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ZABEZPEČENIE ODSTUPU VOZIDIEL - VYUŽITIE SYNERGICKÝCH EFEKTOV MEDZI ŽELEZNIČNOU A CESTNOU DOPRAVOU!

MAINTAINING INTER-VEHICLE SPACING - USING SYNERGETIC EFFECTS BETWEEN RAIL AND ROAD TRAFFIC!

Tak ako doteraz, dopravné služby sú rozhodujúcim kritériom ekonomiky. Toto konštatovanie vytvára predpoklad pre zaoberanie sa rôznym smerovaním a bezpečnostnými zásadami pre dve dôležité základne dopravných systémov, a to: cestnú a železničnú dopravu. Cieľom je určiť, ako dva systémy môžu navzájom prispieť, každý zvlášť vybratými postupmi, k riešeniu a ktoré koncepcie v budúcnosti umožnia túto činnosť.

V železničnej alebo cestnej premávke má dodržanie rozstupu vozidiel priame účinky na viaceré kvalitatívne kritériá dopravného procesu a priepustnosti.

Rôzne teoretické možnosti a praktické aplikované zásady pre dodržanie rozstupu vozidiel sú popísané a odhadnuté so zohľadnením času, bezpečnosti a priepustnosti. Dnes sa používajú rôzne zásady v oboch systémoch, čo je pripisované sčasti historickému rozvíjaniu systému, ale aj jeho pomoci technickou podporou systému. Pretože obidva systémy umožňujú maximálnu dopravnú priepustnosť, je treba zvážiť jej závislosť od dodržiavania odstupu vozidiel.

Synergický potenciál umožní používať a v interdisciplinárnom prístupe zistenie a klasifikovanie dopravného variantu. V budúcnosti bude vozidlová elektronika vyvinutá s rovnakým cieľom a podobným náčrtom podmienok. Železničná doprava potom môže mať zisk zo série efektov cestnej dopravy a tak posilniť svoje trhové postavenie prostredníctvom poskytnutých riešení. Zhodné predstavy v oblasti základnej vozidlovo-traťovej (cestnej) informácie (digitálna mapa) potrebujú priechodné spoločné riešenia. V oblasti dopravného prúdu a automatiky, vodičovej riadiacej činnosti, spoločné štúdium a zdravý rozum prikazujú, že príde k smerovému vedeniu a vozidlovej ochrane.

Now as ever, transportation services are a decisive criterion of an economy. This constitutes the background for dealing with the various routing and protection principles for the two important land-based traffic systems: namely, road and rail transport. The objective is to determine how the two systems could benefit from the respectively chosen approaches to a solution and which future operating concepts this makes possible.

Whether in rail or road traffic, inter-vehicle spacing directly effects several quality criteria of the transport process, and vehicle throughput. The various theoretically possible and practically applied principles for maintaining inter-vehicle spacing will be described and assessed with regard to occupied time, safety, and throughput. Today, various principles are used in both system which is attributable in part to the historical development of the system but also to the possibility of supporting the system through technical assistance systems. For both systems the possible maximum traffic throughput is considered depending on maintaining inter-vehicle spacing.

Synergy potential can be used through an interdisciplinary approach to detection and classification of traffic scenarios. In the future, vehicle electronics will be developed with the same objectives and similar outline conditions. Rail traffic then can profit from the series effect of road traffic and thus reinforce its market position through affordable solutions. Identical concepts in the field of vehicle-based route information (digital map) will permit joint solutions. In the field of convoy formation and automatic, driverless operation, joint studies make sense when it comes to longitudinal guidance and vehicle protection.

1 Routing and Protecting Road and Rail Vehicles - More Than Just a Technical Challenge

1.1 The Social Significance of Transport

Now as ever, transportation services are a decisive criterion of an economy. In the EU 15, passenger traffic increased by more than 10 % during the period 1990-1996. During the same period, cargo transport increased by nearly 10 %. In order to be able to perform these services, investments totalling EURO 70 billion were made in 1996, thereof 65 % for road transport and 25 % for railways. Accordingly, roads and railways together require 90 % of total infrastructure performance. Of the total passenger traffic volume (approx. 35 passenger km per day), approx. 80 % was handled by individual automobile traffic. In 1996, however, there were also approx. 42,000 roadway traffic accident fatalities, which shows an annual decrease of 2-3 %; there were 900 fatalities in rail transport [3]. These figures clearly underscore the grave social

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importance of this issue and make it clear why the subject of safe mobility matters to all social classes, municipalities, and industry. Furthermore, they constitute the background for dealing with the various routing and protection principles for the two important land-based traffic systems: namely, road and rail transport. The objective is to determine how the two systems could benefit from the respectively chosen approaches to a solution and which future operating concepts this makes possible.

1.2 Quality and Performance of Road and Railway Transport

When considered from a "bird's-eye"-view, vehicles operate on traffic routes in traffic flows. These vehicles can be individually powered or coupled vehicle units that lay claim to use the infrastructure for changing location from A to B (routes). Within the meaning of general traffic theory, this claim is a demand (see [3]).

From the standpoint of demand (the infrastructure user), the occupation time or throughput time *T* it takes to cover route s is a unit of time, cost, and quality[1]. There are other units of cost and quality, for example, the speed $v = ds/dt$, the change in speed dv/dt, pollutant emissions and fuel consumption or intactness of the goods transported, but the subject of spacing has never been touched upon.

Within the meaning of traffic theory, infrastructure is a service facility that accommodates demand and/or provides the slots for meeting the demand (supply of infrastructure).

