distribution between axles which can be prevented by keeping vehicles to type approval standard
- insufficient maintenance of suspensions which should be checked at regular intervals
- wheels out of round which can be minimised by a suitable maintenance schedule using rail WIM systems to provide relevant information during service operation (refer chapter 4.5)
- under the same axle loads, tyres over or under inflated can create a disproportionate amount of damage to the pavement (refer chapter 4.3)

As all forces are equal and opposite, high axle loads not only exert high forces on the infrastructure, but also exert high loads on the chassis and the goods being carried. The result is fatigue cracks that can be initiated in the pavement, track, wheel or vehicle chassis and, in the case of extreme loads, the vehicle chassis could become twisted. So it is in both the operator’s and the maintainer’s interest to maintain loads within axle load limits.

5.7 Bonus/malus system

Current EU legislation [4] permits rewarding those operators whose vehicles are under a set limit (bonus payment) or imposing an extra charge (malus payment) if over a set limit. The evidence presented in this chapter is that a small proportion of users are creating a disproportionate amount of damage through overloading. This applies to both road and rail vehicles. In some of the examples, the operator or driver may not be aware of the damage being done and a penalty/reward system could encourage an investigation as to the cause when a vehicle is shown to be overloaded (refer chapter 9.6).

5.8 Conclusions

Axle overloading does occur and inflicts a societal cost in terms of damage to the infrastructure. Overloading can also result in increased levels of noise and vibration. A bonus/malus system may seem a sensible way to alert the operator.

Chapter 6 Factors influencing rail noise emissions

6.1 Introduction

Noise emission of **rail** vehicles is influenced by the following site specific factors:

- ***track system***: hard surfaces such as slab track increase emissions significantly compared to ballast type track systems.
- ***sleeper type***: compared to wood, concrete bi-bloc sleepers can reduce noise emissions by up to 3 dB(A) .
- ***rail support system***: stiffness and damping of the support system has an effect on emissions of about 5 dB(A)
- ***rail roughness***: in contrast to very rough rails, very smooth rails can lower emissions by up to 15 dB(A)

Rail wheel profile

For rail vehicles where brake blocks are applied to the wheel tread, the wheel roughness is affected by the block material and can result in up to 10 dB(A) of noise generation [29].

Type of ground in the vicinity of the receiver position

Sound at the measuring microphone position is composed of a direct and ground reflected component. Soft ground alters ground reflection resulting in a different interference pattern compared to hard ground.

Noise reduction in Austria within the past 15 years

In 1993, Austria became the first European country to limit noise generation from rolling stock by introducing the SchLV [29] ordinance. Only rolling stock registered in Austria was covered by this legislation so due to the international and inter-operative character of rail transport only a limited effect has been expected. However, recent monitoring results [19] show that rolling stock that came into operation after 1993 is less noisy than the older stock and that there was an international improvement as well. New locomotive and multiple unit generations for Austrian Federal Railways ÖBB have had to fulfil SchLV noise limits but are also sold to and used in other European countries.

6.2 Locomotives

Figure 6.1 shows the speed dependent A-weighted pass-by level LpA,pb as measured from the nearest track 7.5m on a TSI-CR-NOI [30] compliant track for different classes of ÖBB locomotives. Classes L1042 and L1044 are electric locomotives, L2143 is a diesel locomotive and L5047 is a diesel multiple unit (DMU). These vehicles have all been put into service before 1993 and therefore did not comply with any legal noise generation limit. Classes L1116 (electric) and 2016 (Diesel) are locomotives that have been ordered in the late 1990s.

The difference in noise generation is obvious. Both new classes have an A-weighted pass-by noise level at 80 km/h of about 80 dB at 7.5 m distance from the track [17,28] (black dotted line). This is a dramatic reduction in noise generation. Since industry delivers the same kind of locomotive and rolling stock to all European countries, with no additional effort for industry, the local generation limits has had a positive European effect even before TSI-CR-NOI limits came into force.

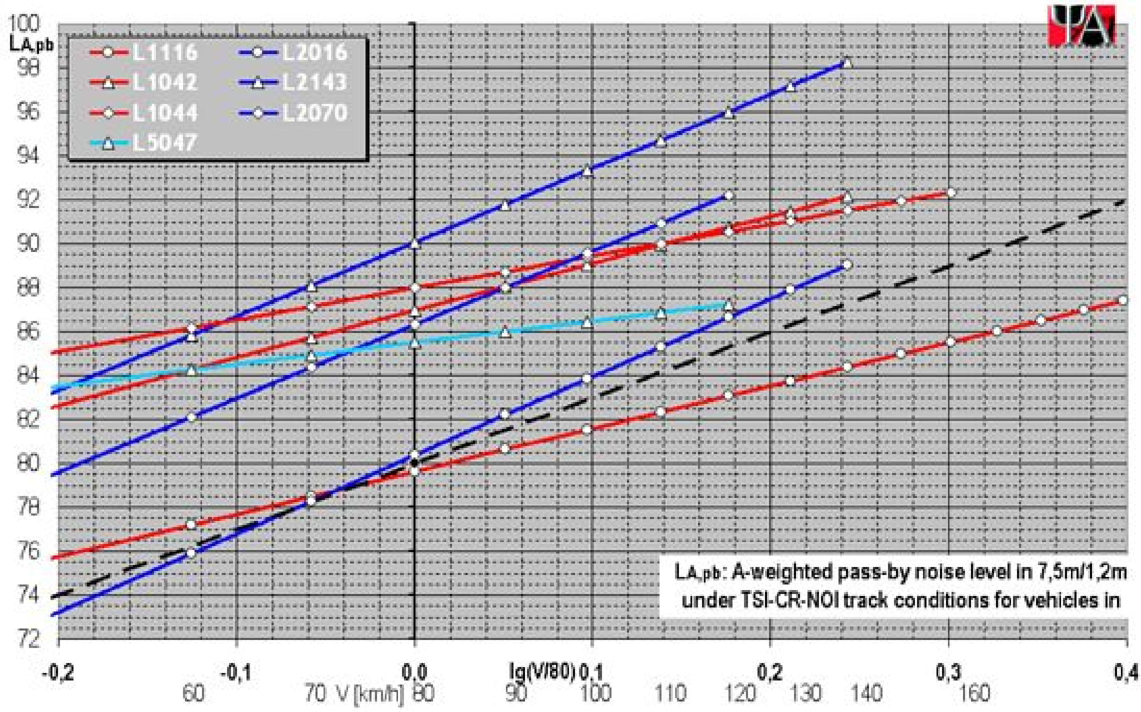


Figure 6.1: Speed dependent A-weighted pass-by level LpA,pb in 7.5m on a TSI-CR-NOI compliant track for different classes of ÖBB locomotives

Table 6.1 noise at 80 km/h for various types of locomotive

Locomotive type	Noise at 80 km/h (dBA)
Pre 1993	
L2143 diesel	90.0
L1044 electric	88.0
L1042 electric	87.0
L5047 DMU	85.5
Post 1993	
L2016 diesel	80.5
L1116 electric	79.5

6.3 Rolling stock

Figure 6.2 shows the speed dependent A-weighted pass-by level LpA,pb in 7.5m on a TSI-CR-NOI [30] compliant track for different train categories. Classes S4020 and S4024 are electric motorised units (EMU) for commuter services, classes 80-33 (double deck, disc braked) and 80-73 (K-bloc brake) are regional trains, pass means intercity passenger trains with cast iron brake (ci), mixed brake (cast iron and disc; mix) and disc brake (disc). CD680 represents the Czech Pendolino and freight means freight trains with cast iron brake.

Modern rolling stock like S4024, 80-33/80-73 and CD680 has an average A-weighted pass-by noise level that is lower than 80 dB at 7.5 m from the track at 80 km/h even in daily operation. On the other hand it is also obvious from this graph that freight trains still generate extreme noise and that the introduction of noise generation limits in Austria was not able to improve the situation at all.

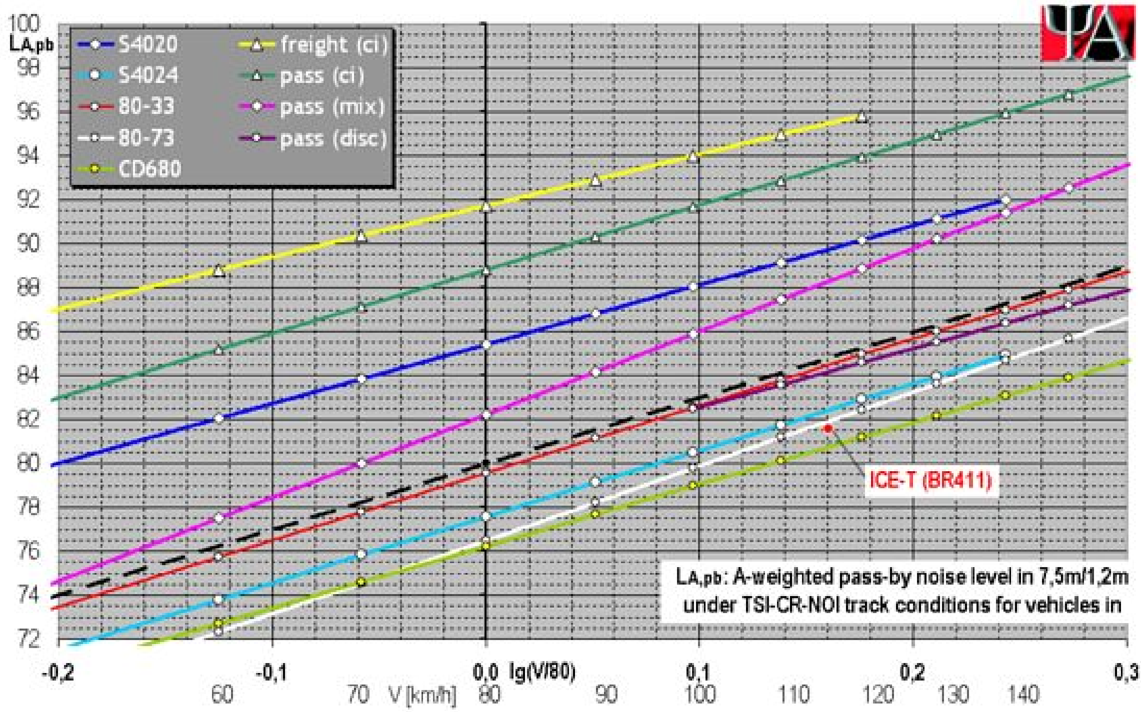


Figure 6.2: Speed dependent A-weighted pass-by level LpA,pb in 7.5m on a TSI-CR-NOI compliant track for different train categories

Table 6.2 noise at 80 km/h for various types of train sets

Train type	Brake type	Noise at 80 km/h (dBA)
Freight	Cast iron	91.5
Pass (ci)	Cast iron	88.5
S4020 EMU	Cast iron and disc	85.5
Pass (mix)	Cast iron and disc	82.5
80-33 pass	Disc	79.5
pass	Disc	79.5
S4024 EMU	Disc	77.5
80-73 pass	tread K-bloc	76.5
CD 680	Disc	76.5

Figure 6.3 shows that abatement of freight noise has to have the highest priority. The height of the total A-weighted equivalent level (LA,eq) during the night is determined by the freight trains on this line. This graph

shows very clearly that noise levels adjacent to this line cannot improve for the inhabitants as long as the noise generation from freight trains is not reduced.

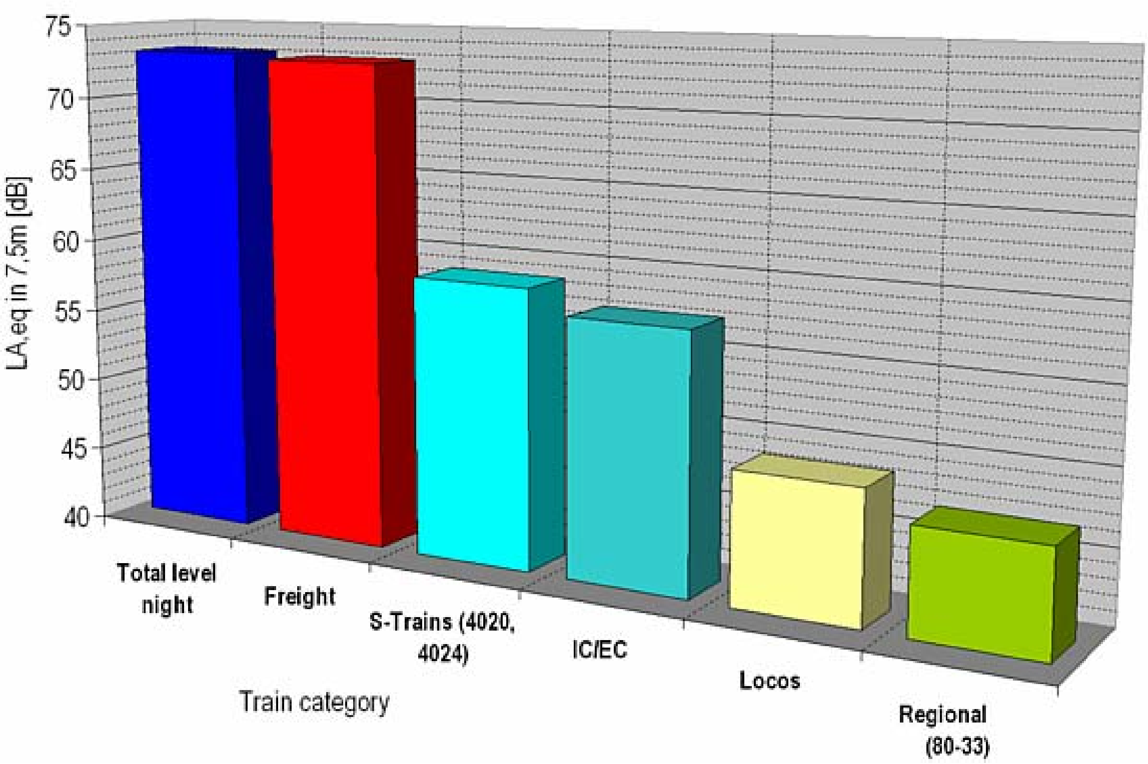


Figure 6.3: A-weighted equivalent level LA,eq in 7.5m on a TSI-CR-NOI compliant track for different train categories

6.4 Influence of braking

Recordings of the speed per axle allow the analysis of noise emissions on braking. Figure 6.4 shows that braking leads to an average increase of A-weighted pass-by level by 3 dB(A). This level does not include the high frequency brake squeal due to brakes being applied before the wheel stops but does include the rubbing contact of the cast iron block on the surface of the rolling wheel tread.

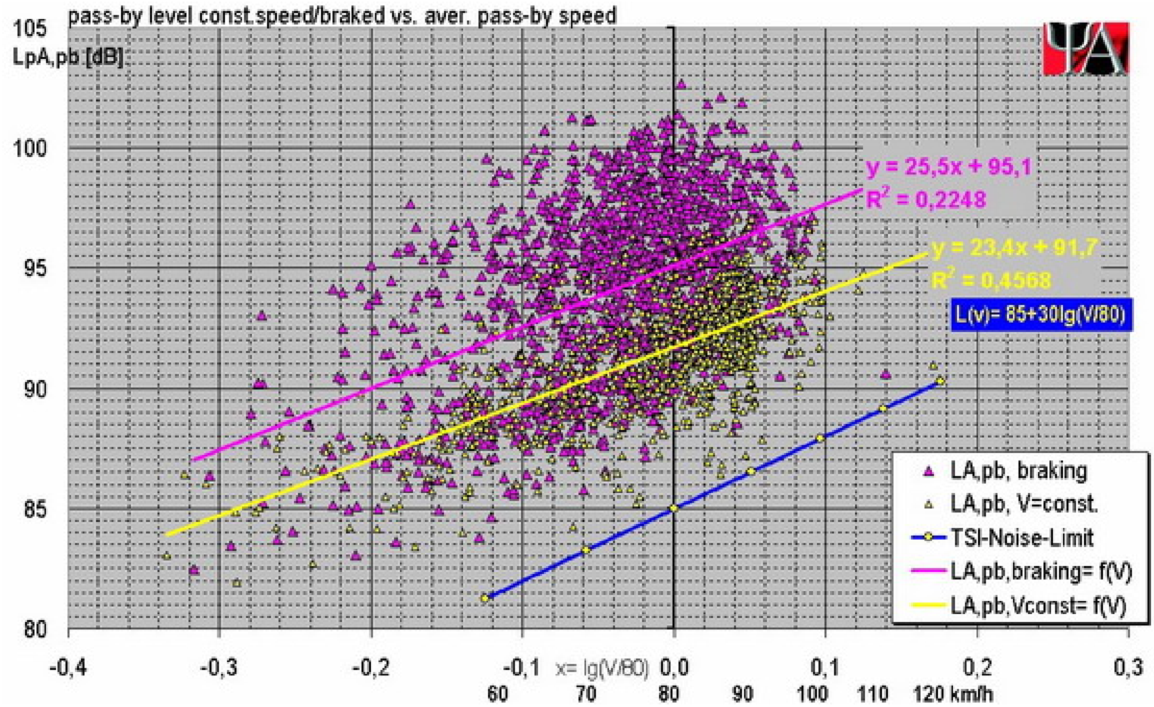


Figure 6.4: Speed dependent A-weighted pass-by level LpA,pb in 7.5m on a TSI-CR-NOI compliant track for freight trains with cast iron brakes rolling at constant speed (purple dots and line) and rolling with brakes on (yellow dots and line)

It might be argued that average pass-by speed is no valid descriptor for a train decelerating and conclusions could be different for a correlation between deceleration and pass-by noise. Figure 6.5 shows the correlation between the logarithm of the deceleration and the average pass-by level. Correlation coefficient r^2 increased from 0.22 in the case of speed dependency to 0.40 for the deceleration dependency. For practical reasons it appears not to be worthwhile to introduce deceleration into the considerations for noise levels.

Average speed is a parameter always available for a railway line. On the other hand, introducing typical deceleration for a line requires additional assumptions on the train operation. Figure 6.6 shows the relationship between average speed and deceleration for the train pass-bys used for Figure 6.4 and Figure 6.5. There is a moderate general trend that trains which run fast will show a higher deceleration that slow trains. However the spread is very high and $r^2 = 0.11$ is quite low. This supports the proposal to focus on average speed as input parameter than on deceleration.

