Comparison of Forces for Discretely Supported and Continuously Embedded Track Systems: Effects on the Track, Vehicle Users and the Environment

1. Introduction

Decade-long development in guided-rail transport – primarily in vehicle technology – must be matched by a corresponding optimization (minimization of costs and maximization of utility) of the life span costs (LSC) for the track. For operators, this includes not only the life cycle costs (LCC) for the track system – foremost all investment and maintenance requirements for safety and comfort. Within the framework of external costs, the factor of environmental protection is a primary issue for the general population. The improvement of environmental protection is justifiably supported through people’s increasing awareness of health and quality of life – both of which are considerably affected by transport measures.

In contrast to other means of transport, rail transport in general is considered to be environmentally-friendly. Internationally however, there is an enormous need to catch up in creating an economic, safe and environmentally-suitable technology for tracks and vehicles. At the Department of Railway Systems, a non-linear, three dimensional overall model (M³Rail) is currently in development to describe the important key interactions between track and vehicle. With M³Rail we are attempting to model the relevant forces of the vehicle and their effects on the track system, the surroundings and on the vehicle user.

By using the M³RAIL model we will aim particularly to improve the modeling of short time dynamics with respect to effects on travel comfort and the long-term behavior of the entire track system – that is, all components of the superstructure and substructure as well as the underground.

The final objective is that with consideration of the dynamics, most track-vehicle components can be tuned so that an optimization of the above-mentioned effects can be reached.

II. FORCES ON TRACK SYSTEMS

The forces affecting tracks result from:

- static axle loads
- moving load dynamics

The static axle loads are determined by the total mass of the vehicle. Depending on the route class, the loads range between 160 kN und 225 kN. Through various influencing factors
(planned super-elevation or sub-elevations, track imperfections, one-sided load etc.) loads may be unevenly distributed - and additionally to the vehicle-related factors – they may create a dynamical component.

The forces exerted by the moving load mainly result from the vehicle’s motion and/or rotating masses. The resulting forces usually do not occur at a right angle to the contact surfaces. They are normally divided into:

- force components perpendicular to the track level, hereafter known as “vertical” force components or “vertical forces”,
- force components transversal to the track level, hereafter known as “horizontal” force components or “horizontal” forces.

Here the dynamical vertical force component derived from the wheel load \([Q]\) is dependent on

- speed,
- contribution of the rotating mass of the vehicle,
- type of rail support (discrete or continuous),
- conditions of the track bed, and
- elasticity of the overall track system.

We can assume a value of up to \(\pm 50\%\) of the static wheel load. Figure 1, an extended graphic from Birmann [Birmann, 1967]), shows the interpolation curves for two older locomotive series of Germany’s DB AG. Investigations using new locomotive series also show this tendency.

![Figure 1: Dynamical vertical forces for two different locomotives (E10299 and E03002)](image-url)
The wheelset is normally displayed as a double cone.

Figure 2: Double cone geometry of wheelset and decomposition of normal force into vertical and horizontal components. During rolling of the double-cone like wheelset on the best-suitable tracks there results a “capped” sine curve like motion of the wheelset in the track gauge channel with a wavelength \( L \approx 20 \text{ m} \).

\[
\text{wavelength} \quad L = 2\pi \frac{r - s_K}{2\gamma} \\
\text{frequency} \quad f = \frac{v}{L} = \frac{v}{2\pi} \frac{2\gamma}{r - s_K}
\]

\( r \) = radius of the running circle \\
\( s_K \) = span of the wheelset \\
\( \gamma \) = slope of the wheel tread \\
\( v \) = speed

Figure 3: Sinusoidal course of wheelset according to Klingel
This motion introduces a dynamic load into the track system with constantly changing “horizontal forces”. Perturbations of this rolling process occur through the following:

- imperfections in the track bed,
- one-sided contact of the wheel (eg. in a curve)
- constantly alternating rail deflections resulting from the changing effects of force, with consideration of:
  - type of track support (discrete or continuous),
  - type of track fastening (discrete or continuous or embedded),
  - horizontal elasticity of superstructure

In particular, the “horizontal” component of vehicle guiding forces (Y) increases to top levels when speed increases, depending on the wheel assembly. Due to increased danger of derailment, this increase of the horizontal component must be limited by controlling the speed. In horizontal direction a force of 100 kN is usually considered. In order to avoid derailment, the vertical (Q) to horizontal (Y) force ratio must be larger than the limiting value:

\[
\frac{Q}{Y} = 0.8.
\]

In addition to vertical and horizontal forces there are longitudinal forces acting on the track. At the site of the track fastenings a longitudinal creep resistance of 10 kN is necessary. Longitudinal forces arise:

- through acceleration (positive and negative)
- from longitudinal stresses due to changes in temperature
- through increased motion resistance due to radiation of the flexural wave from the wheel load
- from longitudinal stresses arising from longitudinal waves

For the following types of railway vehicles

- street car vehicles,
- new vehicles in combined transport for light rail transport and regular rail (urban rail or light regional rail),
- new light urban rail vehicles and
- new light regional rapid transit vehicles (LRT)

there are guidance problems which arise depending on the type of wagon body support on the axle – either inner or outer support
Figure 4: Axle bending and change of Klingel’s wavelength

This results in additional forces which is revealed mainly in rail and/or wheel wear.