The supply of infrastructure results in
- Measurements of performance capability ratios, especially throughput (maximum, available, etc.) and
- The reliability and availability of the infrastructure [1]

The combination of supply and demand results in
- Measurements of operational performance, especially capacity utilisation of infrastructure, transitory values of demands (time, cost, quality ratios) as well as congestion figures (waiting time, probability of waiting, production time, etc.) [8].

The objectives of a demand centre for minimal occupation time to cover the route s and of an infrastructure provider for profitable capacity utilisation of the provider's infrastructure are not free of contradictions:

Both individual vehicles and vehicles or trains in traffic that is channelled into lanes have individual wishes with regard to occupation time (travel time, travel speed, speed/acceleration profiles, etc.). This leads to the task of principally organising convoys of heterogeneous vehicles and speeds so that these convoys ensure
- maximum fullfilment of the individual requirements (of the vehicles)
- maximum satisfaction of the requirements of the infrastructure operator (provision of slots, road/line availability...).

In this context, vehicles must be
- able to move quickly and safely in convoys
- able to overtake one another quickly and safely
- able to get into and out of a traffic flow quickly and safely
- able to move quickly and safely in intersecting traffic
- reliably protectable against other oncoming, flanking, and parallel vehicles.

Furthermore, the throughput through the infrastructure (measured in vehicles per time unit on average or by the income from a road/line price system) must be maximised.

The following principles of maintaining inter-vehicle spacing are evaluated on the basis of these demand from the viewpoints of
- *Occupation time of the demand* on the route s
- *Safety of the demand* in the traffic flow
- *Throughput* for an infrastructure cross-section.

The methods used for railways and roadways are compared for the aforementioned outline conditions in order to identify possible synergetic potential. On this basis, the repercussions for automated and driverless operation are considered.

2 Maintaining Inter-Vehicle Spacing - Principles, Possible Solutions and Assessment

2.1 Principles of Maintaining Inter-Vehicle Spacing[2]

Regardless of the type of solution, it is possible to state generally valid basic relationships for maintaining inter-vehicle spacing. The basic equation for maintaining inter-vehicle spacing results from the safety-dependent necessary inter-vehicle spacing l_B, which is the difference in the braking distances of both vehicles (without accounting for reaction time).

$$l_B = \frac{v_2^2}{2b_2} - \frac{v_1^2}{2b_1} \qquad l_B \geq 0 \qquad (1)$$

where l_B Necessary inter-vehicle spacing
b_1 Maximum braking delay of the lead vehicle

[1] The terms occupation time is defined here as they pertain to production technology (compare [9]). In the generally valid definition, these times consist of the components execution of production, extra time-tolerance for manufacturing inaccuracy, synchronisation time and waiting times. In the context that is relevant here, only the production times, i.e., the times for a driving process, are considered with various principles for maintaining inter-vehicle spacing. The theoretical foundations of t he conceptual axioms and the underlying models were set forth in [6].

[2] Compare especially [16] and [18]

b_2 Maximum braking delay, under any circumstances, of the following vehicle
v_1 Momentary speed of the lead vehicle
v_2 Momentary speed of the following vehicle

Safety is assured only if $l_B \geq 0$. A negative spacing would mean that the following vehicle would penetrate the lead vehicle. This does not yet include an additional margin of safety to cover, for example, errors in speed and distance measurement, idle and transition time in the reaction links of a spacing control, and changes in the length of trains due to changes in tensile force or incline. The use of equation (1) as a regulation for maintaining inter-vehicle spacing is called *"operation at relative braking distance"*. Thus, the safety concept of maintaining inter-vehicle spacing takes the braking distance of the lead vehicle into account. If the lead vehicle, for example, is forced to halt suddenly by an accident, the following vehicle may drive into it.

To avoid this case, the braking distance of the lead vehicle is not taken into account when calculating l_B.

$$lB = \frac{v^2}{2b} \tag{2}$$

In this way, provision is also made for an abrupt stop by the lead vehicle (borderline case braking distance of lead vehicle = 0) as far as the safety concept is concerned. This is called *"operation at absolute braking distance"*.

If a maximum permissible speed is generally used in equation (2), this results in a regulation for maintaining inter-vehicle spacing that is known as *"operation at constant distance spacing"*.

$$l_B = \frac{v_{max}^2}{2b} \tag{3}$$

In this case, the same and thus constant distance which results from the braking distance at the maximum permissible speed is always prescribed regardless of the momentary speed.

2.2 Possible Solutions and Assessment

In the course of development of traffic control principles, among other things on the basis of the aforementioned theoretical regulations for maintaining inter-vehicle spacing, the methods described below were introduced or used (compare [16]). Furthermore, methods that will become feasible in the future are described.

- *Operation at Visual Range*
  The driver of the following vehicle controls the distance between the lead vehicle and the following vehicle based on his view of the route ahead of him. The driver is responsible for safety; there are no technical assistance systems to support him in this task.

In road traffic, there are various rules of thumb for maintaining spacing relative to the lead vehicle, for example, "spacing relative to lead vehicle equals one-half speedometer distance", in other words: $\Delta s = K 1/2 v_{Tacho}$. The proportional constant K computes to 1.8 and has the dimension of a time. Thus, the recommendation means operation with a constant time interval of 1.8 sec. regardless of speed (this time also accounts for the motion of the lead vehicle as well as the reaction time of the driver of the follow ing vehicle - compare "operation at relative braking distance"). In practice, vehicles also operate at shorter intervals depending on the operator's willingness to take risks when travelling in a convoy. Theoretical and practical studies have shown that maximum system throughput for convoy trips is attained at a value of $K \approx 1.2$. At $K < 1.2$, the propensity for spontaneous tailbacks (instability) increases. Temporary disturbances are reduced at $K \geq 1.4$ and resolve themselves; in other words, a steady-state traffic flow is attained (for more remarks on this topic, see, among other sources, [11] and [12]).
Because of the longer braking distance, "visual operation" is used in rail traffic only at very low speeds: trams at $v_{max} = 70$ km/h or trains in emergency operation ($v_{max} = 40$ km/h) or shunting operations ($v_{max} = 25$ km/h) [15].