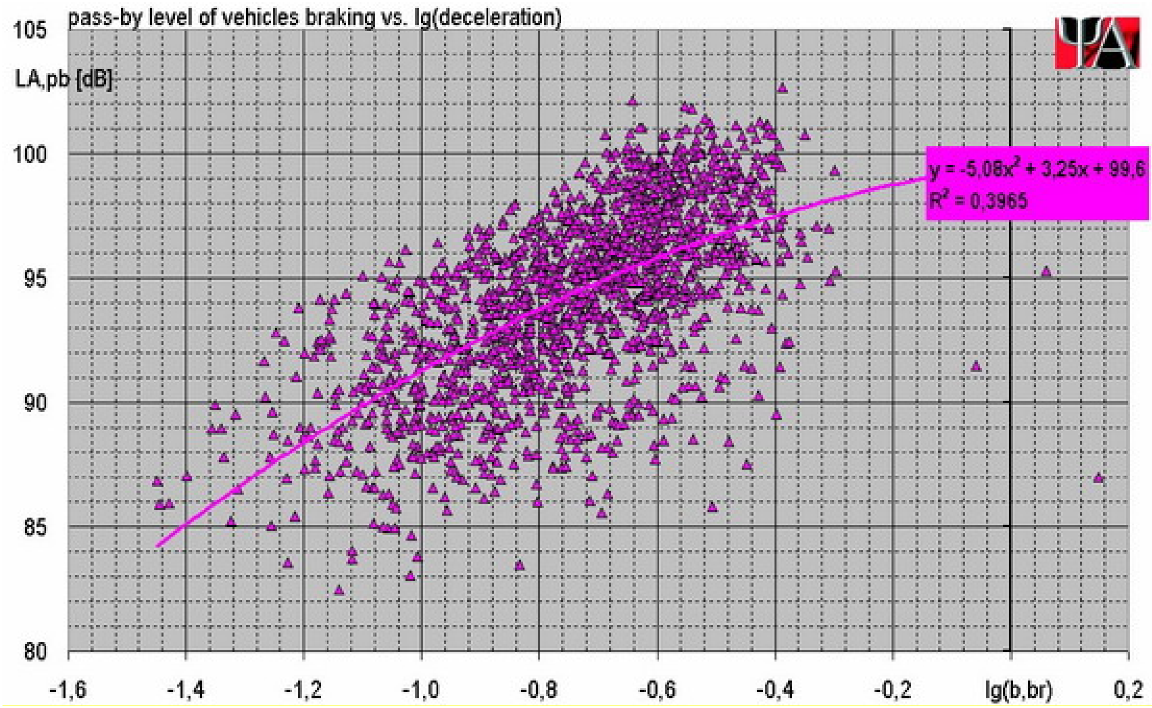


Figure 6.5: Deceleration dependent A-weighted pass-by level LpA,pb in 7.5m on a TSI-CR-NOI compliant track for freight trains with cast iron brakes rolling

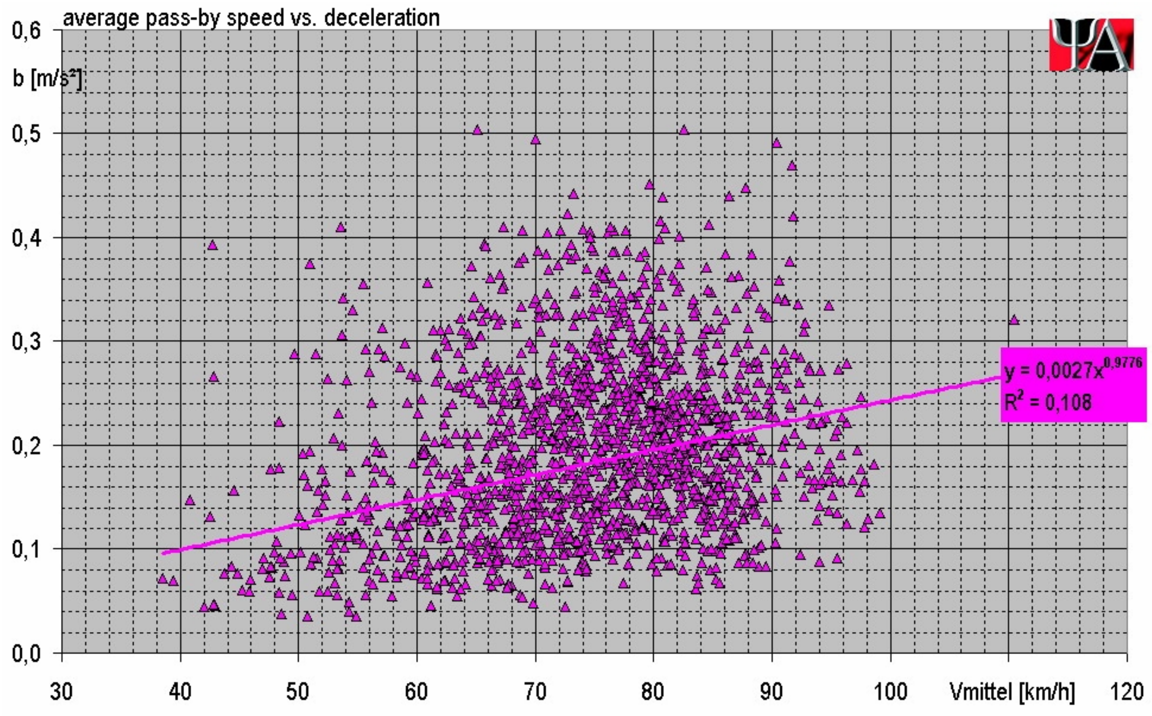


Figure 6.6: Correlation between average pass-by speed (km/h) and deceleration (m/s^2)

6.5 Influence of axles per train on pass-by noise

The TSI-CR-NOIse [30] has introduced a new acoustic parameter for freight wagons called *axles per unit length* (apl). As long as rolling noise is the main source for pass-by noise the number of wheels per train length has a major influence on actual noise level. Even if the sound power radiated by each wheel is equal for different vehicles the measured pass-by level will be different depending on the number of axles (=noise sources) per unit length. From basic acoustics it is known that the noise level will increase by 3 dB if the number of noise sources is doubled and pass-by level will rise by 6 dB if the number of sources is four times higher.

Looking at the extremes of the actual wagon fleet in Europe leads indeed to a spread of 4 in the number of axles per unit length. Freight wagons are mainly the focus of apl consideration since length and number of axles vary very strongly and rolling noise is the main source. A 3-axle car transport wagon for example is more than 26 m long which leads to an apl of about 0.1. A 10-axle ROLA wagon for pick aback traffic on the other hand has a length of about 24 m which means an apl of more than 0.4. So there will be a natural difference in noise emission of these two different vehicle types. The limit setting has taken this effect into account.

Measurements of pass-by levels in parallel with apl show that apl is affecting the pass-by level of freight trains. Left diagram of Figure 6.7 shows the average A-weighted pass-by noise level of different “standard” freight trains with cast iron block brake (yellow triangles and line) as well as of “standard” freight trains with K-block brake (green triangles and line) and disc braked ROLA wagons (blue diamonds and line). The pass-by noise of the ROLA wagons is about 4 to 5 dB more than the noise from the k-block braked wagons. Both disc and k-block brakes keep the wheel smooth so one would expect both wagon categories to have the same noise generation.

When an apl correction to the measured noise level is introduced (Figure 6.7, right diagram) the picture changes. Noise levels of ROLA wagons decrease and after having corrected the levels both ROLA and K-block braked “standard” freight wagon categories have more or less the same noise generation. The reason for that is clear; both wagon categories have the same sort of (smooth) wheels with more or less the same amount of radiated noise. Since “standard” freight wagon have less than half the number of wheels as ROLA wagons the pass-by noise level is more than 3 dB lower.

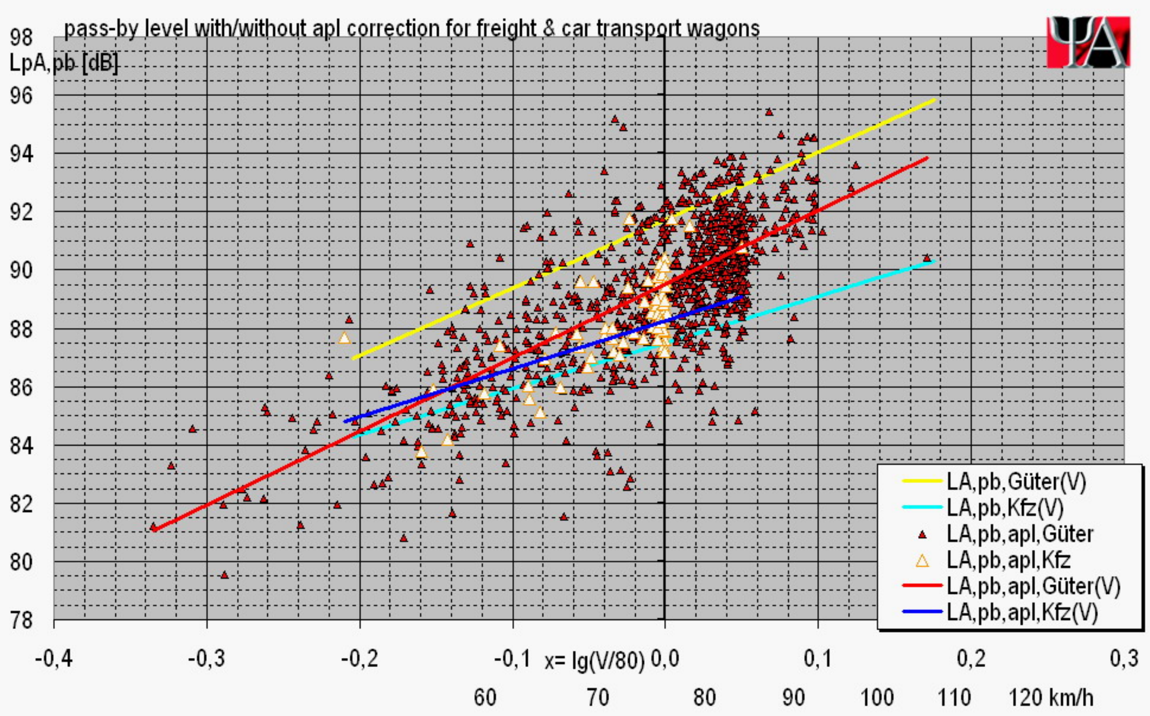


Figure 6.7: Effect of axles per unit length correction on pass-by noise levels from freight trains

6.6 Influence of rail roughness on rolling noise generation

Roughness of the rail head has a considerable influence on rolling noise generation. This knowledge is used in Germany and the Netherlands to reduce railway noise by acoustic grinding of the rails (Besonders überwachtes Gleis BÜG [31]). The experience with acoustic grinding is that different vehicles show different noise reduction potentials which was also found in our measurements.

Figure 6.8 shows rail roughness before (purple line) and after grinding (green lines). Before the grinding roughness was more or less the TSI-CR-NOI limit while after grinding, roughness was reasonably lower. Figure 6.9 shows the average A-weighted pass-by noise for different train categories.

Acoustic rail grinding had no effect on the pass-by levels from freight trains. Wheel roughness is so high for this category that overall noise levels could not be reduced. There was a slight improvement of about 1 dB for the S-Trains (category S4020). This vehicle type has rough wheels and rail roughness has a slight influence on the pass-by level. Finally, a noise reduction of 2 to 3 dB can be observed for all vehicle categories with smooth or very smooth wheels (train types 80-33, S4024).

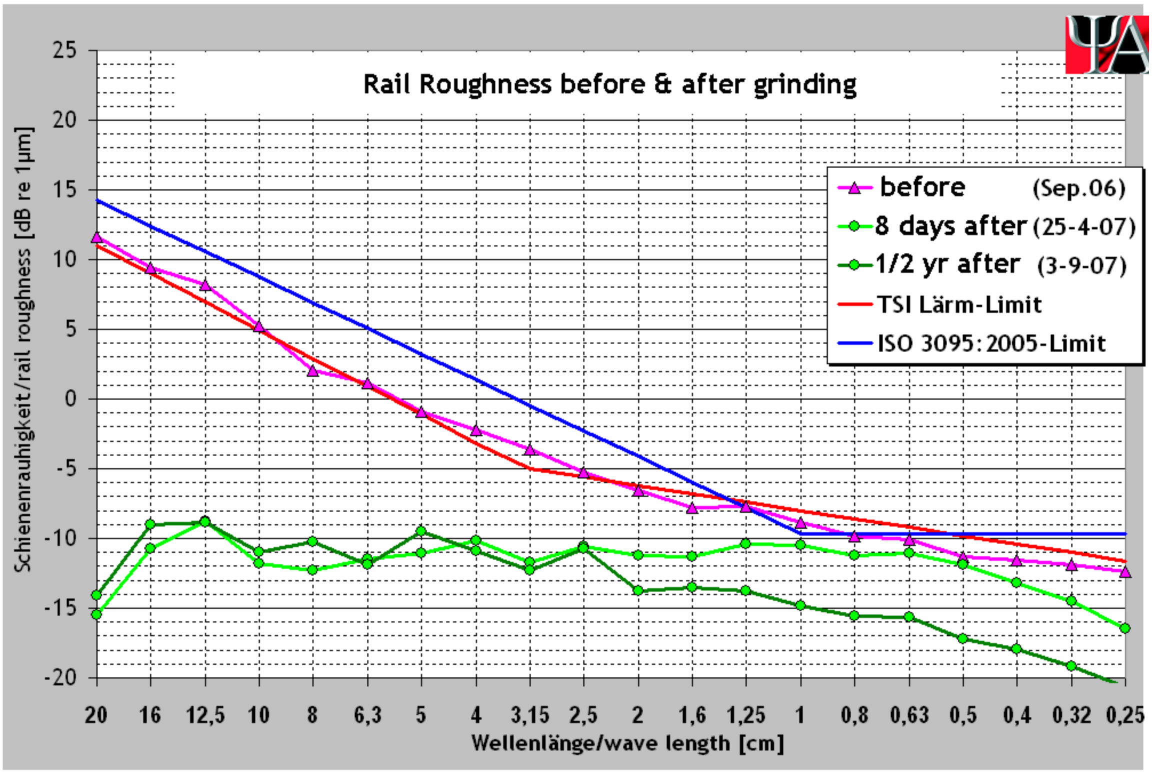


Figure 6.8: Rail roughness before and after grinding

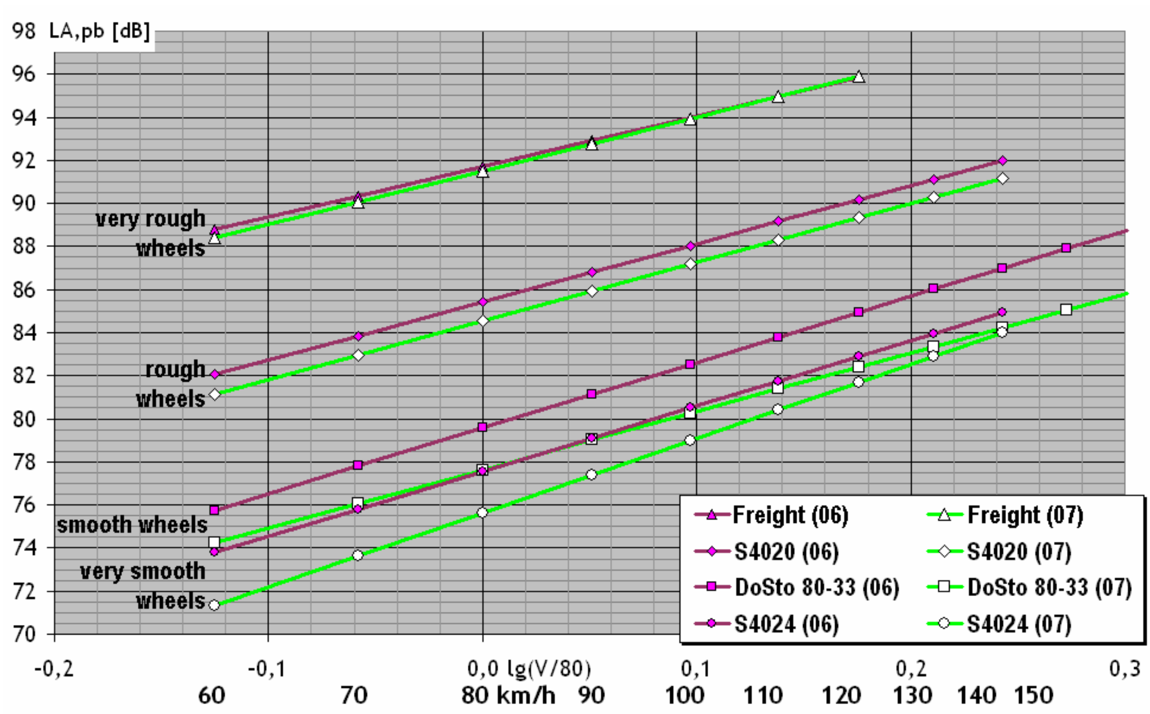


Figure 6.9: Effect of rail roughness on average A-weighted pass-by noise level of different train categories

6.7 Rail vibration and rolling noise generation

As long as rolling noise is dominant and general shape of wheels is the same; rail vibrations correlate rather well with pass-by noise. Figure 6.10 shows the correlation between A-weighted pass-by noise level LpA,pb and vertical railhead vibration Lv,V (blue) and lateral railhead vibrations Lv,H (white). This correlation can be used to cross-check and automatically verify microphone data as well as to reproduce pass-by noise level under adverse meteorological conditions like strong wind, rain or snow.