For outer support of the wagon body a convex bending of the axle occurs. This creates a wheel tilting to the outside above the wheel axle. Consequently, the flange gauge (i.e. the distance between the wheel flanges measured at particular points of the tyre grooves) is reduced. Therefore, for a constant track gauge, a larger flangeway clearance occurs (see Fig. 4). Investigations made by the author resulted in differences of up to 8 mm. The larger flangeway clearance allows the wheel to have a larger rotation angle around the vertical axis. This results in an increased striking of the wheel on the rail, and over long distances a “sideways running” of the wheelset occurs. Until the wheel in contact- due to its larger rolling path compared to the opposite wheel in the wheelset- begins to disengage from the guiding rail edge, an unperturbed sinusoidal motion of the wheelset according to Klingel does not
develop. The striking wheels lead to increased wear for the rails and/or wheels. In extreme cases derailment may occur.

For *inner support* a concave bending of the axle occurs. This creates a wheel tilting to the inside above the wheel axle. As a result the flange gauge is increased. For a constant track gauge, a smaller flangeway clearance occurs. Differences of up to 5 mm occurred during investigations made by the author. The reduction of the flangeway clearance only admits small rotation angles around the vertical axis. Over long distances a “sideways running” occurs. An unperturbed “sine curve” motion cannot develop under these circumstances. The frequent contact of the tilted wheels creates a higher level of wear for the rail and/or wheel. In extreme cases derailment may occur.

In both cases, a cost-intensive wheelset - for example with radially adjustable wheels – may contribute to a solution of these problems. However, often several vehicle generations are used along a route with varying wagon body support. A corrective measure would be the use of a “horizontal” elastic rail support with increased lateral elasticity.

If high speed vehicles are used on regular lines laid out with many curves, often increased rail wear will occur – whenever these vehicles must use lower speeds. This mainly results from the tight turning restriction around the vertical wheelset axle, which helps reduce Y-forces at high velocities. Also in this case, radially adjustable wheels or a “horizontal” track support with higher elasticity may help to avoid rail wear.

If “vertical” and “horizontal” forces are further divided according to their origins, there are a number of dynamical influences that need to be considered. The following listing summarises the main influences together with the responsible vehicle, wheel assembly, and track components:

**“Vertical”:**
- vehicle-dependent: speed
- axle and wheel load

**vehicle/wheel assembly-dependent:**
- rotating mass in the drive units
- (drive unit support suspended vs. non-suspended)
- unbalance in wheels / wheelsets
- polygonisation of wheels / wheelsets

**track-dependent:**
- track imperfections
- rail support (discrete vs. continuous)
“Horizontal” perpendicular to the track:
vehicle-dependent: speed
                   rotating masses
                   wagon body support on axle (inner vs. outer)
wheel assembly-dependent: rigid wheelset or individual wheel
                          wheel tread surface gradient
track-dependent: canting of the rail
                rail support
                (discrete vs. continuous vs. embedded)
                rail fastening (discrete vs. continuous vs. embedded)
                rail support quality

“Horizontal” along the track:
    vehicle-dependent: acceleration
                      track-dependent: rail support (discrete vs. continuous)

It should be noted that these forces add and that the resultant – due to the sine curve motion – oscillates around the wheel-rail contact point within the wheel-rail contact area.

III. COMPARISON OF TRACK SYSTEMS

To more closely examine the forces for various track systems as described in Section 2, the following track systems will be compared:

- Regular ballast track (discretely supported and fastened cross sleeper rails)
- Slab tracks with discrete rail support and fastening
- Slab track with continuously supported and continuously embedded rails

Figure 5: Slab track with continuously supported and continuously embedded rails
Ballast track: For regular ballast track the rails are supported directly on cross sleepers. Together the sleeper and rail form the track span. The track span is supported in the ballast which serves as an elastic vertical load support and counteracts the “horizontal” lateral displacement. The actual “horizontal” contact surface of the sleepers on individual ballast stones amounts to about 7%-10% of the total theoretical sleeper bed surface.