Occupation time
In road traffic, the occupation time depends on the driving behaviour of the participating drivers in the convoys. Because of the strong influence exerted by individual drivers, it is impossible to map the system behaviour deterministically. Theoretically, the minimum occupation time would occur when there is only one vehicle in segment s at a time. As long as multiple vehicles in segment s do not influence one another (so-called free or independent traffic), the minimum occupation time (depending on vehicle speed) would also apply. Inter-vehicle spacing decreases with increasing density. This does not change the occupation time as long as the vehicles do not influence one another. In practice, however, uncoordinated acceleration and braking movements then occur, which diffuse through the convoys in the form of waves. Then speed is reduced and the occupation time increases. At extremely high density, the speed may drop to zero (tailback at $v = 0$), in which case the occupation time increases accordingly. Thus, even without barring accidents, occupation times may become very long in road traffic while they usually remain short where railways are concerned because of the timetable.

Safety
The level of safety attainable in road traffic depends on the driving behaviour of the participating drivers and their willingness to take risks. To begin with, human beings do not pose an increased risk in terms of reliability when piloting vehicles and/or in the special case of maintain inter-vehicle spacing (see also [17]). Rather, the situation becomes critical under special traffic conditions, for example, dense convoy traffic, abrupt braking in the convoy, difficult road conditions, driver fatigue, etc.. "Results of traffic measuring show that especially on motorways, vehicles operate within or even under the zone of minimum safety and the inter-vehicle spacing is influenced only

slightly by the speed. This is apparently attributable to a gross underestimation of the necessary assured clear distance on the part of drivers“ ([18] - S. 87). Road traffic does not attain the same level of safety as rail traffic which is also demonstrated by the accident statistics when averaged over many years.
In rail traffic, “visual operation“ is a special mode of operation. The safety standards inherent in the modes of operation of standard-gauge railways are virtually attained through fixed speed limits and a precise set of regulations for special modes of operation.

Throughput
Depending on traffic density, throughput in road traffic first increases to a maximum, and then, with additional increases in density (increasingly smaller inter-vehicle spacing) reduces erratically (so-called fundamental diagram of road traffic - Fig. 1).

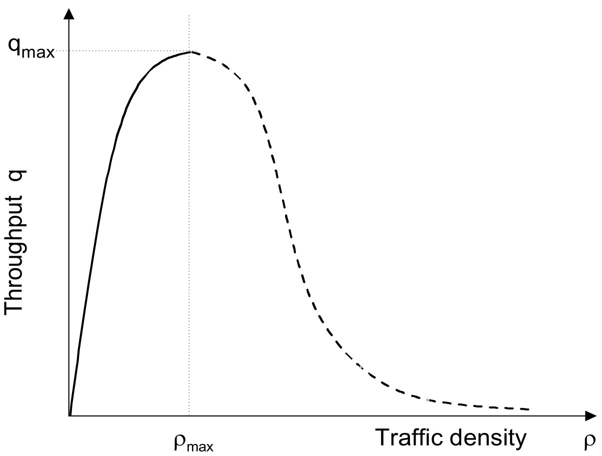

Fig. 1 Fundamental Diagram of Road Traffic

The throughput of rail traffic during “visual operation“ is of course very low, because according timetables do not provide for dense traffic, but rather for free, independent traffic; it is a special mode of operation that is not used in normal operations.

- *Operation at Time Intervals*
  In this principle, a vehicle is allocated a fixed time period that it is permitted to use for carrying out its trip (“timeslot“). As a rule, a start time and an end time are each assigned to a fixed position on the route. Within the timeslot, the vehicle is permitted to be between the two positions. The length of the timeslot and the correlating accuracy of location directly influence all assessment values. Operation at time intervals is a longstanding method in railways and was used when routes were not very busy. With the traditional technique, it was only possible to monitor the time interval between trains at departure. Thus, for reasons of safety, large time intervals between trains and low system throughput resulted. Additional auxiliary technical systems for increasing system safety were not used. The timeslot operation method is not used in road traffic.
  The aforementioned recommendation to drive at “one-half speedometer distance“, however, amounts to a modified form of the principles presented here.
  When modern methods (for example, radio-controlled train control) are used, new possibilities may present themselves in rail traffic since precise reporting of train positions and radio-supported cab signals make it possible to shorten the timeslots.

  Occupation time
  The occupation time in the system depends on the length of the timeslots and this, in turn, depends on the accuracy with which the vehicles can be located. The higher the locational accuracy, the more the timeslots and thus the occupation time can be shortened (threshold: duration for braking from maximum system speed).

  Safety
  The attainable level of safety depends on the feasibility of observing the assigned timeslots and the route assigned to this time.

  Throughput
  The system throughput can be optimised through precise methods for determining vehicle locations.

- *Operation at Fixed Distance Spacing*
  In operation at fixed distance spacing (compare equation (3)), the route is divided into fixed sections (in rail traffic, this is known as “blocking“). Only one vehicle is permitted in each section. The minimum length of a section depends on the maximum braking distance of all vehicles (within the system of Deutsche Bahn AG, for example, 1000 m at a maximum speed of v_{max} = 160 km/h). Operation at fixed distance spacing is the standard procedure for controlling and protecting trains running one behind the other. Today, it is virtually the only method used in rail traffic. Even current developments draw repeatedly on this principle. This method plays virtually no role whatsoever in road traffic.