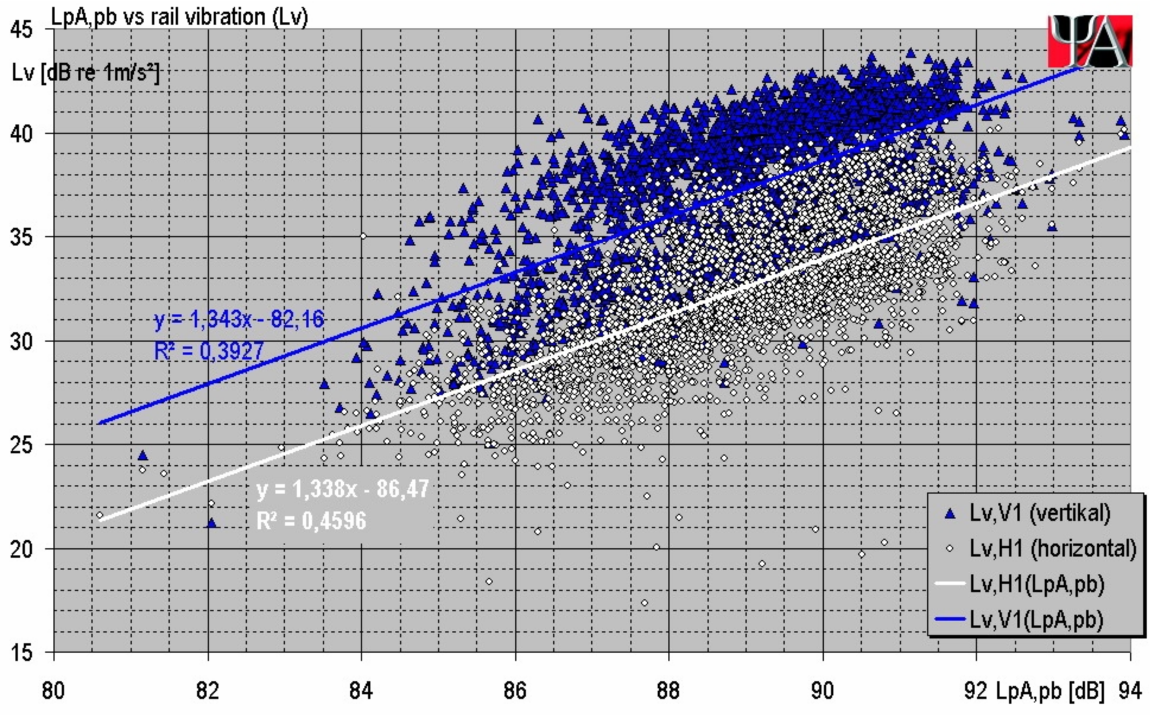


Figure 6.10: A-weighted pass-by noise level LpA,pb versus vertical railhead vibration Lv,V1 and lateral railhead vibrations Lv,H1

6.8 Speed dependency of pass-by noise from rail bound vehicles

A-weighted pass-by noise level LpA,pb shows 3 significant ranges of speed (Figure 6.11). At low speeds up to about 40 km/h traction noise is the dominant source. Speed dependency of traction noise is about 10*lg(V). In a speed range of 50 km/h to about 200 – 250 km/h rolling noise is the major source and noise increases from 25*lg(V) to 35*lg(V). Above 250 km/h aerodynamic noise becomes dominant with up to 60*lg(V) speed characteristics.

The noise limits have been set for conventional rail by the TSI-CR-NOIse regulation of 23 December 2005 [30] and this sets the upper limit for the operating speed of various vehicle types as illustrated in the various figures in the chapter.

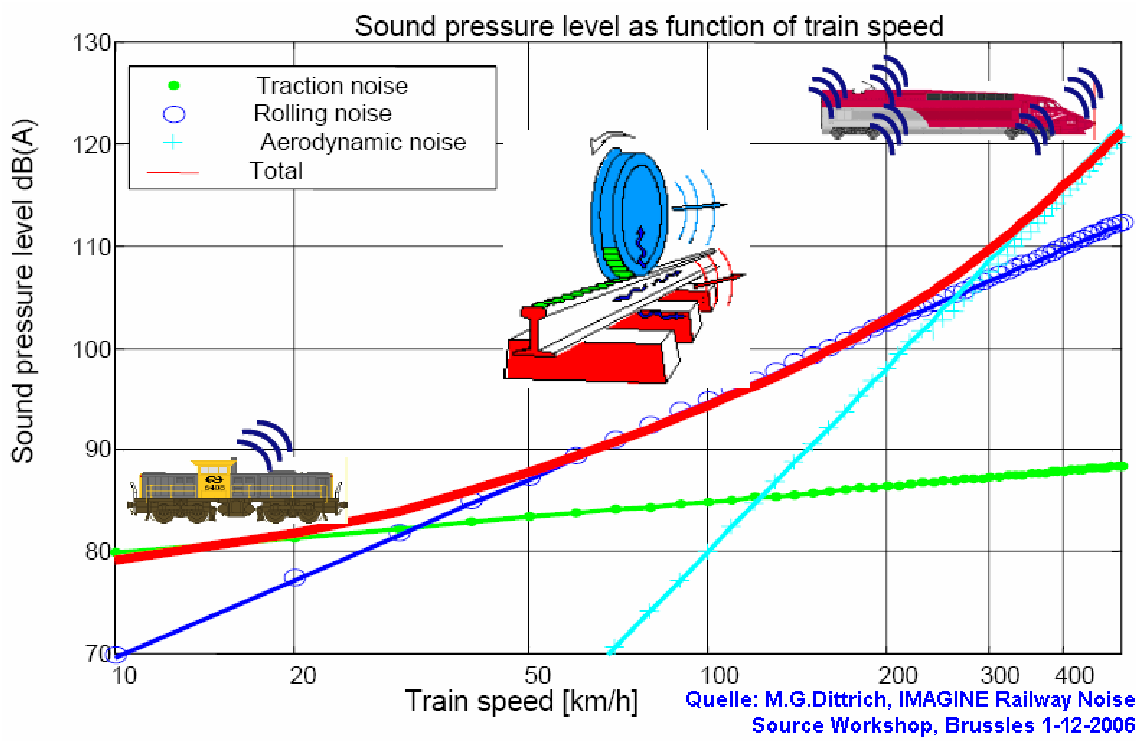


Figure 6.11: pass-by noise level LpA,pb as a function of train speed

6.9 Discussion

The environmental emissions of rolling stock vary by up to 25 dB(A) of which freight has by far the greatest impact and regional the least. Clearly the technology therefore exists for reducing such emissions, but some incentive at European level as well as regulation will be needed to affect the transition from noisy to quiet freight wagons. This is discussed further in chapter 9.

Noise emissions become even more important as the volume of rail freight traffic increases, such as the Rotterdam/Genoa corridor, or operators wish to run their trains at higher speeds. The situation at night is considerably worse because almost all the traffic is freight and permitted night noise levels are much lower than those during the daytime.

The major task of the infrastructure maintainer is to grind the rails regularly in order to reduce noise emissions and the same is true for wheel roughness which is the responsibility of the vehicle operator. However, we have seen that rail grinding has only a notable effect if also the wheel roughness is low.

6.10 Conclusions

Noise emissions from freight trains have become a limiting factor for increasing the capacity of parts of the European rail network. The technology exists for reducing emissions and urgent action is required at national and European level to initiate the transition to quieter vehicles with a life expectancy greater than 10 years.

Chapter 7 Factors influencing road noise emissions

7.1 Introduction

Noise emission of heavy **road** vehicles is influenced by the following site specific factors where indicated values are valid for vehicle speeds above 60 km/h and where tyre noise dominates noise emissions:

- ***type***: with standard dense asphalt as a reference porous asphalt can reduce emission up to 5 dB(A) whilst rough concrete pavement can increase emissions by up to 3 dB(A).
- ***age***: typical life cycles are 25 years; while the acoustical characteristics of dense asphalts remains more or less unaltered, porous asphalts lose much of their noise reduction potential in the first 10 years
- ***condition***: defects created at the surface of the pavement can increase noise emissions considerably.
- ***temperature***: as tyre stiffness depends on temperature, road surface temperature has a systematic effect on noise emissions. For passenger cars and light trucks emission is reduced by about 0.03 dB(A) for an increase of surface temperature by 1°C [28] whilst for heavy vehicles, the temperature effect can be neglected.

Vehicle type and suspension

Noise arising from the wheel/infrastructure interface can be transmitted via the suspension to the vehicle body which can then amplify noise. Suspensions that possess good sound absorption characteristics include air suspension and glass fibre plastic leaf springs [14].

Type of ground in the vicinity of the receiver position

Sound at the measuring microphone position is composed of a direct and ground reflected component. Soft ground alters ground reflection resulting in a different interference pattern compared to hard ground.

7.2 Vehicle type

Obviously the vehicle type has a significant influence on noise emissions. The vehicle classification used is based on COST 323 [5] classes (refer figure 1.5) which can be translated into Swiss 10 categories and UK DfT classes according to Table 7.2.

Table 7.2: Equivalence between Swiss 10 categories, UK DfT scheme and COST 323 vehicle classes.

COST Category	Description	Swiss 10 Class	UK Class	note
COST 3	More than 2 axle rigid lorry	8	32 and 33	Swiss class 8 includes 2 axles
COST 4	Tractor with semi-trailer supported by single or tandem axles	10	51,52 and 55	
COST 5	Tractor with semi-trailer supported by tridem axles	10	54 and 56	
COST 6	Lorry with trailer	9	41 – 44	

The road traffic data presented in the following sections were collected at the Swiss footprint site in *Lenzburg* in September 2005 and at the three UK Footprint measurement sites at Plymouth, Sparkford and Tomatin in the UK [22].

In Figure 7.1 the statistics of all pass-by measurements at the Lenzburg site for each vehicle category is shown. The highest maximum levels are found for COST class 6 (chapter 1.4). However the differences between classes 4, 5 and 6 are small (below 1 dB(A)). More detailed information about the noise level distribution can be found in the histograms in Figure 7.2 to 7.4 in which both the recorded data and then normalised to a speed of 80 km/h are shown. The variance within each class is about 2 dB(A) for 50% of the vehicles

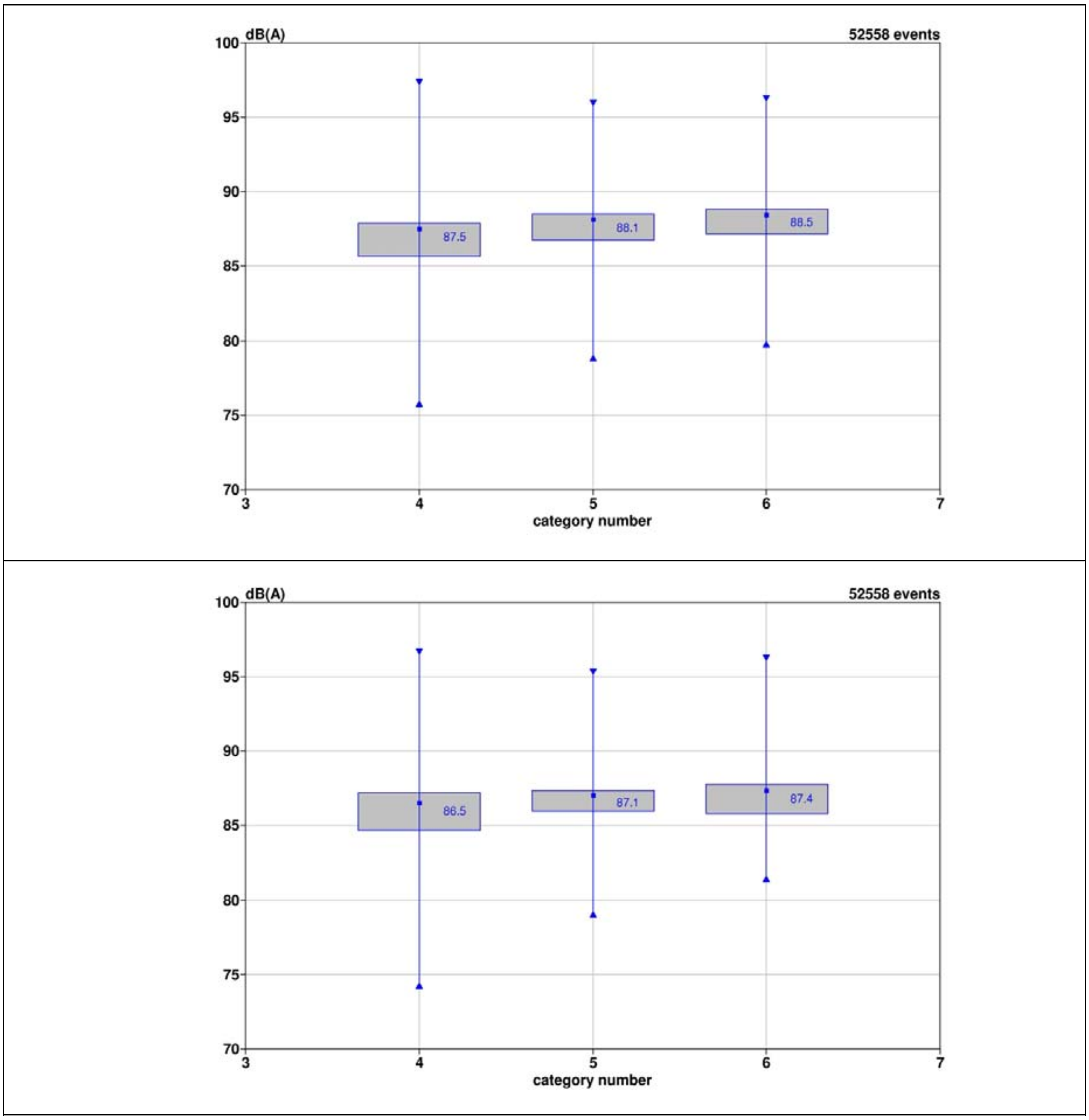


Figure 7.1: Statistics of all Lenzburg measurements in COST 323 classes. The vertical lines bounded by triangles show maximum and minimum values, the grey shaded boxes denote the 50 % span, the labelled squares stand for the energetic mean values. Top: original data, bottom: levels normalized for 80 km/h (see below).

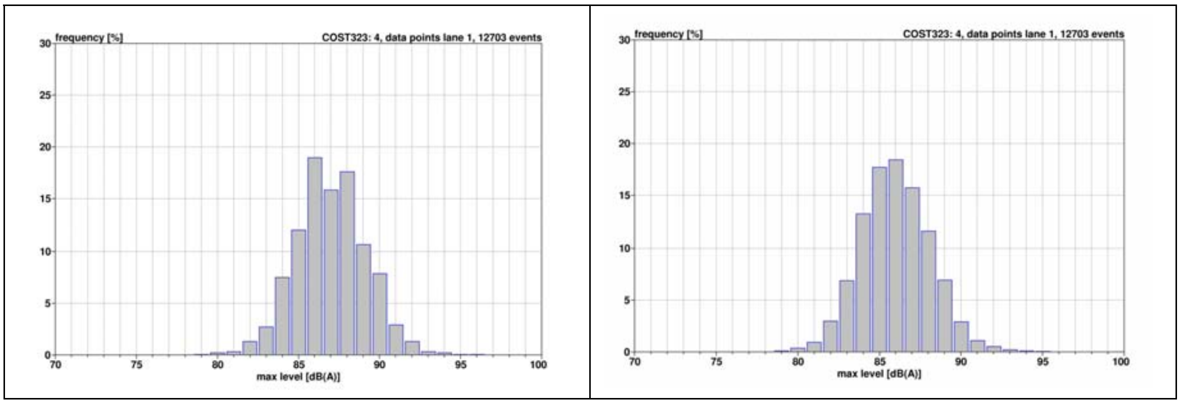


Figure 7.2: Histogram of all Lenzburg maximum pass-by levels [dB(A)] for COST class 4 vehicles. Left: original data, right: levels normalized for 80 km/h (see below).

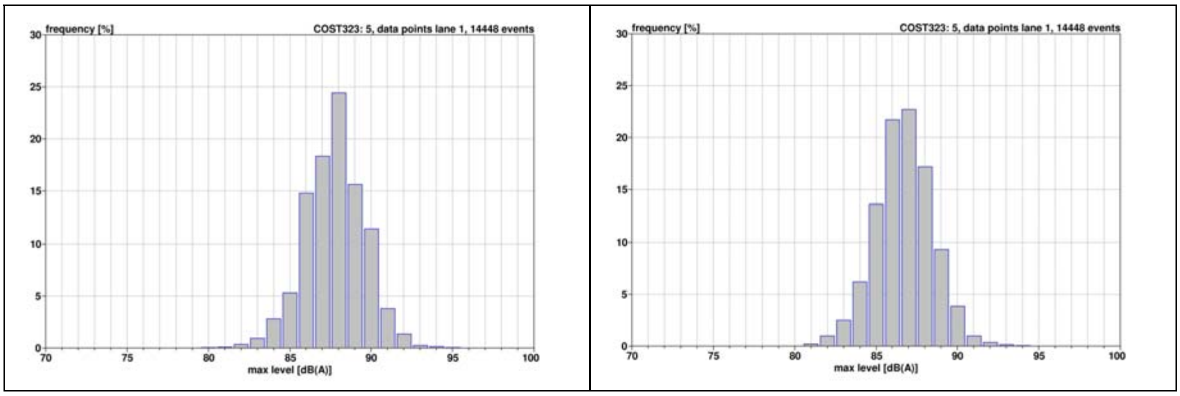


Figure 7.3: Histogram of all Lenzburg maximum pass-by levels [dB(A)] for COST class 5 vehicles. Left: original data, right: levels normalized for 80 km/h (see below).

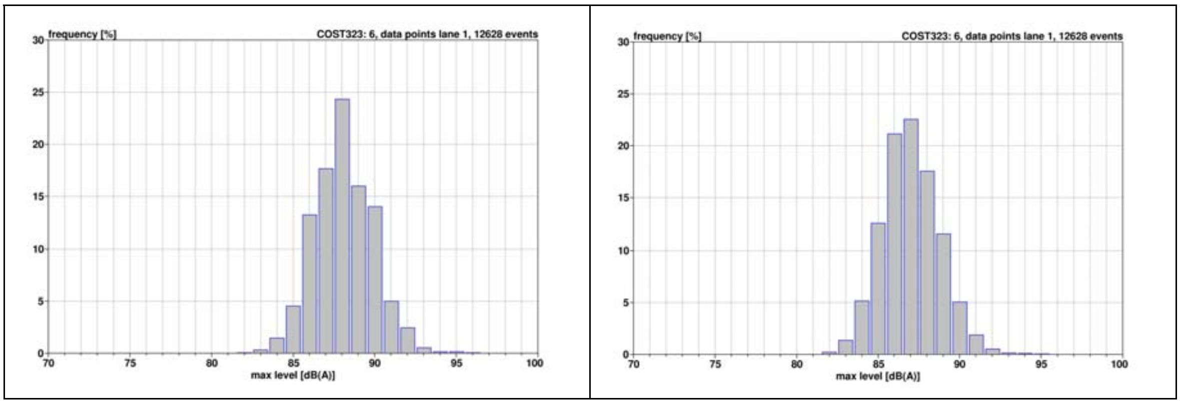


Figure 7.4: Histogram of all Lenzburg maximum pass-by levels [dB(A)] for COST class 6 vehicles. Left: original data, right: levels normalized for 80 km/h (see below).

Figure 7.5 shows a comparison of the average pass-by levels between the four sites Lenzburg, Plymouth, Sparkford and Tomatin for 3 different classes of vehicles with measured levels normalised for a speed of 80 km/h. As can be seen from the data, there are significant and systematic differences between the four sites. This is most probably due to variable road surfaces and pavement conditions. Furthermore there are differences in the vehicle fleet. At the Swiss site (Lenzburg) class 6 vehicles are the noisiest while in the UK (Plymouth, Sparkford and Tomatin) class 6 vehicles are the quietest ones. The reasons for this are not known and require further investigation in order to be able to consider classifying vehicles in terms of their environmental friendliness (refer chapter 9) .