In the “vertical” direction, the vibrations caused by the moving load dynamics are absorbed on one hand by the elastic rail fastening, the railpad, and the baseplate pad, and on the other hand by the ballast. However, the ballast has unfavorable rheological properties at certain frequencies. It must also be taken into consideration that the static stiffness of the railpad and baseplate pad increases with the load. The dynamical stiffness and damping increase with frequency. Furthermore, their stiffness increases with age. The stiffness of the railpad and baseplate pad also increase with decreasing temperature.

Further load and vibration distribution occurs through the frost and substrate protection layers and through the underground base and substructure layers. It must be considered that:

- Through the quasi-pointlike wheel contact, the rails are stressed at top levels under the contact surface.
- The first rail-wheel eigenfrequency occurs between 50 -100 Hz.
- Through discrete support the loads are transmitted into the ballast only at the sleeper-stone contact points. This leads to peak stress levels at both the rail-sleeper bearing surface and the sleeper-ballast bed surface.

Track imperfections lead to a higher level of wear. Wear may occur also due to elasticity (receptance) of the entire ballast track system under current construction conditions (e.g. high substrate compression, unsuitable railpad or intermediate plate stiffness, possible covering of sleepers etc.). The total track receptance critically depends on the stiffness of the substrate. Because the properties of the substrate dominate the receptance of the entire track system in the frequency region between 50-150 Hz, the use of railpads with varying thickness is insufficient to compensate for a very stiff substrate.

Also in the “horizontal” direction there are stress peaks for the rail’s bearing areas due to discrete support and high stress loads for rail fastening points (support and fixing points). Despite a certain elastic fastening of the rails, there also will result disturbances in the “sine curve motion” with a capping of the amplitude (see Section 2). The wave length of the lateral
bending mode of the rail is about 6 meters. Thus, it does not differ substantially from the one in “vertical” direction. Should problems due to manufacturer error occur in track gauge tolerances or occur through mixed use of various vehicles (inner and outer support of the wagon body on the wheel assembly, stiff control of bogies for high speed trains) then stress increases, which in turn leads to further increased wear.

Slab tracks with discrete rail support and fastening: Also for this type of slab track the rails are supported discretely on concrete cross sleepers embedded in concrete or on appropriately shaped support points. The rail fastening is analogous to the ballast track. However to reduce non-suspended mass, increased elasticity must be ensured in vertical and horizontal directions at the fastening points. This is needed due to the monolithic construction of the concrete plates and their completely flat positioning, which provides only a limited vertical vibration damping effect and does not ensure sufficient lateral displacement as in the case of ballast tracks. Therefore, the receptance of this type of track system resembles most closely the one of a ballast track on a rather stiff substrate. The vertical and horizontal loads are transmitted at discrete points as in the case of ballast tracks. The stresses at the rail fastening positions (support and fixing points) are nearly identical to the ones for ballast tracks, yet their receptance behaviour is dependent on the railpad elasticity, i.e., for an equally stiff railpad together with an extremely soft baseplate, adverse effects are markedly less. While the stiffness is constant over a larger frequency range, the damping is mainly effective at the resonance frequencies. Through the rigid support of the concrete plate, this track system reacts considerably more sensitively to changes of the flange gauge, track gauge, and flangeway clearance, for example due to manufacturing errors in the gauge width, or due to mixed use of various vehicles (inner/outer support of wagon body on the wheel assembly, stiff control of bogies for high speed trains).

Slab tracks with continuously supported and continuously embedded rails: In contrast to present-day track construction, slab track systems with continuously supported and continuously embedded rails reduce the number of technical components needed to the following:

- Rails: guiding devices, load support
- Poured mass: reduces vibration, distributes forces for continuously elastic support and continuously elastic embedding
- Concrete: load support / distribution and track gauge control
Through the complete embedding of the rail base, rail web and parts of the rail head (Fig.5), there occurs a completely different stress-deformation behavior compared to systems with discrete support with discrete fastening or a vertical continuous support with discrete fastening points in a horizontal direction. There are no stress peaks created by the system (in contrast to discrete support/fastening) and transferred back into the system using this type of construction. The system’s vibration behavior can be partly controlled through the adjustment of only three different materials and masses. Not only due to the monolithic concrete body, which is continuously supported over a large area, but also due to the rails which are completely surrounded and continuously elastically embedded, the forces are absorbed by a large damping area independent of the inclination of the rail-wheel contact force. Through the effect of force distribution found in this type of support and fastening system, the rails are less stressed. Investigations of different rail profiles optimised for this track system, which also reduce noise generating vibrations depending on the elastic poured mass used, are being carried out within the framework of the M³RAIL research project.

As a consequence of the continuous elastic rail support and fastening, this type of track is relatively insensitive to varying vehicle designs (inner and outer support of wagon body on the wheel assembly, rigid control of bogies for high speed trains).