  Occupation time
  The occupation time is influenced by the length of the fixed sections into which the route is divided. The longer the section, the longer the mean occupation time of a vehicle in the system. This effect applies disproportionately at low speeds, because the length of the section is proportional to the maximum system speed. In mixed traffic, slow and fast vehicles obstruct one another, which leads to an additional increase in the occupation time due to the increase in the waiting time (according to timetable) (Fig. 2 - compare [7] and [15]). The figure shows expected value ET_W of the loading of the system in trains per time unit. This waiting time function has a progressively increasing run. It converges with a loading value ρ that is characterised as the maximum operative capability LF_{max}.

  Safety
  This principle for maintaining inter-vehicle spacing offers the highest standard of safety in rail traffic with the associated train

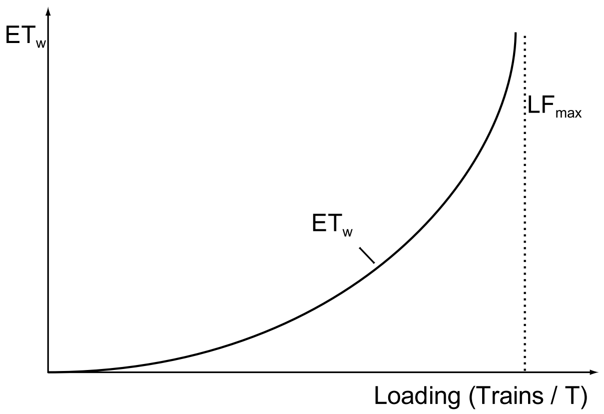

Fig. 2 Waiting Time Function in Rail Traffic

protection systems (signals, axle-counting circuits, track circuits, etc.). Additionally, the driver is supplemented and safeguarded by train running control and protection systems (for example, punctual train running control or linear train running control). Thus, fail-safe behaviour is attained. The system will not leave the secure state in the event of one technical or human error.

Throughput
The throughput of the system depends on the length of the fixed sections of the route ("blocking"). Especially at low speeds, this subdivision leads to low system throughput. In new developments ("high-performance block"), the block length is shortened through additional technical equipment, and thus the system throughput is increased (compare, among others [22]).

The objectives "maximisation of throughput" and "minimisation of occupation time" are not free of contradictions. In road traffic, both objectives are assessed using the so-called "rating" (= traffic performance per hour or the product of traffic intensity and speed) - [18] - S. 80.

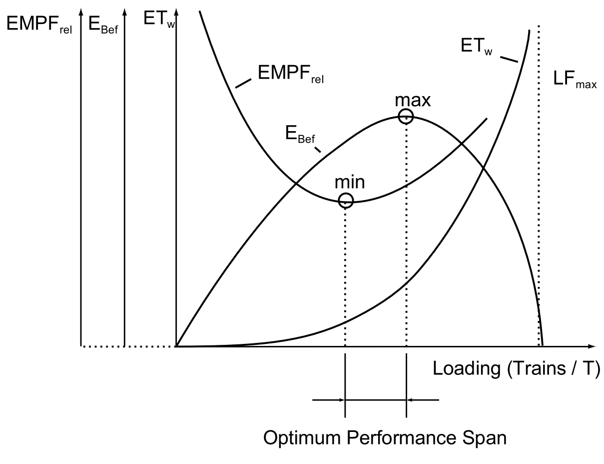

Fig. 3 Optimum Performance Span in Rail Traffic

In rail traffic, [7] an attempt has been made to find an optimum operating range (Fig. 3 - compare also [15]). The lower threshold of this optimum performance span results from the minimum of the relative sensitivity of the system $EMPF_{rel}$. The relative sensitivity is the first partial derivation of the waiting time function (introduced above) to the load ρ, in relation to the value of the waiting time ET_W. The upper threshold of the band of optimum system performance results from the maximum transport energy E_{Bef}. The transport energy is the product of the system load and the mean transport speed which decreases with increasing loading. Operational experience to date has shown that when this theoretical view is applied, the practical loading of the system should rather be set toward the bottom threshold of the optimum performance span.

- *Operation with Variable Distance Spacing (Rail Traffic: Positive Train Separation)*
  In this variant, the safety distance spacing is coupled to the following vehicle. A differentiation is made between operation at *maximum braking distance* (equation (3), but with non-stationary distance spacing) and operation at *absolute* (equation (2)), or *relative braking distance* (equation (1)). In the first case, the distance spacing equals the maximum occurring braking distance. When operating at absolute braking distance, the speed and braking characteristics of the following vehicle are taken into account, while the braking distance of the lead vehicle is additionally used for the relative braking distance.

Occupation time
The occupation time in the system is relatively short in comparison to the method of maintaining inter-vehicle spacing described above, because the incidence of mutual interference is minimal with or without a timetable even with mixed traffic (non-uniform vehicle speeds and/or lengths).

Safety
In rail traffic, the level of safety attainable when operating at maximum and absolute braking distance equals the high level of safety of the principle "operation at fixed distance spacing". This likewise requires technical auxiliary systems for vehicle protection and vehicle control, the technical design of which, however, differs from the systems that have been known and introduced to date (for example, vehicle-based location and train integrity monitoring).
In rail traffic today, operation at relative braking distance is considered critical in terms of safety. Fixed obstacles along the route lead to problems, especially with dense traffic. Moreover, use of this principle in rail traffic is prohibited under currently valid regulations.

Throughput
System throughput can be maximised in particular with the approach "operation at relative braking distance". Here it is technically possible to reduce inter-vehicle spacing to "zero" and thus attain maximum throughput.