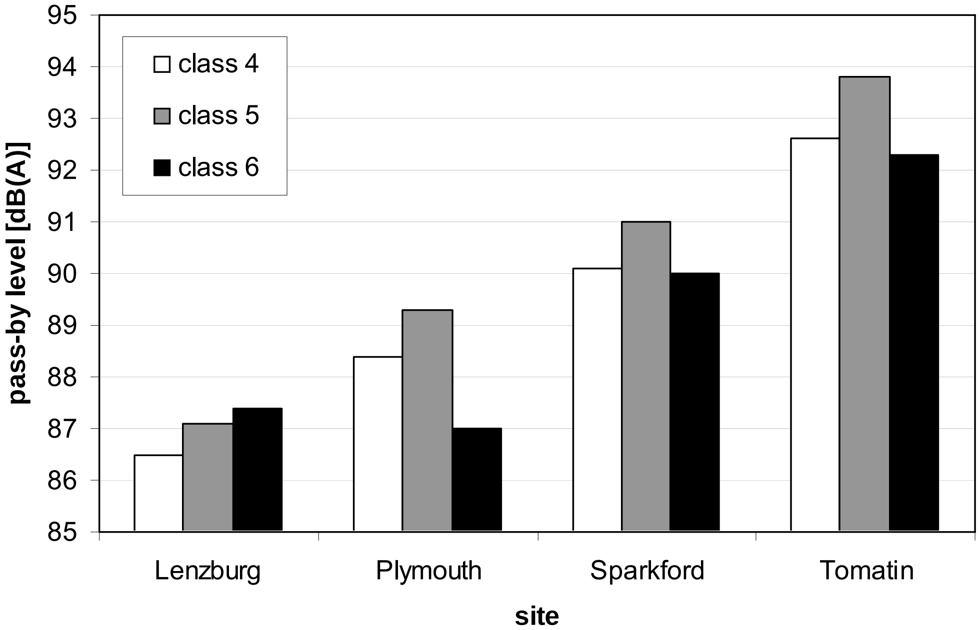


Figure 7.5: Comparison of average pass-by levels normalised for 80 km/h at different sites, evaluated for the COST 323 classes 4, 5 and 6.

7.3 Road vehicle speed

For a given site and vehicle category the most important parameter influencing sound emission is vehicle speed.

Figure 7.6 to 7.8 show the measured and, for possible interference with neighbouring vehicles, corrected maximum pass-by levels in different speed classes for the Lenzburg site. The tilted line is the expected speed dependency for heavy vehicles according to the Swiss road traffic noise model SonRoad [16] which has a speed dependency around 80 km/h of 0.17 dB per km/h. The value is very similar to that measured for trains in the speed range 50 to 100 km/hour where rolling noise predominates (Figure 6.11).

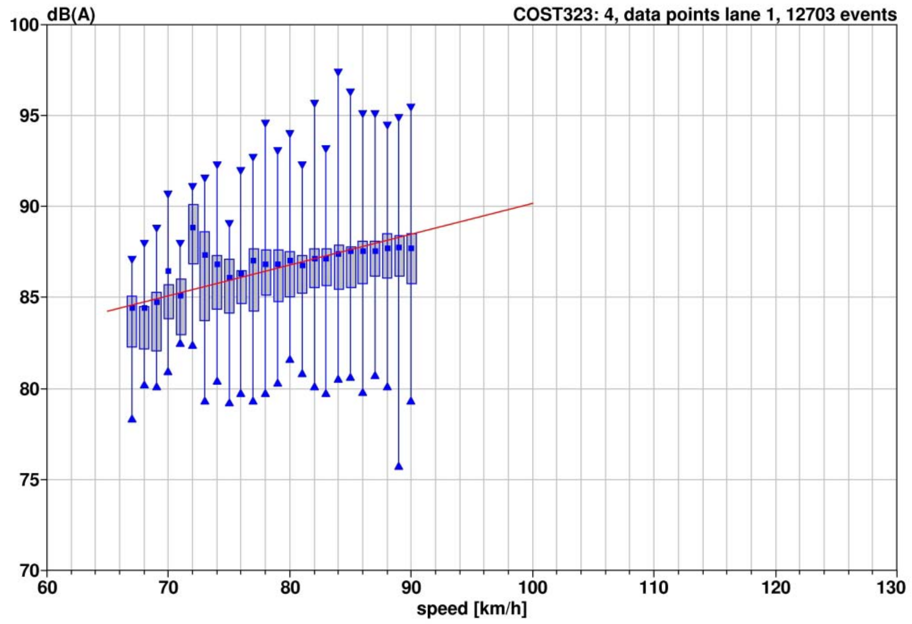


Figure 7.6: Maximum pass-by levels [dB(A)] for COST 4 vehicles in different speed classes. The vertical lines bounded by triangles show maximum and minimum values, the grey shaded boxes denote the 50 % span, the squares stand for the energetic mean values.

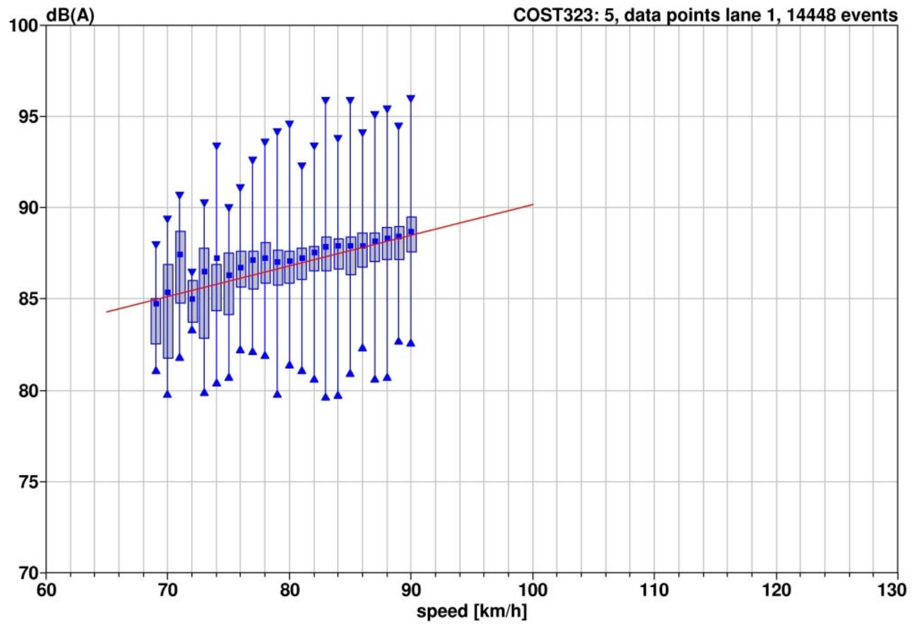


Figure 7.7: Maximum pass-by levels [dB(A)] for COST 5 vehicles in different speed classes.

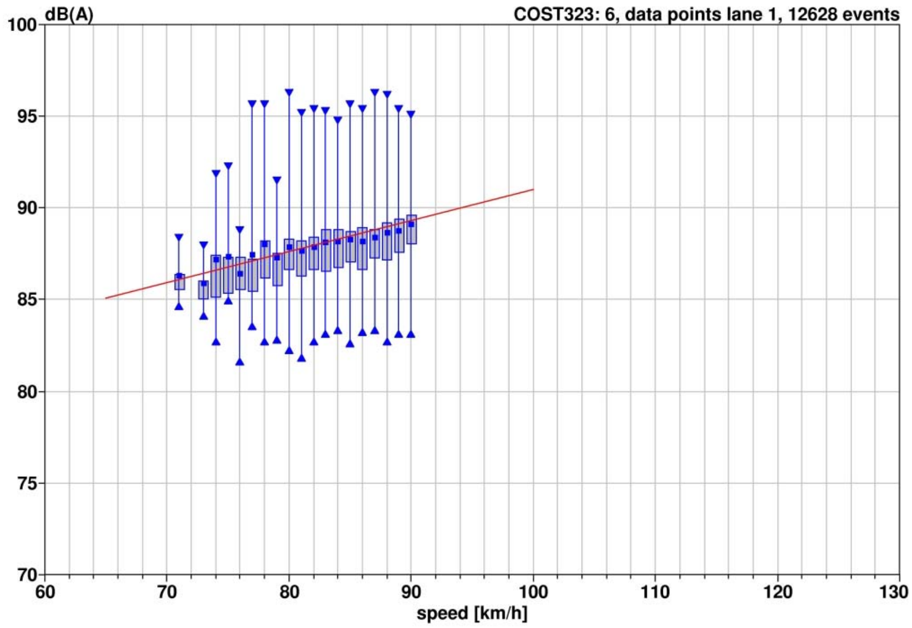


Figure 7.8: Maximum pass-by levels [dB(A)] for COST 6 vehicles in different speed classes.

The measured speed dependency coincides well with the SonRoad calculation model. In the analysis it was found that about 10% of the heavy vehicles had reported speeds above 90 km/h. This is very implausible and indicates that WIM system can produces the wrong vehicle classification. The error rate is in the order of 10%. For our evaluation only vehicles with speeds below 90 km/h were considered.

7.4 Vehicle mass

The influence of vehicle mass was evaluated after normalising the measurements to a reference speed of 80 km/h (assumed speed dependency according to SonRoad). Figure 7.8 to 7.11 show the measured maximum pass-by levels in different weight classes for the Lenzburg site. The influence of weight on sound emission is relatively small. This is an important aspect when it comes to the question of an optimisation of the quotient ton/dB.

Table 7.2 Effect of vehicle class on noise increase per tonne

COST class	Noise increase dB(A) per tonne
4	0.12
5	0.06
6	0.03

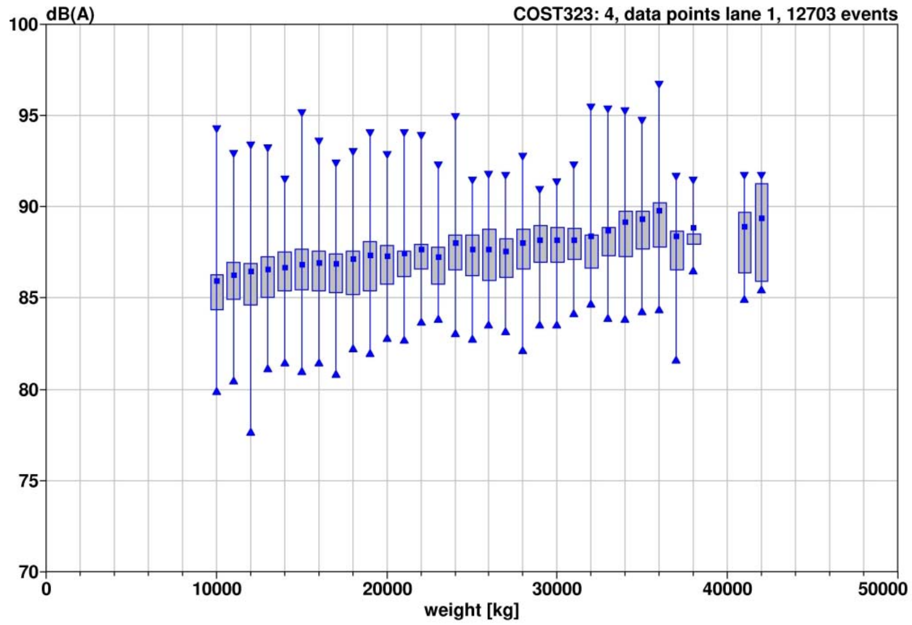


Figure 7.8: Maximum pass-by levels [dB(A)] for COST 4 vehicles in different weight classes.

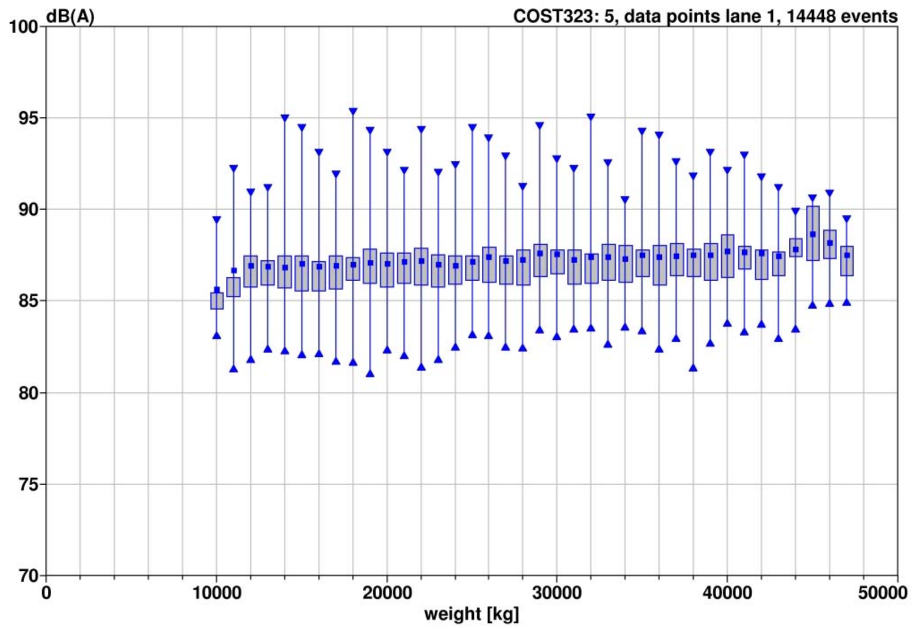


Figure 7.9: Maximum pass-by levels [dB(A)] for COST 5 vehicles in different weight classes.

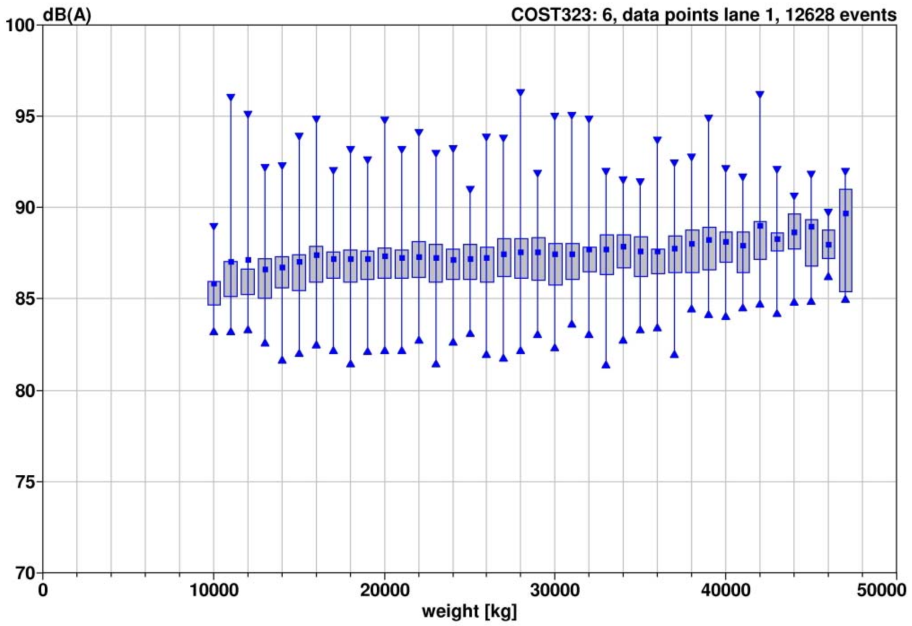


Figure 7.10: Maximum pass-by levels [dB(A)] for COST 6 vehicles in different weight classes.

7.5 Discussion

Unlike rail vehicles (Figure 6.3), noise emissions from road vehicles are relatively independent of vehicle class and much more dependent upon the type of the infrastructure at the measurement site (Figure 7.5). Speed has a similar effect on all types of vehicle classes with an upper limit of 90 km/h for road freight. With rail freight, the restrictions on speed are limited by ride quality and dynamic loading rather than noise emissions so it will be possible to run at higher line speeds provided that the bogies and wagon have low noise emissions.

7.6 Conclusions

As shown above in Figure 7.5, there are site specific factors that have an effect on sound emission of the same order of magnitude as differences between quiet and noisy vehicles. It is therefore important to introduce relative and *not* absolute bonus/malus thresholds. In that sense the median value of all vehicles could be used as a reference for each site. One strategy would be to consider the 25% quietest vehicles as “environmentally friendly” and the 25% loudest vehicles as “environmentally unfriendly”. Such a scheme based on the level distribution would account for the fact that the level differences between quiet and loud vehicles is highest for low-noise sites and smallest for loud sites. This is discussed further in chapter 9.

Vehicle speed is identified as an important parameter influencing noise emissions. The speed dependency on noise can be calculated with high accuracy. It is proposed to normalize measured sound levels for a reference speed of 80 km/h before comparing them with bonus/malus thresholds. Then the acoustical footprint describes the vehicle and not the driving condition. It would be too easy to get the “environmentally friendly” label just by lowering the speed at the Footprint station.

In order to minimize sound emission for a given amount of goods to be carried, it is beneficial to use the heaviest vehicles possible which also results in the minimal number of trucks.

Chapter 8: Vehicle pollutant emissions

8.1 Exhaust gas emissions from diesel engines

Heavy duty vehicles are normally powered by diesel engines, a small portion of buses and motor-coaches being powered by natural gas engines. Because most heavy vehicles use diesel engines, this section focuses on diesel engine technology.