IV. EFFECTS ON THE TRACK, VEHICLE USERS AND THE ENVIRONMENT

As shown in Section 1, apart from availability LCC is important for nearly all kinds of fixed assets. Since fixed assets for public transport represents one whole for operators, users and the general population, the influences on LCC must be considered as a whole. Here, consideration of LSC is suitable. In co-operation with international partners, the author has determined LSC for the area of track systems.

In order to determine the effect of the forces exerted by the rolling stock on various track systems on the LSC, their effects and consequences must be studied in more detail. Six main areas are considered

- Track wear
- Vehicle wear
- Comfort impediments in vehicles
- Noise immission in the vehicle
- Noise emission within the environment
- Underground vibrations
**Track Wear:** The wear caused by vertical forces – especially the dynamical ones – on the rail and on the track can be minimized depending on the type of rail support used. In as far as ballast tracks are used, this type of construction is recommended for lower to mid-level speeds. For higher speeds, based on the basic experience gained from test sections, a construction type using elastically supported and elastically embedded rails is recommended. In contrast to regular ballast tracks, these offer the lowest maintenance costs and the lowest LSC based on previous knowledge. To absorb the horizontal forces from the dynamic rolling process, rail fastening must also be elastically supported. However, an overly-prominent tilting of the rail should be excluded. As a result, there are of course limits to elasticity in the case of discrete fastening. For construction using continuously supported and continuously embedded rails the limiting value may to some degree be controlled through a variation of material characteristics.

**Vehicle Wear:** Provided that rails are regularly maintained, the vertical forces due to the interaction with the track are important. However, the horizontal forces contribute mainly to wheel wear. Reduction of wear can be achieved through a horizontal elastic fixing/support of rails which best allows an unperturbed “sine curve” motion to develop. Since normally at least three vehicle generations (in part with large design variation) travel within a partial rail network, the probability is very high that different types of wagon support are used on the axles. To achieve the least possible amount of track wear in the horizontal direction, based on basic experience gained from test sections, the most effective construction type recommended uses continuously supported and continuously embedded rails.

**Comfort impediments/ Noise immisions in the vehicle:** Provided that rails are regularly maintained, the vertical forces are only important as interaction with the track in connection with primary and secondary vehicle suspension systems. To compensate for negative effects on comfort (unsettled vehicle travel, vibrations, etc.) stemming from wheel/rail interactions, the overall track system must be an elastic system. The best prerequisites for this are provided by a construction form using continuously supported and continuously embedded rails. Using this construction design the dynamical forces (see Fig. 1) for lower speeds can be effectively reduced.
Noise Emission within the Environment: In addition to the normally good technical vibration design of the vehicle, the technical vibration design of the track has a considerable influence on the level of air-borne noise transmitted to the environment. For a noise level reduction, noise-reducing measures must be carried out on the tracks. In case passive design measures, such as noise protection walls and noise protection windows etc. are not used, vibrations caused by the wheel-rail interaction must be damped directly at the source. In addition to vibration-reducing wheels, various research projects are investigating the possibility of employing vibration-reducing track systems. Here the reference system is the standard ballast track. Sound reflecting systems such as regular slab tracks increase noise emissions considerably. Construction using elastically supported and elastically embedded rails have not yet witnessed a breakthrough. They must be developed further to achieve significant noise level reductions, as is currently underway in various research projects.

Underground Vibrations: As already mentioned, besides a vibration-reducing design for vehicles, a vibration-reducing design for tracks also has considerable influence on the level of ground-borne sound transmission, for example into urban buildings and the secondary air-borne vibrations which occur there. For the soil, which is part of the track system, physical factors as well as rheological and hydrological factors must also be included in the vibration analysis. Ballast tracks reveal certain problems in this regard. In slab track construction, mass (normally concrete) is utilised to damp vibrations more or less effectively depending on the type. Additional damping is also achieved successfully using continuously supported and continuously embedded rails. On test routes, damping levels of up to 20 dB depending on the vehicle velocity were achieved.

V. Future Perspectives

As shown in the previous sections, forces on track systems affect the tracks themselves, the vehicle users and the environment. To help reduce negative effects and to increase the utility of track systems in the sense of LSC, it should be attempted on one hand to further develop existing track systems using ballast tracks and slab tracks. On the other hand, new developments such as construction using elastically supported and elastic embedded rails also show promise of success. Should an optimisation of the track system be possible under the factors provided, public transport will be ensured a more lasting, wider level of acceptance.
Literatur

[1] Birmann, F.
Messungen am Gleis
Glasers Annalen 91 (1967) Nr. 9, S. 293-298

Die Entwicklung fortschrittlicher Triebdrehgestelle mit radial einstellbaren Radsätzen
ETR 38 (1989) H. 1/2, S 55-58

Oberbauforschung - Oberbautechnik, Stand und Weiterentwicklung
ETR 34 (1985) H. 10, S. 715 - 720 sowie neuere Veröffentlichungen