The aforementioned methods for maintain inter-vehicle spacing are of varying importance for the road and rail traffic segments. The methods must be assessed differently with regard to the attainable levels of safety, as shown above. With regard to the occupation time and/or the throughput or, more generally, with regard to the traffic energy of the system, comparable conclusions can be drawn.

Fig. 4 shows the basically attainable operative capability of the various methods using the example of ICE train trips in rail traffic ([19]). The diagram is normalised to the inter-vehicle spacing maintenance principle "operation at constant distance spacing with station and warning signals" (Q_i/Q_{HV} = 1.0). Various operational cases of ICE train trips are considered. The influence of locational accuracy on the operative capability of the system is apparent. With the principle "operation at relative braking distance", it is possible to increase maximum throughput by a factor of up to 4.36 in comparison to the reference case. Additional increases would be possible through techniques such as convoys or rendezvous techniques. In both traffic systems, these considerations must always be made from the point of view of the required level of safety and the currently valid regulations. Rail traffic is at an advantage in this connection, because the lower number of degrees of independence i n the rail system offers better possibilities for technical support with the objective of a higher level of safety.

3 Technical Solutions

3.1 Rail Traffic[1]

Besides application of the prescribed operating procedures, route- and vehicle-based technical equipment is also used to implement the aforementioned methods of maintaining inter-vehicle spacing. In the process, train protection systems are used which, among other things, are responsible for protecting trains running one after the other - in other words, for maintaining the necessary spacings - without intervening directly in the train control system.

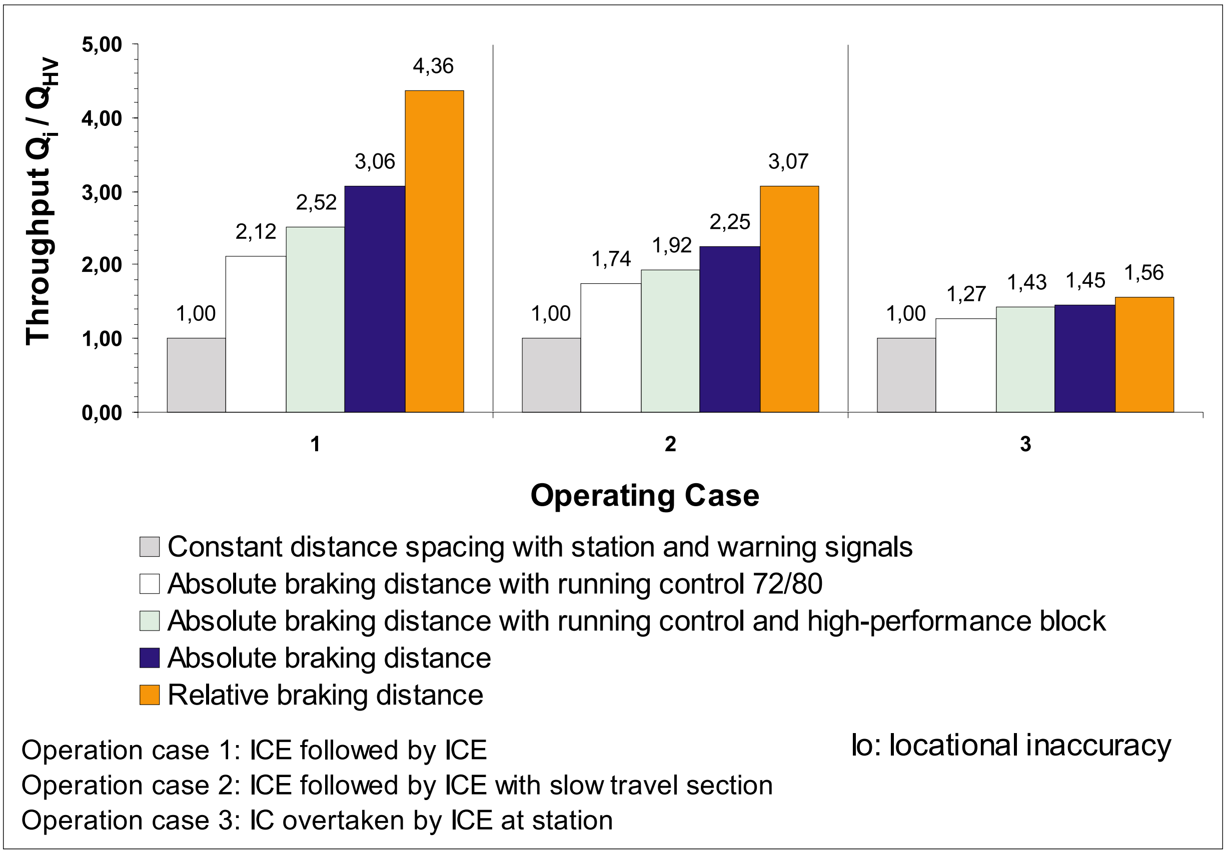

Fig. 4 Normalised maximum throughput Q_i/Q_{HV} of various regulations and systems for maintaining inter-vehicle spacing on newly constructed ICE routes for various operating cases (compare [19])

[1] The technical safety systems and train running control systems have developed in very different directions over many decades. Depending on the high service life of the components, many solutions remain in service even today. A description of this complex family of solutions would far exceed the bounds of the problems under discussion. For this reason, only a few technical implementations are addressed as examples.

One example is a typical facility for operating at fixed distance spacing. In this case, each block of a route is optically protected by an entry signal that is visible to the driver. Due to the long braking distances and limited visibility, at higher speeds, an additional signal (warning signal) that conveys information about the position of station signal is provided at a great distance from the station signal. To monitor the actions of the vehicle driver, facilities can be provided for, at a suit able distance from the signal equipment, which together with equipment aboard the vehicle can detect when the maximum permissible speed is exceeded or the vehicle driver fails to carry out an operating action at this point and, if necessary, trigger the brakes (punctual train running control "PZB").