Diesel engines convert chemical energy to mechanical energy by compression ignition and combustion of a liquid fuel. The fuel is injected with high pressure to the combustion chambers where it mixes with air. In regions where a certain bandwidth of the air-to-fuel ratio is reached, the diffusion-controlled combustion process takes place. Within these combustion zones, the stoichiometry varies: Certain regions face a deficit of air ("rich zones"), other regions face an excess of air ("lean zones"). Due to incomplete combustion and the oxidation of nitrogen at high temperatures, carbon monoxide (CO), unburned hydrocarbons (UHC), particles and oxides of nitrogen (NO_x that represents the sum of NO and NO_2) are formed. Rich zones lead to high amounts of CO, UHC and particles, lean zones lead to high amounts of NO_x. All these emissions (CO, UHC, NO_x and particles) are limited in engine emission regulations. The different emissions have different effects:

- CO emissions are poisonous for the blood when high concentrations are present. CO levels from diesel engines are non-critically low and can be relatively easily lowered close to zero using an oxidation catalyst.
- Some hydrocarbons lead to the typical diesel exhaust smell and some are suspected to be carcinogenic (aromatic compounds, polycyclic aromatic hydrocarbons). As for CO, UHC levels from diesel engines are non-critically low and can be relatively easily lowered close to zero using an oxidation catalyst.
- The effect of NO_x is critical. NO is less hazardous than NO_2. NO_2 is a lung irritant and contributes in presence of sunlight and volatile organic compounds strongly to the formation of ozone. Raw emissions from diesel engines consist mainly from NO while some exhaust gas after treatment technologies (e.g. catalyzed particle filters) oxidize NO to NO_2. It is likely that NO_2 (and not only the sum of NO and NO_2 as up to now) will be limited in future legislations.
- Particles are usually divided into solid and volatile particles. Solid particles (soot) consist of agglomerated carbonaceous primary particles that are normally larger compared to the smaller volatile particles. In respect to their difference in size distribution, these two kinds of particles are sometimes called "accumulation mode particles" and "nucleation mode particles". The formation of volatile (nucleation mode) particles depends very strongly on their "history" in the dilution process with ambient air after the exhaust pipe (dilution, cooling, humidity, residence time, and presence of hydrocarbons). Particles from diesel engines have typical diameters between 10 and 400 nm. Unfortunately, these small particles can not be intercepted by the nose but are passed through the bronchia and even to the lung alveolus. The larger particles can cause allergic asthma, the smallest are suspected to pass through to the blood system and particles with condensates are suspected to promote cancer. It can be said that the smaller the particles are, the deeper they enter the human body.
- In engine emission regulations, particle mass emissions are limited. To measure particle masses, the engine's exhaust gases are diluted with conditioned air and sucked through a filter. The weighing of the filter prior and after the measurement allows the determination of the particle mass. Because concerns about health effects are attributed especially to very small particles and these small particles do significantly contribute to the mass, particle counting methods have been established in the past few years. It is very likely that particle number emission limits for engines will be introduced as soon as new European legislations will be adopted.
- Different particle definitions cause often confusions. For ambient air, limits for PM10 exist and are monitored in many sites across Europe. PM10 describes the mass of particles with sizes smaller than 10 μm (10'000 nm). It is not surprising that the PM10 measurements are usually not dominated by the large number of small particles from diesel combustion but by smaller numbers of less problematic larger particles (pollen, road dust re-suspension, abrasion, etc.). Several countries

started activities to establish PM2.5 limits (mass of particles with sizes smaller than 2.5 μm) as an additional air quality standard.

8.2 Reducing pollutant emissions

To reduce tailpipe pollutant emissions, either the engine's raw emissions created during the combustion process can be lowered or the engine's emissions can be removed using exhaust gas after treatment. These two groups are explained in the subsequent sections.

8.2.1 Raw emission reduction

For good efficiency of the thermodynamic cycle, high combustion temperatures are necessary. Unfortunately, high temperatures cause high NO_x because nitrogen that is present in the air is oxidised. In engine development, this fact is known as the "fuel-consumption versus NO_x trade-off". One possibility to reduce NO_x without too much fuel consumption penalty is exhaust gas recirculation (EGR). To do so, hot exhaust gases are cooled and fed back to the air intake side of the engine. With this measure, the oxygen content in the fresh air is lowered and less NO_x is formed during combustion. Unfortunately, the reduction of the available oxygen increases particle, UHC and CO emissions. For all diesel engines but especially for those with EGR, a "NO_x versus particles trade-off" exists.

Old engines had relatively simple injection systems that just had the possibility to inject the fuel once per working cycle. More modern injection systems (e.g. common rail) have the possibility to inject up to five times different quantities of fuel per working cycle. This degree of freedom is used to achieve cleaner combustion by better air/fuel mixing and combustion shape forming. It is possible with these new systems to lower the emission levels but the trade-offs described above remain.

8.2.2 Exhaust gas after treatment

CO and UHC

CO and UHC can be relatively easily removed to a large extent using an oxidation catalyst. Such catalysts oxidise CO and UHC using oxygen present in the exhaust gas with precious metals being the catalytic active materials. Oxidation catalysts can also be coated in a way that the oxidation of NO to NO_2 is promoted which helps to regenerate particle traps (see later), this obviously also increases NO_2 emissions.

NO_x

NO_x has to be removed if the combustion of the diesel engine is set-up for low-particle but high-NO_x emissions. One possibility is NO_x storage in a special catalyst. As soon as the catalyst's NO_x storage capacity is fully used, it has to be regenerated by a phase of engine operation under rich combustion conditions. This phase leads on the one hand to increased fuel consumption and on the other hand to very high particle emissions so that a particle trap (see later) is absolutely necessary. Because of these two drawbacks, NO_x storage technology is not used in the very efficiency-sensitive heavy duty engine market.

The other possibility is called Selective Catalytic Reduction (SCR) where NO_x is converted to N_2 and H_2O using ammonia (NH_3). Due to safety and other issues, ammonia is not transported on board of the vehicle but hydrolysed at temperatures above 200 °C in the exhaust system from an aqueous urea ($CO(NH_2)_2$) solution. This solution (32.5% urea, rest water) is available at many fuelling stations across Europe under the market name "AdBlue". SCR technology is used for European heavy duty vehicles since the year 2005.

Particles

Particles can be removed very efficiently using so-called wall-flow particle traps. Best available technology filters remove particles to the level of the ambient air. In wall-flow particle traps, the exhaust gas stream is pressed through a micro-porous ceramic material. This technology has the drawback that a pressure-drop is induced over the filter which increases the engine's fuel consumption. Particle filters regenerate automatically (i.e. the soot is oxidised) when the temperature is high enough. In some applications (e.g.

urban buses), the engine power is very low over long periods of time so that the particle filter is not regenerated automatically. Therefore, catalyzed particle filters are often used where the catalyst produces NO_2. NO_2 is able to start the regeneration of the trap at lower temperatures but the NO_2 emissions are obviously also increased (the NO_2 emissions of urban buses using such traps can often be smelled, the smell is similar to chlorine). If less NO_2 has to be emitted, the filter regeneration is guaranteed by the addition of fuel before the trap or by lowering the engine efficiency (which increases the exhaust gas temperature) by late injection or other measures.

There exists also particle after treatment systems with less effectiveness than the wall-flow particle traps. Some manufacturers use a so-called PM-catalyst. In a PM-catalyst, the exhaust gas flows along open catalyzed channels that promote the oxidation of particles. PM-catalysts have the advantage that they add less back-pressure to the engine; they can not plug and do not need a special regeneration strategy.

Figure 8.1 depicts the efficiency of a wall-flow particle trap and a PM-cat. The measurements were performed on a modern heavy duty diesel engine running at full load at Empa using a Scanning Mobility Particle Sizer (SMPS) spectrometer. It can be seen that a PM-cat is able to reduce about 30% of the particles over the whole size spectrum. The results from the wall-flow trap show the extremely high efficiency of such a system: the particle emissions are reduced to virtually zero over the whole size spectrum.

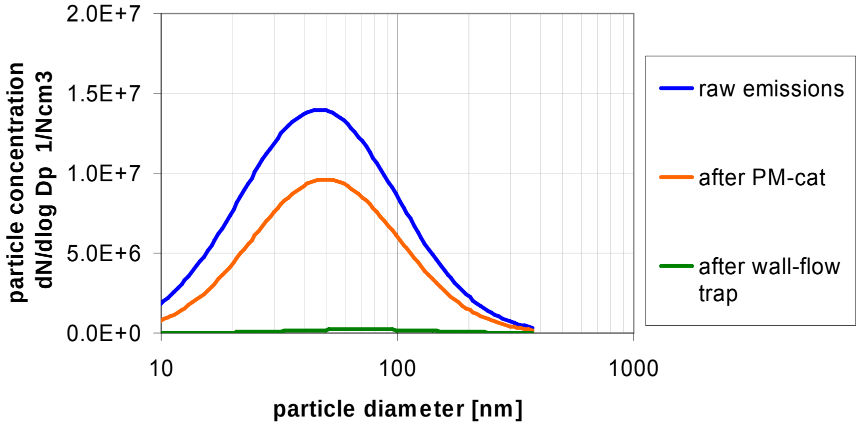


Figure 8.1: Particle size distributions prior and after a wall-flow trap and a PM-catalyst.

8.3 Emission limits

Pollutant emissions of heavy duty engines are limited in most countries worldwide. Currently, three different important legislations with different limits, procedures and reference fuels exist: EC (Europe), EPA (USA) and Japan. There are activities in the UNECE work package 29 (World Forum for Harmonization of Vehicle Regulations) that have the goal to establish worldwide emission standards and procedures in the future. For the European perspective, the current emission legislation is described in the directive 2005/55/EC [7]. The emissions are determined on engine test benches, i.e. the engine is directly coupled to a dynamometer and the emissions are measured in steady state operating points and/or in transient cycles. Figure 8.2 depicts a typical setup.

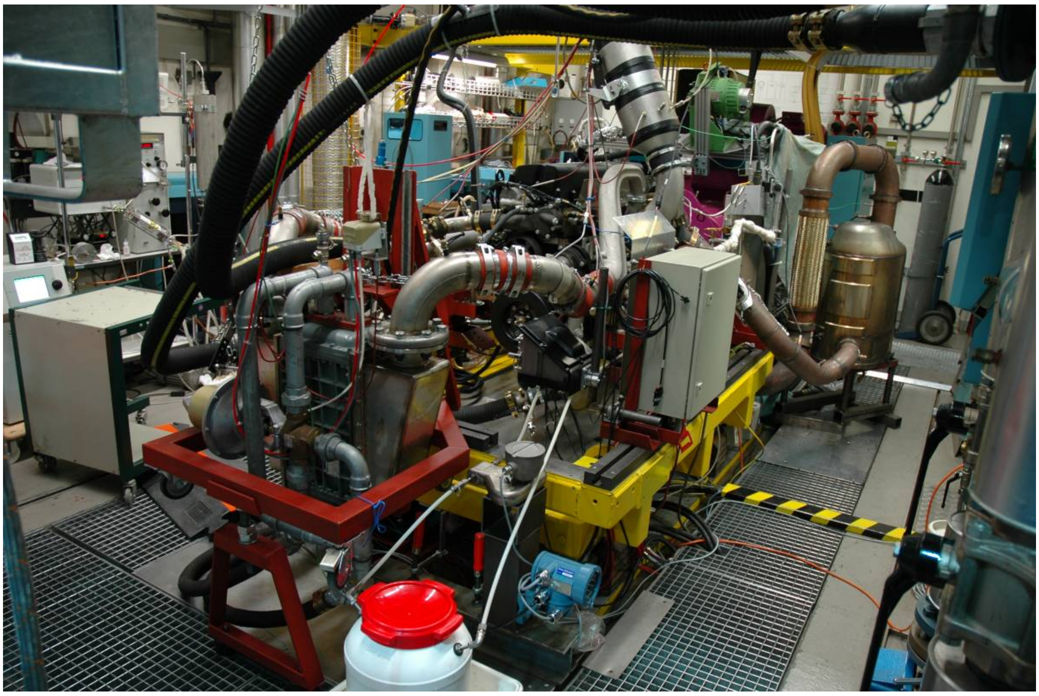


Figure 8.2: Heavy duty engine on an engine test bench at Empa.

For certification tests, the combustion air is conditioned and a reference fuel is used. In the actual European legislation, engines without exhaust gas after treatment systems are driven in a 13-mode test (ESC: European Stationary Cycle). If an engine has an exhaust gas after treatment system it is additionally driven in a transient cycle (ETC: European Transient Cycle). These cycles are defined relative to the engine's performance: Normalised speed versus normalised torque is unnormalised using engine-specific data (minimum and maximum speed, full load torque). The emissions are determined in a work-specific manner (i.e. in grams per kilowatt-hour of engine work). Figure 8.3 depicts the European emission limit values for the stages Euro-I up to Euro-V. It can clearly be seen that the emission limits have been strongly tightened over the last two decades. The European Commission is in the definition phase of the next stage (Euro-VI, most likely coming into force in 2013) and a reduction of 67% particles and 80% NO_x relative to Euro-V is likely to be decided.

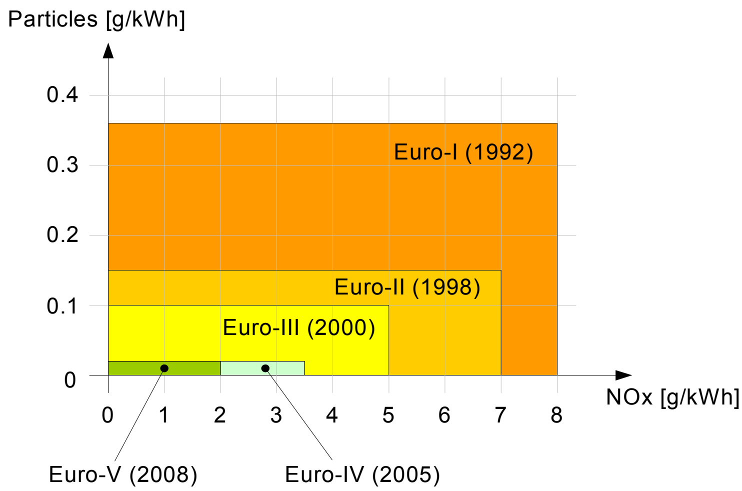


Figure 8.3: NOx and particle limits for heavy duty engines for the Euro-I to Euro-V stages.

Heavy duty engines up to the Euro-III stage were comparably simple and did not need any exhaust gas after treatment. Some vehicles used particle traps to meet local regulations (e.g. at construction sites in tunnels) or as voluntary measures (e.g. urban buses). The adoption of the Euro-IV and Euro-V emission stages made the use of emission reduction technologies necessary. Some manufacturers followed the path to implement a low-particle/high-NO_x combustion strategy and lower the NO_x with SCR exhaust gas after treatment. Other manufacturers followed the low-NO_x combustion path using EGR and reduced particle emissions with a PM-catalyst. Recently, one manufacturer introduced an engine that does not need a particle or NO_x after treatment to meet the Euro-V limits. The engine combines low-particle and low-NO_x combustion by high-pressure boosting and high EGR rates using two-stage EGR cooling.

8.4 Pollutant emissions from heavy duty vehicles

Type-approved engines can be installed in different kinds of heavy duty vehicles (bus, tractor-trailer, rigid truck, etc.). The power consumption of the different vehicles vary very much due to differences in vehicle mass, air drag, driving pattern, road slope, load of auxiliaries such as air-conditioning, etc. Therefore, the emission factors in g/km for the different vehicles are not straightforward to calculate, even if the type approval emission data of the engine is known. There exists only two approaches to determine the pollutant emissions of individual heavy duty vehicles:

1. Put the vehicle on a roller dynamometer, simulate the road load and drive representative cycles.
2. Drive the vehicle on the street and equip it with mobile emission analysers.

Both approached are very intensive regarding time and monetary resources. The mobile emission measurement approach has become more important, there are ideas on the European level to implement "Not-To-Exceed" (NTE) pollutant emission limits which could be monitored on selected vehicles using portable emission measurement devices. Some countries perform in-use compliance programs. Heavy duty vehicles that are suspicious for high pollutant emissions are brought into laboratories and put on a roller dynamometer. If the roller dynamometer tests indicate high emissions, the engine is dismounted and put on an engine test bench where the type approval tests are driven. If the engine behaves outside the tolerances, the manufacturer is forced to develop a technical upgrade and apply it to all the engines affected.

There are also attempts to measure emissions of vehicles driving by a measurement site remotely. Unfortunately, these approaches do not give reliable data; mainly because the dilution ratio of the exhaust gases with ambient can not be determined. Additionally, a single-shot measurement does not give any useful information on the overall pollutant emission performance of a vehicle; the emission behaviour is very non-linear.

In order to create systematic data for emission factors (g/km) of heavy duty vehicles on an aggregated level, the environmental agencies of Austria, Germany and Switzerland have established cooperative research activities. The Netherlands and Sweden have also joined the group. A major outcome of this group is the HBEFA (Handbook of Emission Factors for Road Transport, www.hbefa.net (19)) which was launched 1995 and is frequently updated with emission data of new technologies. This HBEFA methodology was also used for the European FP5 project ARTEMIS (Assessment and Reliability of Transport Emission Models and Inventory Systems).

The basic HBEFA method to estimate emission factors for the different heavy duty vehicles is to remove in-use engines from vehicles and measure them on test benches. The pollutant emissions of the different vehicles are then modelled using the measured pollutant data which are combined with vehicle and driving pattern parameters. The methodology is described in [15]. The simulation gives systematic emission factors for different categories of the HDV fleet (see Figure 8.4 and 8.5) with different loadings for different representative driving cycles at different road gradients. The results are emission factors for more than 30.000 combinations of vehicle categories, driving cycles, road gradients and vehicle loadings. These simulated emission factors are then used as an input for the HBEFA that allows the user a simple simulation of aggregated emission factors for different traffic situations. HBEFA data is normally used for national emission reporting, for sensitivity studies or for local environmental studies.