If one wants to boost system performance (for example, by shortening block distances), then continually active (linear) train running control systems must be used to ensure compliance with the necessary spacings. Moreover, these systems serve to support and monitor the vehicle driver. In the event of driver error, the system will maintain the safe state (fail-safe behaviour).

Safety equipment in rail traffic was originally mechanical or electromechanical in design and is still in use in this form today. As in other fields of technology, today electronic systems are being substituted in place of mechanical solutions for control tasks. Increasingly, modern communications technologies and powerful electronic components are being used in these systems (for example, radio-based technologies in combination with GPS location for indirect determination of spacing). Furthermore, there is a clear trend toward eliminating complex technology from the route and the stationary equipment and putting it inside the vehicles instead. This should reduce the fixed costs and maintenance outlay for the railway operation at the expense of transport-related costs.

3.2 Road Traffic

Today's road traffic is characterised by operating with short spacings, fast-changing scenes, and convoys. There is virtually no route technology to support the maintenance of inter-vehicle distance, aside from the boundary post spaced at 50 m, which can help the driver to estimate distances. Operation is according to the principle "operation at visual range" (see above). Depending on his/her mentality, the driver of the following vehicle follows at absolute braking distance or (if he or she is prone to take risks) at relative braking distance by allowing for the speed of the lead vehicle in his or her braking distance. Maintaining inter-vehicle spacing depends almost entirely on the driver's assessment ability, for example, with regard to the traffic situation, vehicle braking distances, the respective road conditions, etc.. For these cases, vehicle-based technical assistance systems that also assist drivers in taking responsibility for safety (driver assistance systems, for example, ABS, ASR, outside temperature indicator, sleep alarm, proximity warning radar). All systems are, as a rule, vehicle-based; in some cases, they use various items of information from outside the vehicle in data processing and display and control technology. Various methods of determining the distance to the lead vehicle were investigated and, in part, implemented in devices.

- *Radar Technologies - Doppler Radar (Example: Distronic)*
  One example of an application of Doppler radar technology to the problem of maintaining inter-vehicle spacing is Daimler-Chrysler's Distronic proximity-controlled cruise control (Fig. 5-[14]). The system constantly keeps road vehicles at the correct distance from the vehicles in front of them. An electronic processor automatically activates the brakes if the distance to the vehicle ahead is reduced and accelerates automatically to the programmed target speed again as soon as traffic density permits (cruise-control function). The heart of the system is a compact radar antenna mounted behind the radiator grille which incorporates three interrogator-responder units. These

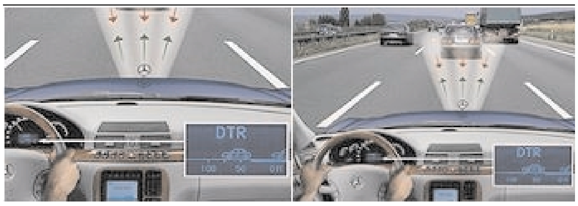

Fig. 5 The Distronic's radar antenna covers all three lanes

units continually send out their signals at an angle of three degrees and cover all three lanes of the motorway at a distance of approx. 80 metres. If the short-wave radar impulses (77 Gigahertz) hit an obstacle, they are reflected and change frequency in the process. A digital signal processor computes the relative speed between the two vehicles on the basis of this frequency change, while the distance is computed based on the transit time of the reflected signal. Normally the system is set for a specific time interval. The speed of the lead vehicle also flows into the computation of the time and distance intervals. One interesting fact is that this does not require any technology along the route.

- *Optical Methods/Radio-Based Methods (Example: Electronic Drawbar)*

Fig. 6 An electronic drawbar as a prototype implementation for coupling two lorries

3.3 Similarity and Differences in Maintaining Inter-Vehicle Spacing

Principle of Maintaining Inter-Vehicle Spacing	Rail Application	Road Application	Technology Along the Route	Vehicle Technology	Potential for Synergy
Operation at visual range	Only in special modes of operation and emergencies	Standard procedure today	Rail: none Road: roadway markings, roadside borders	Rail: none Road: headlights; Compare operation at relative braking distance	
Operation at time interval	No longer used today. Potential for innovation through new technologies!	Irrelevant (exception: modified form "Distance = half speedometer")	Rail: none Road: irrelevant	Rail: none Road: irrelevant	
Operation at fixed distance spacing	Standard procedure today	Irrelevant and/or is not applied	Rail: signals, switches, INDUSI punctual train running control, track conductor, axle counting circuits Road: irrelevant	Rail: secure vehicle computer, wheel pulse generator, processing equipment, punctual and linear train running control Road: irrelevant	Vehicle control methods, monitoring of dangerous spots, approaching dangerous spots (Rail–> Road)
Operation at maximum braking distance ("moving block")	Selective implementations exist. Will soon be state of the art.		Rail: Balise transmission system Road: irrelevant	Rail: precise location method (balise reader, GPS), train integrity monitoring (train length), secure vehicle computer Road: irrelevant	
Operation at absolute braking distance ("moving block")	Selective implementations exist. Will soon be state of the art.	Used in combination with operation at visual range and driver as control (assistance system). Proximity-controlled cruise controls by various automobile manufacturers (for example, Distronic by Mercedes Benz)	Rail: Balise transmission system Road: none		
Operation at relative braking distance ("moving block")	Currently the subject of research. Potential for boosting performance. Reservations with regard to safety.			Rail: Obstacle detection sensors Road: Doppler radar with subsequent high-performance processing	Radar sensors with subsequent high-performance processing (Road –> Rail) Obstacle detection (Rail <– –> Road
Convoy operation / rendezvous techniques	Currently the subject of research. Increased potential for boosting performance as well as advantages with regard to energy consumption. Reservations with regard to safety.	Electronic drawbar is currently in the research stage.	Rail: none Road: none	Rail: multiple traction control, train coupling and sharing possibilities Road: optical sensors, high-performance processing, image processing	Optical sensors, image processing, high-performance processing (Road –> Rail)

Under the auspices of the co-operative European research project “Promote Chauffeur“, researchers have been working on development of driver assistance systems for utility vehicles since 1996 ([23]). One of the results of this was Daimler-Chrysler’s 1 June 1999 presentation of the “Electronic Drawbar“ in a research vehicle (Fig. 6). In a coupled lorry unit consisting of two vehicles, the lead vehicle is steered conventionally. The second vehicle follows the first and is steered actively and automatically by a longitudinal and transverse steering system. This process is implemented without any mechanical connection whatsoever between the vehicles.

The heart of this “electronic drawbar“ consists of two onboard computers, one in each vehicle, which interconnect all data pertaining to the vehicles and their surroundings. There is a constant 2.4 Gigahertz radio link between the vehicles. Besides the radio link, the vehicles are additionally connected by an optical contact: two video cameras in the rear vehicle continually scan a special code pattern, consisting of infrared lamps, on the back of the lead vehicle. On the basis of the images delivered by the cameras, an image processing system not only calculates the distance between the vehicles, but also detects changes in the direction of the lead vehicle. The second vehicle follows the first and is automatically supplied with all data via the cab of the lead vehicle. The second vehicle steers, brakes, and accelerates just like the first one, in the process maintaining a variable, speed-related distance ranging 6 - 15 metres. Technically, the lorry can travel at speeds of up to 80 km/h. The mini-convoy can handle curves with a radius of up to 50 m.

Thus, this system operates at distances less than the braking distance of the following vehicle, but for now only in the trial stage of operation.

4 Technical Potential for Synergy

4.1 Obstacle and Distance Sensors

If in future maintenance of assured clear distances between vehicles in road and rail traffic is to be supported by vehicle-based systems, then both systems must measure the basic physical quantities speed, position, and distance. Likewise, in the future, detection of obstacles (stationary and moveable) will become increasing important in both systems, for example, for automatic driving processes. A good place to begin with is a joint examination of suitable sensors. The short list could include the sensors listed below:

- GPS- and radio-based location for determining positions at long distances (indirect)
- Radar sensors (Doppler radar) for medium distances
- Optical sensors for short distances
- Radar and optical methods of detecting obstacles and/or registering scenarios

Due to the differences between road and rail traffic at average speeds of travel and the braking distances, however, the outline conditions for such sensor systems may vary considerably. Nevertheless, similar vehicle-based systems can be used as supplements and solutions for special cases, with which for example, through early warning of a crash that is no longer avoidable, the consequences of the accident can be reduced through initiation of appropriate protective measures. These measures include intervention in the brake control system and triggering elements in the vehicle to increase passenger safety.

4.2 Vehicle Electronics

The vehicle-based electronic processing systems in use today in both spheres of application are generally distributed microelectronic computer systems. Due to the spatial separation of the systems, serial communications buses will be used to couple the components. Comparable safety levels must be met for both the control components and the communications buses. Likewise, the requirements for real-time data processing and observation of deterministic time conditions (note the difference: in a maximum time vs. precisely at this time) with both systems. Specifically, potentials for synergy should be reviewed in the areas

- Safe computer system architecture
- Safe time-deterministic communications bus
- High-performance processors
- Operating systems and runtime environments for safe embedded SW processes
- SW solution modules for comparable functionalities (for example, braking curves, algorithms for longitudinal guidance, speed-controlled maintenance of inter-vehicle spacing...)
- Design and development processes for developing safe embedded systems.

For reasons of cost, electronics system vendors in both spheres of application must endeavour to use the cost advantages of a larger series (economy of scale). Thus in any case, the railway industry will carefully consider whether the aforementioned components and solution functions can be carried over from the road vehicle sector with its comparatively large series. Until now, however, this was too often prevented by specific design and licensing regulations, the adaptation of which - even if technically possible - always constitutes a mid- to long-term process.

4.3 Approaching Dangerous Spots

In rail traffic, the principle of operation at visual range, which is predominant in road traffic, has been replaced for reasons of physics by other approaches to maintaining inter-vehicle spacing. Thus, there are limits to the ways in which the assistance systems introduced for supporting the driver can be applied to railways. Refinement of signalling technology infrastructure in road traffic will progress only slowly, in small steps. This means that procedures for approaching dangerous spots will continue to differ significantly from one another in future. Since vehicle-based electronic signalling and monitoring equipment will be available for both types of transportation - even if for different reasons -

synergy can be anticipated when setting up and using electronic map systems. These map systems would not only describe the routes, but also clearly indicate dangerous spots; the information in these systems would be adapted dynamically to changing circumstances. The methods for this dynamic adaptation of the information - if necessary, even automatic learning from specific traffic situations - can be implemented in the same or similar ways.

4.4 Convoy Operations and Rendezvous Techniques

The "electronic drawbar" concept described above is an attempt to introduce the rail traffic concept of "marshalling", with appropriate modifications, to road traffic. In keeping with the prerequisites of road traffic, the only approach possible here is a vehicle-based one that relies on the aforementioned equipment for maintaining inter-vehicle spacing.