FS	FS-Name	FS	FS-Name	FS	FS-Name
		1413000	RigidTruck gasoline		
1423105	RigidTruck <7,5t 50ies	1423205	RigidTruck 7,5-12t 50ies	1423305	RigidTruck 12-14t 50ies
1423106	RigidTruck <7,5t 60ies	1423206	RigidTruck 7,5-12t 60ies	1423306	RigidTruck 12-14t 60ies
1423107	RigidTruck <7,5t 70ies	1423207	RigidTruck 7,5-12t 70ies	1423307	RigidTruck 12-14t 70ies
1423108	RigidTruck <7,5t 80ies	1423208	RigidTruck 7,5-12t 80ies	1423308	RigidTruck 12-14t 80ies
1423110	RigidTruck <7,5t EURO1	1423210	RigidTruck 7,5-12t EURO1	1423310	RigidTruck 12-14t EURO1
1423120	RigidTruck <7,5t EURO2	1423220	RigidTruck 7,5-12t EURO2	1423320	RigidTruck 12-14t EURO2
1423130	RigidTruck <7,5t EURO3	1423230	RigidTruck 7,5-12t EURO3	1423330	RigidTruck 12-14t EURO3
1423140	RigidTruck <7,5t EURO4	1423240	RigidTruck 7,5-12t EURO4	1423340	RigidTruck 12-14t EURO4
1423150	RigidTruck <7,5t EURO5	1423250	RigidTruck 7,5-12t EURO5	1423350	RigidTruck 12-14t EURO5
1423405	RigidTruck 14-20t 50ies	1423505	RigidTruck 20-26t 50ies	1423605	RigidTruck 26-28t 50ies
1423406	RigidTruck 14-20t 60ies	1423506	RigidTruck 20-26t 60ies	1423606	RigidTruck 26-28t 60ies
1423407	RigidTruck 14-20t 70ies	1423507	RigidTruck 20-26t 70ies	1423607	RigidTruck 26-28t 70ies
1423408	RigidTruck 14-20t 80ies	1423508	RigidTruck 20-26t 80ies	1423608	RigidTruck 26-28t 80ies
1423410	RigidTruck 14-20t EURO1	1423510	RigidTruck 20-26t EURO1	1423610	RigidTruck 26-28t EURO1
1423420	RigidTruck 14-20t EURO2	1423520	RigidTruck 20-26t EURO2	1423620	RigidTruck 26-28t EURO2
1423430	RigidTruck 14-20t EURO3	1423530	RigidTruck 20-26t EURO3	1423630	RigidTruck 26-28t EURO3
1423440	RigidTruck 14-20t EURO4	1423540	RigidTruck 20-26t EURO4	1423640	RigidTruck 26-28t EURO4
1423450	RigidTruck 14-20t EURO5	1423550	RigidTruck 20-26t EURO5	1423650	RigidTruck 26-28t EURO5
1423705	RigidTruck 28-32t 50ies	1423805	RigidTruck >32t 50ies	1425005	TT/AT <7,5t 50ies
1423706	RigidTruck 28-32t 60ies	1423806	RigidTruck >32t 60ies	1425006	TT/AT <7,5t 60ies
1423707	RigidTruck 28-32t 70ies	1423807	RigidTruck >32t 70ies	1425007	TT/AT <7,5t 70ies
1423708	RigidTruck 28-32t 80ies	1423808	RigidTruck >32t 80ies	1425008	TT/AT <7,5t 80ies
1423710	RigidTruck 28-32t EURO1	1423810	RigidTruck >32t EURO1	1425010	TT/AT <7,5t EURO1
1423720	RigidTruck 28-32t EURO2	1423820	RigidTruck >32t EURO2	1425020	TT/AT <7,5t EURO2
1423730	RigidTruck 28-32t EURO3	1423830	RigidTruck >32t EURO3	1425030	TT/AT <7,5t EURO3
1423740	RigidTruck 28-32t EURO4	1423840	RigidTruck >32t EURO4	1425040	TT/AT <7,5t EURO4
1423750	RigidTruck 28-32t EURO5	1423850	RigidTruck >32t EURO5	1425050	TT/AT <7,5t EURO5
1425105	TT/AT <28t 50ies	1425205	TT/AT 28-34t 50ies	1425305	TT/AT >34-40t 50ies
1425106	TT/AT <28t 60ies	1425206	TT/AT 28-34t 60ies	1425306	TT/AT >34-40t 60ies
1425107	TT/AT <28t 70ies	1425207	TT/AT 28-34t 70ies	1425307	TT/AT >34-40t 70ies
1425108	TT/AT <28t 80ies	1425208	TT/AT 28-34t 80ies	1425308	TT/AT >34-40t 80ies
1425110	TT/AT <28t EURO1	1425210	TT/AT 28-34t EURO1	1425310	TT/AT >34-40t EURO1
1425120	TT/AT <28t EURO2	1425220	TT/AT 28-34t EURO2	1425320	TT/AT >34-40t EURO2
1425130	TT/AT <28t EURO3	1425230	TT/AT 28-34t EURO3	1425330	TT/AT >34-40t EURO3
1425140	TT/AT <28t EURO4	1425240	TT/AT 28-34t EURO4	1425340	TT/AT >34-40t EURO4
1425150	TT/AT <28t EURO5	1425250	TT/AT 28-34t EURO5	1425350	TT/AT >34-40t EURO5
1423109	RigidTruck <7,5t DE-East	1423209	RigidTruck 7,5-12t DE-East		
		1425109	TT/AT <28t DE-East	1425209	TT/AT 28-34t DE-East

Figure 8.4: HBEFA vehicle categories for heavy goods vehicles (from [3]).

FS	FS-Name	FS	FS-Name	FS	FS-Name
		626105	Coach <18t Standard 50ies	626205	Coach >18t 3-Axes 50ies
		626106	Coach <18t Standard 60ies	626206	Coach >18t 3-Axes 60ies
		626107	Coach <18t Standard 70ies	626207	Coach >18t 3-Axes 70ies
		626108	Coach <18t Standard 80ies	626208	Coach >18t 3-Axes 80ies
		626110	Coach <18t Standard EURO1	626210	Coach >18t 3-Axes EURO1
		626120	Coach <18t Standard EURO2	626220	Coach >18t 3-Axes EURO2
		626130	Coach <18t Standard EURO3	626230	Coach >18t 3-Axes EURO3
		626140	Coach <18t Standard EURO4	626240	Coach >18t 3-Axes EURO4
		626150	Coach <18t Standard EURO5	626250	Coach >18t 3-Axes EURO5
		626909	Coach <16t DE-East		
727105	Ubus Midi <15t 50ies	727205	Ubus Standard 15-18t 50ies	727305	Ubus Artic. >18t 50ies
727106	Ubus Midi <15t 60ies	727206	Ubus Standard 15-18t 60ies	727306	Ubus Artic. >18t 60ies
727107	Ubus Midi <15t 70ies	727207	Ubus Standard 15-18t 70ies	727307	Ubus Artic. >18t 70ies
727108	Ubus Midi <15t 80ies	727208	Ubus Standard 15-18t 80ies	727308	Ubus Artic. >18t 80ies
727110	Ubus Midi <15t EURO1	727210	Ubus Standard 15-18t EURO1	727310	Ubus Artic. >18t EURO1
727120	Ubus Midi <15t EURO2	727220	Ubus Standard 15-18t EURO2	727320	Ubus Artic. >18t EURO2
727130	Ubus Midi <15t EURO3	727230	Ubus Standard 15-18t EURO3	727330	Ubus Artic. >18t EURO3
727140	Ubus Midi <15t EURO4	727240	Ubus Standard 15-18t EURO4	727340	Ubus Artic. >18t EURO4
727150	Ubus Midi <15t EURO5	727250	Ubus Standard 15-18t EURO5	727350	Ubus Artic. >18t EURO5
		727709	Ubus <20t DE-East	727809	Ubus >20t DE-East

Figure 8.5: HBEFA vehicle categories for buses (from [3]).

The drawback of the HBEFA method is that the available emission factor data is only valid for an average vehicle of the category. Additionally, new engine technologies coming to the market have to firstly collect mileage before they can be dismounted and measured to create new data for the HBEFA. The consequence is that the current version 2.1 of HBEFA (released in 2004) does not include confirmed data on Euro-IV and Euro-V technologies but relies on estimations. An update with confirmed Euro-IV and Euro-V data is likely to be released soon. Figure 8.6 depicts the emission values provided by HBEFA 2.1 for a tractor-trailer with a mass of 40 tons (category "TT/AT >34-40t" from Figure 8.4). The emissions are plotted versus the average cycle speed. It is important to notice that these values are not valid for constant-speed driving but for driving cycles. Cycles with slower average speed are typically of urban or rural nature with a lot of dynamics (unsteady driving, stop-and-go) and therefore with a lot of acceleration work. The faster cycles are typically cycles with free-flow traffic and low dynamics but higher rolling- and air drag resistances.

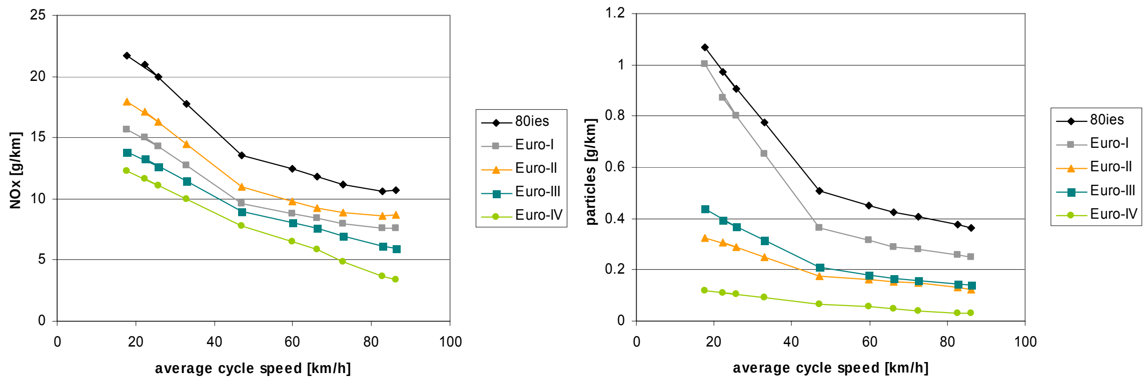


Figure 8.6: HBEFA emission values (NO_x and particles) for a fully loaded tractor-trailer (40 tons).

The emission data of Figure 8.6 shows for example, that the NO_x emissions of the considered Euro-II vehicle is higher than for the Euro-I vehicle. This is surprising because the limit values were tightened (see Figure 8.3). The reason is that Euro-II engines were equipped with electronic controlled injection systems while Euro-I engines has simple mechanical injection systems. This flexibility was used by the manufacturers to calibrate the engines to the emission goals in the operating points relevant for the emission regulations and to calibrate the engines to low fuel consumption outside these regions. This fact was recognised by the legislation and a "control area" was introduced where the certification official could ask for additional measurements.

8.5 Influence of fuels on pollutant emissions

As long as the fuel properties are within the limits for mineral diesel (European Norm EN590), the emissions are not significantly affected by the existing slight differences between different mineral diesel fuels. As soon as important properties change (e.g. cetane number, ash content, oxygen content, lubricity, vapour pressure, viscosity, density), engine emissions, performance, durability and noise can be changed. However, the following alternative fuels are gaining more importance and should be discussed:

- Fuels synthesised from fossil or biogenic gas (gas-to-liquid GTL, biomass-to-liquid BTL, coal-to-liquid CTL), usually produced with the Fischer-Tropsch process.
- FAME (Fatty Acid Methyl Ester), often called "bio diesel", made from different vegetable oils. A US standard (ASTM D 6751) exists since 2001; a European standard (EN 14214) exists since 2004.
- Neat vegetable oil. A German pre-standard exists for rapeseed oil fuel (DIN V 51605).
- Recycled waste oil from fossil or biogenic sources.

The influences of these fuels on the pollutant emissions are summarised in the next sections.

8.5.1 Synthetic diesel (GTL, BTL, CTL)

These fuels are very well suited for diesel combustion. The cetane number is high and the viscosity is close to the viscosity of mineral diesel. The density is about 7% lower compared to mineral diesel; the lower heating values are similar. This leads to slightly higher volumetric fuel consumptions. Synthetic diesel fuels need a lubricity additive. The combustion is cleaner compared to mineral diesel, especially regarding NO_x and the number of particles. Synthetic diesel fuel is virtually free of ash which makes it unproblematic for the use with particle traps.

8.5.2 FAME (bio diesel)

FAME fuels have a slightly higher viscosity, an about 5% higher density and more ash than mineral diesel. Their lower heating value is about 12% lower than the one of mineral diesel. This leads to higher volumetric fuel consumptions. FAME fuels degrade sealings and plastics made for normal mineral diesel use; engines have to be equipped with FAME compatible materials if FAME is used. If pure FAME fuel is used, their higher viscosity can cause problems with increased injection pressures (reduced durability of the injection system). The higher ash content can cause problems in vehicles equipped with particle traps. FAME fuels contain oxygen. This leads to increased NO_x emissions (about 30% according to Empa experiments).

8.5.3 Neat vegetable oils

These fuels are normally not used in the transport sector. Their properties can vary massively so that no generally valid statement on their performance can be made. If their properties are close to the German pre-standard for vegetable oils, the following effects can be expected. Since the density and the viscosity are much higher compared to mineral diesel, the pressure levels in the injection system can be dramatically affected (measurements at Empa showed an increase of the injection pressure of about 40%). Since vegetable oils contain oxygen, the NO_x emissions increase (about 40% according to Empa experiments). Vegetable oils can contain catalyst poisons (sulphur, phosphor) which can lead to a fast catalyst deactivation. Their high ash content can cause problems for engines with particle traps.

8.5.4 Recycled waste oil

For this group, no generally valid statement can be made. On the one hand, waste oil can be refined to a high-quality synthetic diesel- or FAME-like which leads to the properties described above. On the other hand, waste oil can be used with less reconditioning effort and cause large problems. If the waste oil is contaminated with problematic additives, highly problematic emissions can be generated. If the fuel contains for example chlorine (e.g. waste deep-fry oils with salt contamination), dioxin can be generated during the combustion process.

8.6 Other factors influencing pollutant emissions

In addition to the engine technology, the vehicle parameters, the driving pattern, the fuel used and the load of auxiliaries, there are a number of other factors influencing the pollutant emissions. Most important are the ambient conditions: temperature, humidity, pressure. The humidity influences mainly NO_x: more humidity gives less NO_x. The ambient temperature has an influence on several levels: low ambient temperatures cause lower temperature level of the exhaust gas treatment systems and thus a longer warm-up time and less conversion efficiency. High ambient temperatures cause a higher temperature level during combustion and thus more NO_x. Higher altitudes (less ambient pressure) cause less air for the combustion (directly and/or because of turbocharger speed limitations) and therefore increased particle emissions.

Another important source of increased pollutant emissions is the malfunctioning of engine or exhaust gas after treatment components. With older technology, only periodic inspections were able to detect such faults. The actual emission legislations include also regulations regarding on board diagnosis (i.e. the engine control unit has to detect emission-relevant faults of the systems). Severe faults lead to a power reduction of the engine so that the driver is forced to resolve the problem immediately.

8.7 Conclusions

Area-wide pollutant emissions of in-use heavy duty vehicles can not be measured cost-efficiently. If pollutant emission fluxes on a regional or country level have to be estimated, aggregated systematic emission data as provided by the "Handbook Emission Factors for Road Transport" is necessary. For lowest possible pollutant emissions of individual vehicles it is important that the engine works properly and an allowed fuel is used. This can be ensured with periodic inspections and monitored with national in-use compliance programs.

Chapter 9 Setting limits for environmentally friendly vehicles

9.1 Introduction

All vehicles will have some impact on the infrastructure and the environment. To reduce this impact has been the goal of the European Community since it was founded in 1957, but their strategies have not always been successful. This is partly due to the lack of political will and partly due to the success of the European single market where every enlargement including new Member States has led to an increase in transit traffic and more pollution. As pollution knows no boundaries, the EU is competent to act on behalf of its Members to promote more sustainable transport policies.

There have been a series of regulations to limit *local pollutants* from road and more recently rail vehicles. These pollutants and their limits are described in some detail in chapter 8. Furthermore, limits are being imposed on *emissions of greenhouse gases* to help limit global warming.

Starting with the White Paper on Transport in 2001, the EU has introduced a series of legislative and regulatory initiatives of which the major items are listed in Table 9.1.

Table 9.1: Major transport initiatives

Title	Reference	Environmental objective
White paper: "European transport policy for 2010 : time to decide"	COM(2001) 370 final	Possible initiatives to limit impact of transport
Environmental Noise Directive	2002/49/EC	Mapping and strategies for noise reduction
EU Directive on Energy End Use Efficiency & Energy Services	2006/32/EC	Public procurement of energy efficient vehicles
Amendment to the 'Eurovignette' directive	2006/38/EC	Enhanced scope for differential charging
TSI railway noise	2006/66/EC	Sets noise limits for new vehicles

These have been further enhanced in 2008 with two climate change initiatives – the Renewable Energy directive and the 'Green Transport' package (Table 9.2).

Table 9.2: 2008 Initiatives

Title	Reference	Environmental objective
Renewable energy directive	COM(2008) 19 final	20% increase in energy efficiency and use of renewable energy
Greening transport	COM(2008) 433 final	Reducing pollution
Strategy for internalisation of external costs	SEC(2008) 2207	User pays 'full' cost
Rail noise abatement measures addressing the existing fleet	SEC (2008) 2203	Reduce noise emitted by freight vehicles
Charging of heavy goods vehicles for use of certain infrastructures	SEC(2008) 2208	

The renewable energy directive will require transport to contribute towards the targets of both energy efficiency and renewable energy use. This can be achieved for road and rail transport by the following actions –

- increasing energy efficiency of prime power source and drive-line
- switching from internal combustion engines to electric motors whose electricity can be provided by renewable sources
- increasing the proportion of biofuels blended with petrol or diesel

The 'Green Transport' package proposes a new strategy for internalising the external costs to transfer these costs from society to the user so that the various transport modes reflect their true usage cost. It identifies three specific costs which should be charged namely air pollution, noise and congestion which may be time of day and location dependent. For heavy goods vehicles it sets an upper limit for charging these impacts which the Commission estimate add 4 to 5 eurocents/km. These charges are additional to those that may be charged to cover the variable costs of use of the infrastructure.

This proposal for goods vehicles will also enable the internalisation of costs for other modes to be levied such as rail the principle for which has already been established in directive 2001/14/EC. One benefit of this income would be to generate revenue that should be used to make transport more sustainable

R1: Footprint measurement systems can determine the nature and magnitude of the environmental impacts and how such impacts depend upon vehicle class and flow.

9.2 Environmental noise

The EU, like Switzerland, has undertaken a survey of all areas where noise emissions are likely to have exceeded statutory limits [2, 21] and strategies are being developed to reduce noise emissions in areas where these limits have been exceeded. This also impacts on transport directly and so there is on-going discussion about the effectiveness of various measures to reduce traffic noise. These include introducing lower speed limits, limiting access, erecting barriers or implementing noise reduction measures at source [1].

All countries have set *noise* limits from various sources and the increasing volume of road and rail traffic has resulted in increasing noise. As regulations take time to be effective and can only be applied to local and not to transit traffic, noise barriers have been erected alongside major roads and railway lines where noise limits have been exceeded.

For *railway* vehicles, Austria introduced legislation in 1993 (refer chapter 6) and a European regulation (TSI) restricted noise emissions for *new* vehicles from 1 July 2006 (28). Within the 2008 Green Transport Package was a communication from the Commission about limiting railway noise from *existing* vehicles particularly those braking with cast iron brake blocks on the wheel tread.

R2: Footprint measurement systems can detect which vehicles have excessive noise emissions and what may be the origin of this impact whether by vehicle class, speed, type of infrastructure or lack of maintenance of the vehicle or its suspension system.

9.3 Vehicle mass, axle load and forces

Through a variety of sensors embedded in the pavement or attached to the track, it has been possible to measure quasi-static and dynamic forces primarily in the vertical, but for rail, also in the lateral direction. As illustrated in previous chapters, such measurements show that a *small proportion* of vehicles, both road and rail, are excessively loaded and exceed existing limits (refer annex 1). It is likely that such overloaded vehicles will result in a *disproportionate* amount of damage to the pavement or track.

R3: Footprint measurement systems can detect which vehicles exert forces in excess of legal limits and can provide information to operators and drivers about the nature of this excessive force such as inappropriate loading, condition of suspension system, wheel quality or tyre pressure.

9.4 Variation in impacts between vehicles

The parameters which describe the impact of a vehicle on its surroundings constitute its environmental footprint. These are -

- gross vehicle mass
- axle load
- noise
- vibration
- environmental emissions

These impacts, with the exception of environmental emissions, are illustrated for five road vehicles measured at Lenzburg (Figure 9.1).