The technical solutions found in road traffic can be reapplied to certain areas of rail traffic. They will be interesting when engineers want to dispense with mechanical coupling mechanisms in order to reduce weight and expense in ultralight vehicles, but without giving up the advantages of marshalling. These advantages are not only flexibility in operation, but also potentially higher capacity utilisation of routes. In implementation, however, varying throughput values will result due to the variou s outline conditions such as masses, locational accuracy, prescribed inter-vehicle spacing, and other factors. Nevertheless, procedural similarities in forming convoys, dissolving convoys, getting into lane (analogous model switching and lane changing), getting out of lane (analogous model switching and lane changing), and convoy speed permit joint consideration of many aspects of this complex of problems. Thus, synergetic effects are anticipated in the area of various methods for partial solutions to the problem.

4.5 Automatic and Driverless Operation

In the field of automatic and driverless operation, rail traffic has consistently taken advantage to date of its systemic advantage of pre-existing tracking. Thus, automatic and driverless operation has been instituted in many places. The following table presents selected sample system solutions.

Besides the systems listed above, there are also many other systems in operation or preparation. All systems run on selected and demarcated travel ways or with a special operating permit. This is generally due to regulations that demand exclusion of danger to human beings and animals that may cross the travel way purposely or inadvertently. Automatic, driverless operation in the standard-gauge railway system requires that the regulations be amended without lowering the established high standard of s afety in rail traffic. Work in this field is pressing ahead in various places around the world.

When it comes to automatic, driverless operation, road traffic has the disadvantage of the lack of transverse vehicle guidance. Moreover, the road system entails an additional degree of independence in comparison to the rail system. The resulting complex traffic scenarios make system automatisation considerably more difficult. Nevertheless, there are various systemic approaches for "seeing and autonomous research-stage vehicles" (compare, among others, [2]).

In this field, synergy will arise primarily in the area of sensor problems (see above), convoy operations (see above), longitudinal guidance, and vehicle protection. With regard to vehicle protection, in this connection, it is primarily interdisciplinary studies of predictive accident detection and initiation of measures to protect people and passengers that will lead to success. It is fairly likely that the strategies for driving processes will be relatively different.

5 Summary, Outlook, and Recommendations for Action

Whether in rail traffic or road traffic, inter-vehicle spacing has an equally direct effect on the occupation time of vehicles in the system, the safety of the transport process, and vehicle throughput. In this context, the parties participating in the transport process, namely system users (users of the infrastructure) and system operators (infrastructure providers) have very different and in part contradictory criteria for optimisation.

The various theoretically possible and practically applied principles for maintaining inter-vehicle spacing have been described and assessed with regard to occupation time, safety, and throughput. Today, various principles are used in both systems,

System	Principle	Characteristics
Docklands Light Railway (London - [21])	Wheel-rail system	Automatic, driverless operation, max. speed 80 km/h, vehicle length 28m, capacity 284 persons/vehicle
People Mover System (various airports world-wide)	Rubber-tired vehicle on elevated travel way	Automatic, driverless operation, max. speed 50 km/h, max. vehicle length 58m, max. capacity 400 persons per unit
U4 System (Frankfurt, Germany subway system - [13])	Wheel-rail system. Subway system converted for automatic operation	Automatic, driverless operation, point-to-point connection as part of an existing subway system, pilot application, max. speed 80 km/h
Automatic signal-controlled traction vehicle (SST - [5])	Wheel-rail system in pilot operation with special operating permit	Fully automated operation on a 13km route, cargo transport as required, individual vehicles

which is attributable in part to the historical development of the system but also to the possibility of supporting the system through technical assistance systems. On the other hand, it is possible to consider for both systems the possible maximum traffic throughput of various principles for maintaining inter-vehicle spacing and this was done in a comparative presentation. In any case, the only way to increase the throughput of the system is to shorten the inter-vehicle spacings. On the other hand, short inter-vehicle spacings with uncoordinated mutual relative movements can lead to longer occupation times. In any case, a new principle for maintaining inter-vehicle spacing must always be introduced without degrading established standards of safety. In this connection, bounds are set by the valid regulations in both systems. A review of regulations in light of modern HW and SW technologies could eventually open up new paths.

The technical solutions being applied in practice today differ widely. Rail traffic is still founded largely on route-based technology. This technical feature is being removed in modern developments. In this connection, rail traffic is moving closer to road traffic, where today, by nature, the technical assistance systems offered are largely vehicle based. Thus, the greatest potential for synergy between the two systems is also in the field of distributed and intelligent vehicle-based solutions for vehicle guidance and protection [10].

In the field of *sensor systems for detection of obstacles and distances,* besides development of sensors on the basis of various physical effects, the main opportunity which presents itself is that of joint studies of signal analysis and processing ("sensotronics"). Synergy potential can also be used through an interdisciplinary approach to detection and classification of traffic scenarios. In the future, *vehicle electronics* will be developed with the same objectives and similar outline conditions. In this connection, rail traffic can profit from the series effect of road traffic and thus reinforce its market position through affordable solutions. Where *approaching dangerous spots* is concerned, identical concepts in the field of vehicle-based route information (digital map) will permit joint solutions. In the field of *convoy formation* and *automatic driverless operation,* joint studies make sense when it comes to longitudinal guidance and vehicle protection. In the field of vehicle protection, it primarily relates to predictive accident detection for the purpose of protecting persons and passengers.

In any case, existing systems cannot be adopted without modification, due to the varying outline conditions. They do, however, constitute a technical basis upon which system solutions can be created without excess outlay in each respective system. Furthermore, when researching future solutions, it imperative to first always follow an interdisciplinary approach, in order to take full advantage of the potential for synergy that undoubtedly exists.

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