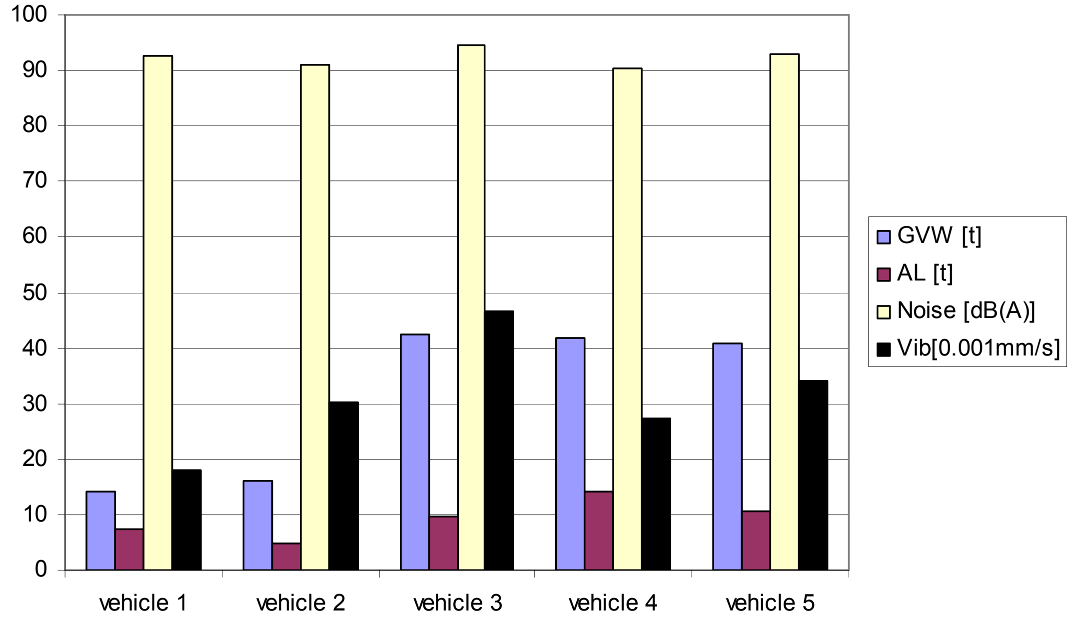


Figure 9.1: Comparison of Footprint parameters for various types of vehicle, Lenzburg, CH

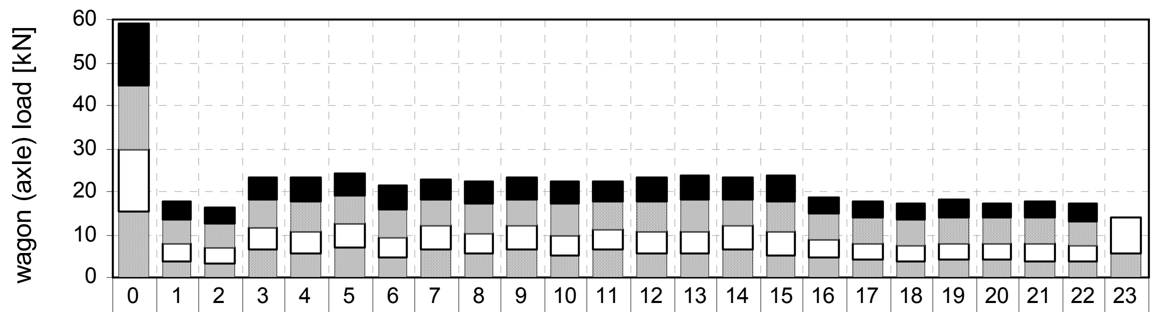
These parameters vary considerably - whilst vehicles 3 to 5 have similar GVM, vehicle 4 has a higher axle load which will lead to more damage to the pavement and vehicle 3 has the highest noise and vibration levels. The noise emissions are independent of GVM which varies by a factor of 4 between the lightest and heaviest vehicle.

The variation in axle loads for the various wagons of a freight train is compared in Figure 9.2 but none exceed the axle load limit.

An environmentally friendly vehicle can be defined in terms of its environmental footprint whose impacts shall be significantly less than the average for each vehicle class.

R4: An environmentally friendly vehicle possesses a small environmental footprint

R5: An environmentally friendly vehicle can be defined as one whose impacts are significantly less than average for each vehicle class and impact



	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Axle 4	14.8	4.0	3.5	5.2	5.5	4.9	5.4	4.8	5.3	5.1	5.5	4.4	5.6	5.5	4.8	6.1	3.9	3.9	3.9	4.0	3.6	3.6	3.9	
Axle 3	14.5	5.8	5.8	6.2	7.0	6.6	6.4	6.0	7.0	6.2	7.1	6.6	7.0	7.4	6.2	7.0	6.0	5.8	5.8	6.1	5.8	6.0	5.6	
Axle 2	14.8	3.9	3.6	5.3	5.3	5.6	4.7	5.3	4.7	5.5	5.0	5.0	5.4	5.2	5.5	5.4	4.0	4.0	4.0	4.0	4.0	4.2	3.9	8.5
Axle 1	15.2	3.8	3.4	6.4	5.4	7.1	4.7	6.7	5.4	6.5	5.0	6.3	5.4	5.4	6.6	5.2	4.7	4.2	3.5	4.1	4.0	3.8	3.6	5.6

wagon order

Figure 9.2: Distribution of axle load and total wagons load along one freight train in the Czech Republic

9.5 Setting the limits

For many of the parameters describing environmental impacts, it is possible to use Footprint measuring stations to collect and sort the data for a particular vehicle class. This is illustrated in Figure 9.3 for a set of noise measurements for road vehicles [26].

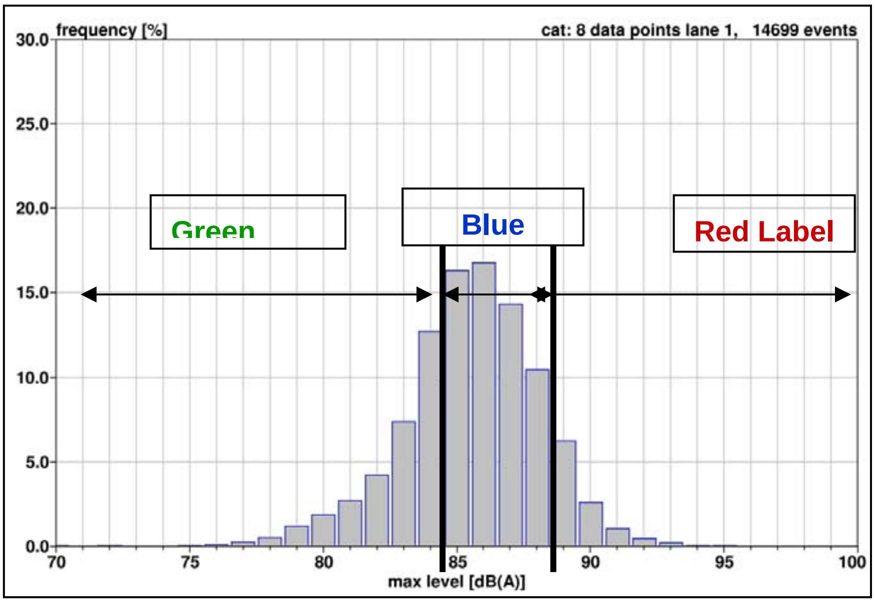


Figure 9.3: Possible limits for road vehicles as measured at Lenzburg, CH

From this data set, a suitable interval can be specified about the mean to reflect the variations between the vehicles in any one class for this impact –

- the 'average' vehicle impact can be classified as the blue band
- those vehicles in the band below can be classified as *environmentally friendly* (green band)
- those in the band above as *environmentally harmful* (red band*)*.

A similar histogram of noise data is illustrated in Figure 9.4 for rail vehicles [1]. This shows that passenger trains have become significantly quieter between 2003 and 2007 however freight rolling stock in 2007 has a similar characteristic to that of passenger stock from 1980.

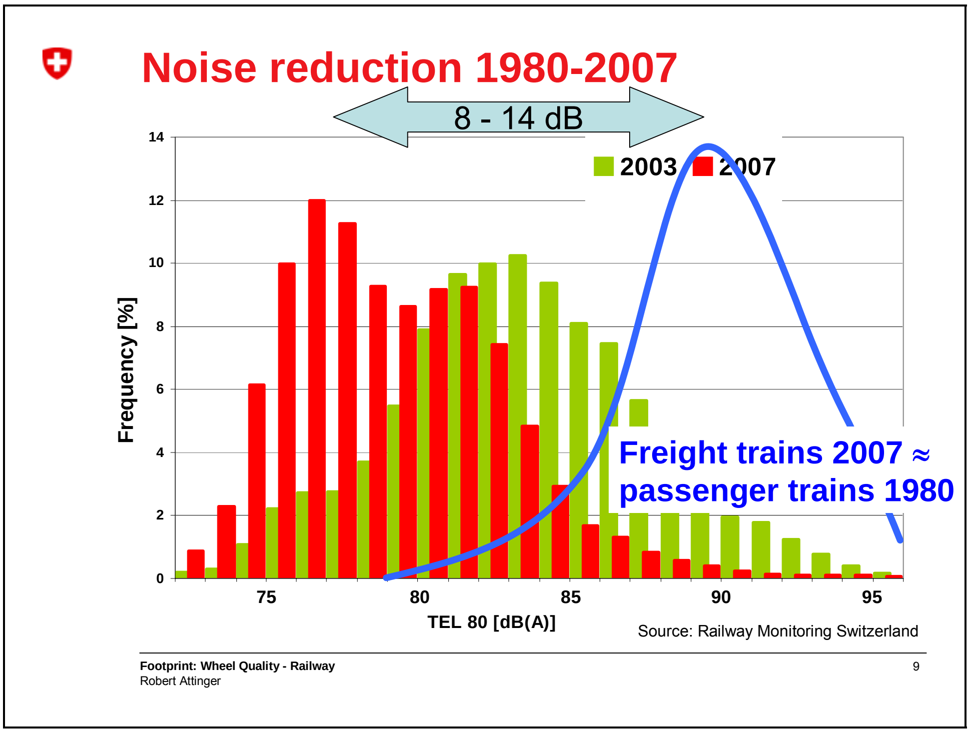


Figure 9.4: Histogram of noise emissions for passenger and freight trains as measured at a Swiss monitoring site [1]

The low noise freight wagons (<86 dB(A)) are associated with new rolling stock built after the introduction of the TSI noise emission regulation in 2006 (28) whilst the other noisier vehicles are much older. As the life of a railway vehicle can be as long as 30 - 40 years, action is needed on reducing noise from existing stock which COM (2008) 433 (4) final addresses.

R6: Limits to be set for each environmental impact and vehicle class which can define the degree of environmental friendliness of the vehicle. Such limits may be classified as average, environmentally friendly or environmentally harmful.

9.6 Bonus/malus system for user charging

EU legislation requires modes to be treated evenly with respect regards to infrastructure pricing though some variation can be tolerated. As Member States currently have non-harmonised pricing schemes for both road and rail mode, one option that has been discussed is that of a bonus/malus system.

The fundamental concept is that those vehicles that have a low environmental impact (i.e. environmentally friendly) will be rewarded with a reduction in the user charging (*bonus*) and those vehicles that are unfriendly (i.e. environmentally harmful) will be charged at a higher rate (*malus*). In principle, such a scheme could be developed to be revenue neutral.

Such a scheme has been proposed by the Commission as a favoured option for reducing noise emissions from the existing railway fleet (SEC 2008 2203, Table 9.2). The Commission's proposal does not stipulate noise measurements in daily operation for the time being.

R7: Footprint measuring stations can be used to measure the threshold limits to set bonus and malus payments if so desired and subsequently to base charges on actual noise generation in daily operation.

9.7 External costs

There is still no agreement between Member States to charge a part or all of the external cost. EU legislation has in recent years allowed differential charging with a proviso that they should be levied on both road and rail mode.

At the present time, operators do not pay any external costs, but this will change if the Commission 'green' transport policy. This will mean that some of the financial burden currently being carried by society will be transferred to the operator. However, implementation of the Environmental Noise Directive (2002/49/EC, Table 9.1) will require a noise abatement strategy which could result in operators of noisy vehicles being charged and of quiet vehicles rewarded.

One way of designating the environmental impact of vehicles is to develop an environmental label which lists not only energy efficiency and CO_2 emissions, but also other environmental burdens like local pollutants (SOx, NOx and PM_{10}) and noise. This was discussed at the Footprint Workshop held on 26 November 2008 in Dübendorf where both Swiss Office for the Environment and Swiss Office for Spatial Planning discussed the implications of labelling and differentiated taxation [1].

9.8 Overall conclusions

It is possible to use Footprint measuring stations to determine the impact of vehicles on the environment and infrastructure. The collected data can be analysed to determine environmentally friendly and harmful limits for each impact.

Footprint measuring stations can also identify which vehicles should receive a discount on their user charges and which should have to pay a surcharge. If this recommendation is viewed favourably by Member States, then further work is required to develop and refine these concepts. This work could be undertaken within a second phase of the Footprint project.

1 Chapter 10 Ranking the impacts by mode

The major impacts of road and rail vehicles with the infrastructure and environment are described in this report. Together with some of the impacts of air travel, these can be qualitatively compared with road and rail in order to obtain a ranking of all three modes.

10.1 Conveyance of freight

The current ECE limit is 44 tonnes (gross) for six axle road vehicles with road friendly suspensions [10]. Freight trains can convey up to 2000 tonnes at any one time (equivalent to 40 freight wagons), whilst aircraft can carry up to 100 tonnes. So for bulk goods such as aggregate or coal rail is the obvious mode over long distances.

With increasing congestion on major roads and motorways, rail, unlike road, can compete with air freight for overnight deliveries up to perhaps 800 km. If however goods are fragile, then road and air are currently more benign than rail as they have 'better quality' suspensions. But new suspension designs are being evolved for rail freight that will also allow fragile goods to be conveyed.

For short distances up to maybe 200 km, road is the preferred choice but for greater distances other modes need to be considered and some form of intermodal transport may provide the best option. The operator's preferred choice is summarised in Table 10.1. Note that noise emissions and pollutants have until now been given a low priority on this list as society has borne these socio-environmental costs; particularly those living adjacent to major traffic corridors.

Table 10.1: Operator ranking of requirements, choice of mode and their impacts

	road	rail	air
individual or bulk	batch	bulk	individual
fragility of goods	good	variable	excellent
distance moved	short	medium	long
just in time	Not always possible due to congestion	possible	possible
mass	medium	high	low
speed	slow	medium	high
initial cost	medium	medium	high
noise emissions	low	low	high
pollution	low	low	high
Flexibility to deliver to any location	high	medium	low

10.2 Infrastructure maintainer's concerns

The infrastructure maintainer's primary concern for road and rail modes is axle load because the higher the load, the stronger must be the pavement and substructure to withstand both static and dynamic loading. The secondary concern is that of gross mass because the life of structures like bridges is primarily affected by static loads as dynamic loads can be limited by reducing speed. Both axle load and gross mass can affect the alignment of the pavement or track which must be maintained within close limits in order to limit dynamic loading, noise and vibration.

Implementation of the Environmental Noise directive now requires the maintainer to keep noise emissions within prescribed limits which can be provided by a noise management strategy. The likely ranking of impacts is listed in Table 10.2 for the three modes. Note that noise emissions have now risen in importance due to ever increasing amounts of traffic which in some areas also causes local pollutants to exceed WHO limits.

Table 10.2: Infrastructure maintainer ranking of impacts by mode

	road	rail	air
pavement loading (axle load)	high	medium	low
structural loading (GVM)	medium	low	high
infrastructure alignment	high	high	n/a
dynamic loading	high	medium	n/a
Noise (i)	medium	Medium	high
Vibration (ii)	Low	medium	n/a
local pollutants (iii)	high	low	n/a

(i) noise level is dependent upon volume of traffic and speed particularly for major roads and railway lines

(ii) vibration levels for road vehicles will likely depend upon the stiffness and strength of the pavement

(iii) assumes electric traction for rail

10.3 Societal concerns

Unlike the operator's or infrastructure maintainer's concerns, societal concerns have until recently been linked to local environmental emissions like pollutants and noise. These can only be reduced by developing strategies to promote more sustainable use of transport which may well involve using more than one mode.. Use of intermodal transport is increasing and is helping to reduce greenhouse gas emissions and increase infrastructure capacity. No community likes transit traffic to go through their town or village, because they suffer the impact without any direct gain and their likely concerns are ranked in Table 10.3 for the three modes.

Table 10.3: Societal ranking of impacts by mode

	road	**rail**	**air**
local pollutants	high	small	small
noise emissions (i)	medium	low	high
global emissions	high	low	increasing
infrastructure capacity	saturating	expanding	limited
transit traffic	high	low	medium
sustainability	medium	high	low

(i) the current data shows that noise emissions per vehicle are similar for road and rail, but this will change as EU regulations will result in lower noise emissions from rail vehicles (refer chapter 9.5)

10.4 Comparison of modes (passenger)

In terms of land use, a double track railway and six lane motorway have the same carrying capacity/hour, but rail requires only 33% of the area that the roadway would require. For distances up to 600 km, there is an increasing expansion of high speed rail links to reduce the dependence on both road transport and short-haul aircraft.

The distance travelled per passenger unit of energy (kWh) is significantly higher for trains than any other mode (Figure 10.1) and consequently the carbon emissions per passenger per 100 km is significantly lower (Figure 10.2) [12, 27].

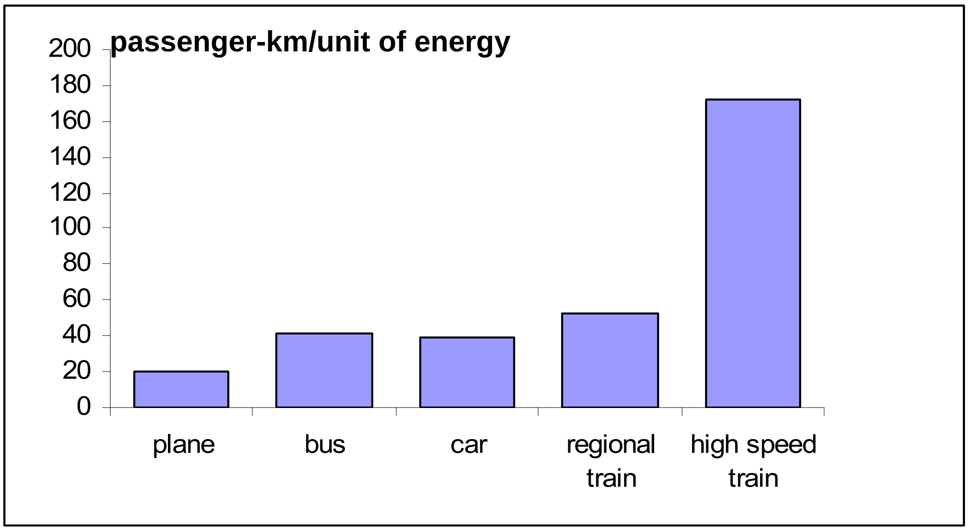


Figure 10.1: Distance travelled by passenger (km) per mode per unit of energy (kWh)

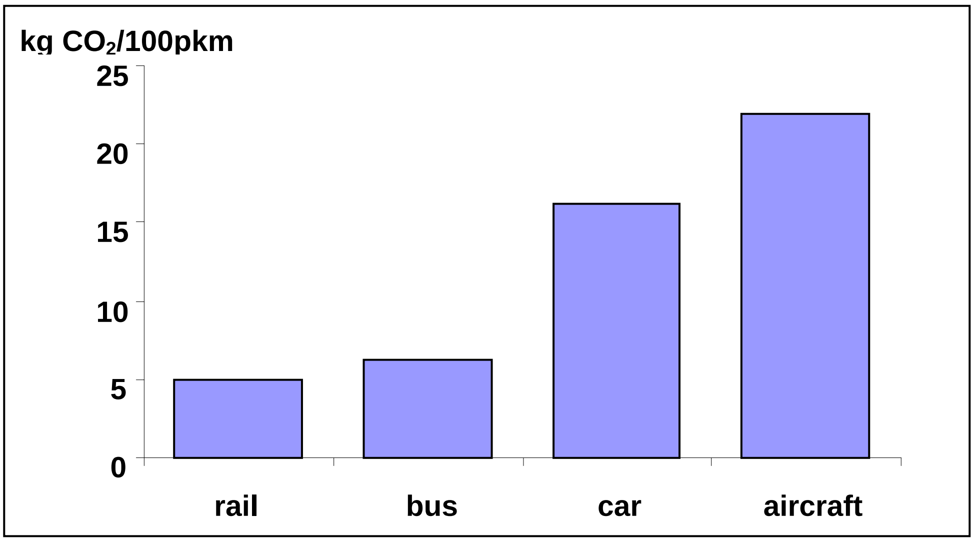


Figure 10.2: Carbon emissions (kg CO_2) per passenger per 100 km

Modern passenger trains have become significantly quieter in terms of noise emissions over the past 5 years with a reduction of average noise level by 4 dB(A) to 79 dB(A) (from figure 9.4) whereas for buses the average noise level is significantly higher at 88 dB(A) and for cars 86 dB(A) (Figure 10.3).

The increasing use of intermodal transport enables each mode to be used most efficiently and with the least impact Such integrated transport solutions are now very common in all cities and large towns.

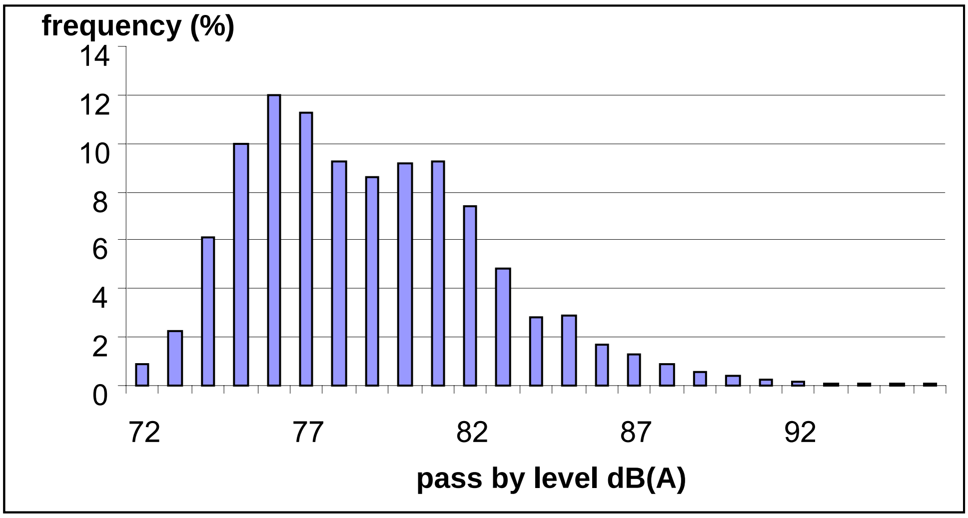


Figure 10.3a: Pass by noise emissions (dB(A)) for passenger trains (CH)

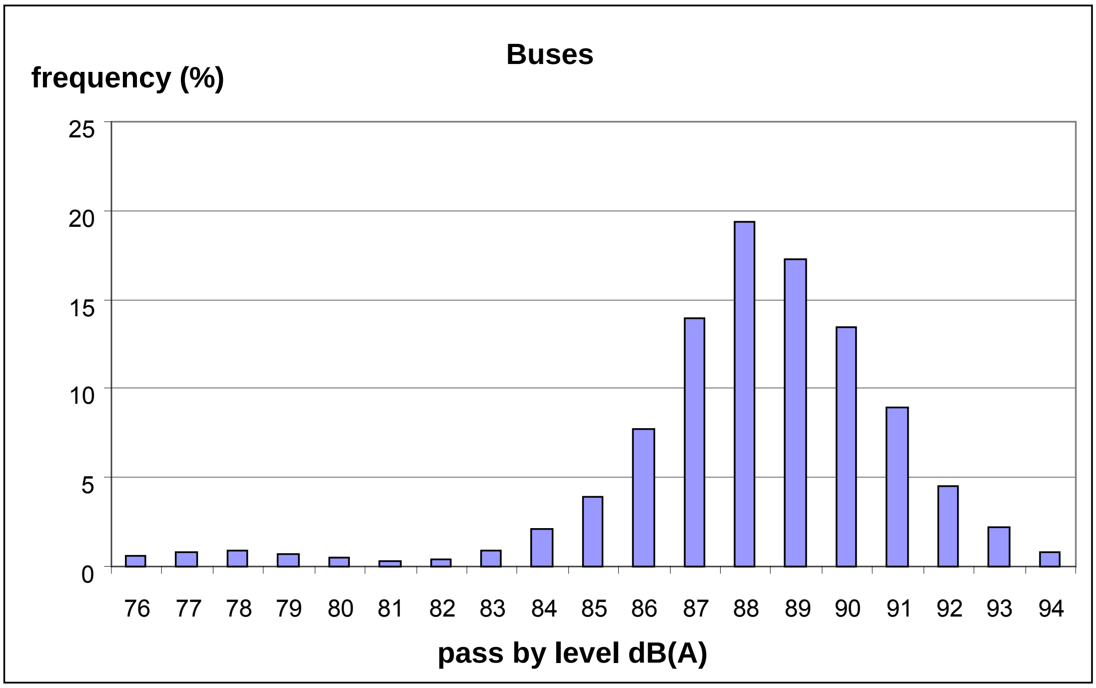


Figure 10.3b: Pass by noise emissions (dB(A)) for buses at 80 km/h (UK)

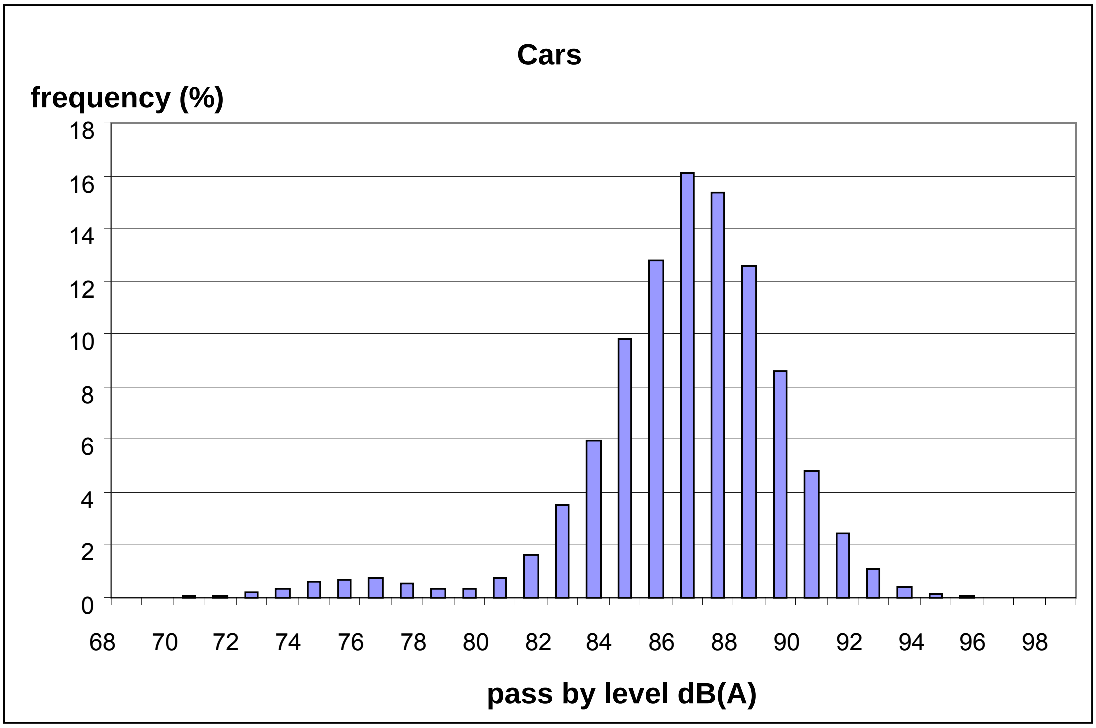


Figure 10.3c: Pass by noise emissions (dB(A)) for cars at 80 km/h (UK)

10.5 Comparison of modes (freight)

The simplest comparison is that of a container being transported either by road or rail. The maximum weight of a container is ca 30 tonnes which can be carried either by a 5/6 axle trailer or by a freight train which could comprise a locomotive and up to 38 wagons carrying containers. As with passenger conveyance, the energy consumption is significantly higher for road than rail (Figure 10.4) and so the carbon emissions are significantly less even with rail being pulled by a diesel rather than an electric locomotive (Figure 10.5) [27, 32]. Air freight will have even higher emissions.

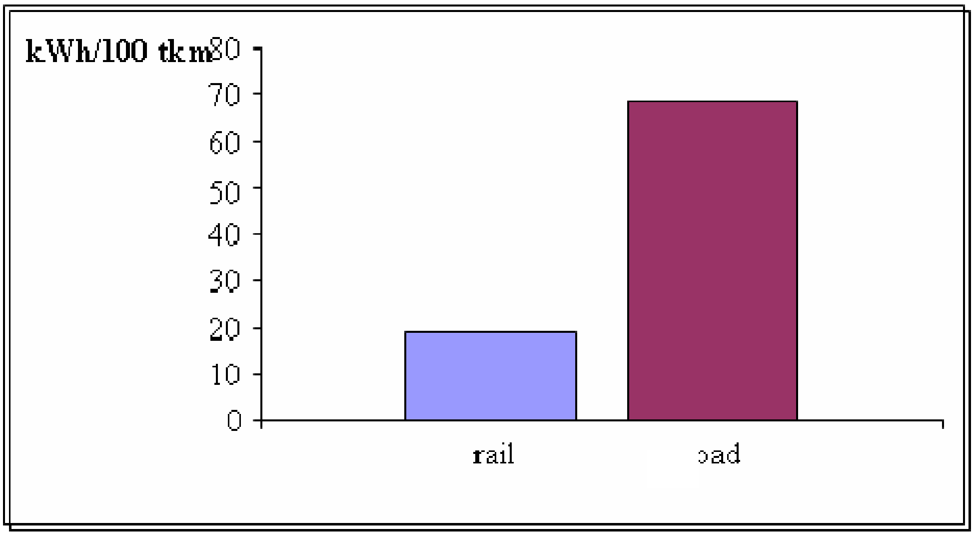


Figure 10.4: Energy consumed (kWh) per 100tkm for road and rail freight

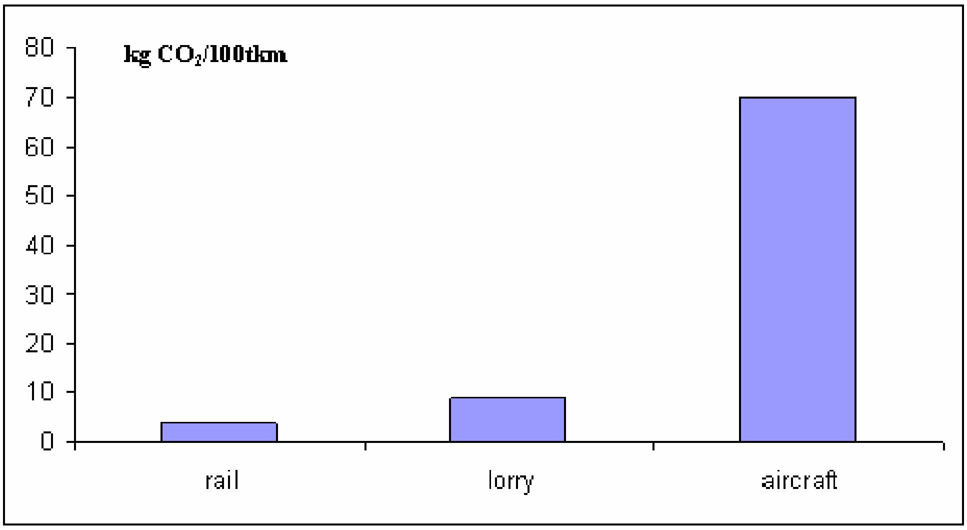


Figure 10.5: Carbon emissions (kg CO_2) per 100tkm

For road freight, the noise emissions at 80 km/h have been measured at four sites and vary between 87 and 94 dB(A) (Figure 7.5) and these have been averaged in Figure 10.6; for rail freight vehicles manufactured pre 2007, average noise levels are 88-92 dB(A) (Figures 6.2 and 9.4). These values for road and rail are surprisingly similar . However, for rail vehicles manufactured from 2007 onwards, the noise emissions may not exceed 86 dB(A) so rail freight will become progressively quieter than road freight. This should allow more freight to be conveyed on railway lines which are currently underused at night when passenger trains are not being operated.

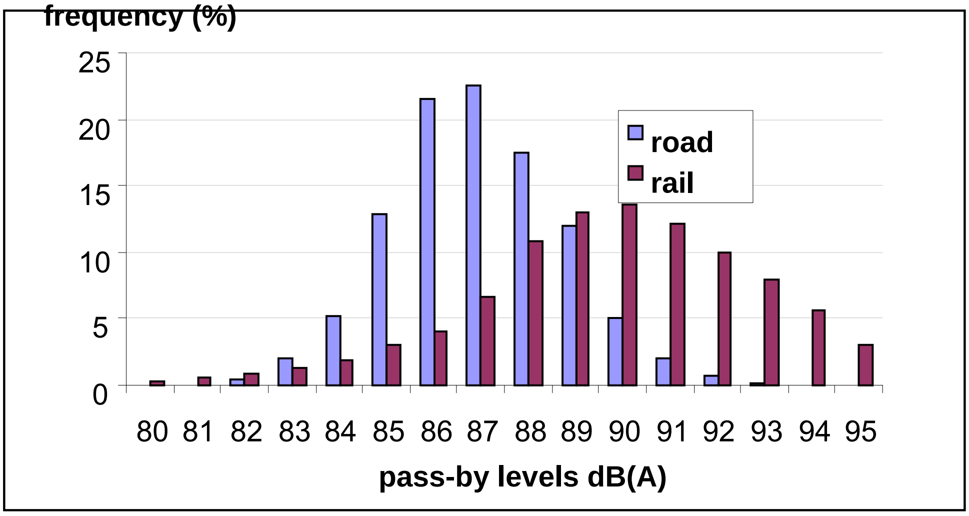


Figure 10.6: Pass by noise emissions for heavy lorries and rail freight in 2007. Note that rail vehicles manufactured from 2007 onwards may not exceed 86 dB(A) level.

10.6 Discussion and conclusions

There are clear distinctions between the concerns of operators, infrastructure maintainers and society. In the past, solutions have been developed to reduce one impact but the increasing desire for mobility and globalisation of manufactured goods require more holistic solutions which requires making better use of all modes to reduce all impacts.

What footprint measuring systems can do is to measure such impacts and help communities decide what strategies are most likely to reduce the socio-environmental impact of transport.

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Annex 1: Road vehicle legal load limits

In the examples given below, the axle loads and gross weights of vehicles are a function of the axle spacing, single or double axles and suspension system. For example the drive axle is allowed 11.5 t whereas a single non-drive axle is allowed 10 t.

A1.1 UK legal limits

The legal limits for axle loads and gross weight in the UK are listed in A2.2. It should be noted that each goods vehicle in the UK has it's own plated weight and is dependent on the individual characteristics such as those mentioned in A2.1.

Table A1.1: UK allowable gross vehicle weights (GVW) and axle loads

Configuration	Allowable GVW [t]	Special provisions
Articulated - 3 axles	26	
Articulated 4 axles	36	38 with road friendly suspension
Articulated 5 axles	40	
Articulated 6 axles	44	
Rigid 4 axle	30…32	32 with road friendly suspension
Rigid 3 axle	25…26	26 with road friendly suspension
Rigid 2 axle	18	
Configuration	Allowable Axle Load [t]	
Driving tandem axle complying with * below	19	
- but if axles are < 1m apart	11.5	
- if 1m to 1.3m apart	16	
Driving tandem axle not complying with * below	18	
- but if axles are < 1m apart	11.5	
- if 1m to 1.3m apart	16	
Non-driving tandem axle	20	
- but if axles are < 1m apart	11	
- If 1m to 1.3m apart	16	
- if 1.3m to 1.8m apart	18	
Triaxle	24	
- but if any two axles 1.3m or less apart	21	

* (a) The driving axle is fitted with twin tyres and road-friendly suspension or (b) each driving axle has twin tyres and no axle has an axle weight exceeding 9.5 t.

A2.1 Swiss legal limit

The legal limits for axle loads and gross weight in Switzerland are listed in A2.1.

Table A2.1: Swiss allowable gross vehicle weights (GVW) and axle loads [www.admin.ch/ch/d/sr/741_11/a67.html]

Configuration	Allowable GVW [t]	Special provisions
More than 4 axles	40	44
4 axles	32	
3 axle trolley bus	28	
3 axle	25…26	26 with double axle / air-suspension/ or similar
2 axle	18	
Configuration	Allowable Axle Load [t]	Vehicle in operation before 1.10.1997
Single axle (11.5 t on drive axle)	10…11.5	12
Double axle (<1.00m apart)	11.5	
Double axle (between1.0 and 1.3m apart)	16	
Double axle (between1.3 and 1.80m apart)	18	
Double axle (between1.3 and 1.80m apart w. springs)	19	20
Double axle (>1.8m apart)	20	
Triple axle (<1.3m apart)	21	
Triple axle (Between 1.3m and 1.4m apart)	21	
Triple axle (>1.4m apart)	27	

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