Sustainable Design of Underground Rail Systems—Aerodynamics at the Interface of Rolling Stock and Civil Construction

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Abstract In high-speed rail tunnels and heavy duty underground systems, aerodynamic issues have a substantial impact on the consumption of energy and resources. Together with the interrelated thermal conditions and the tunnel ventilation, various parameters of tunnel and vehicle design affect the resulting life-cycle costs and consequently the sustainability of these systems. For example, the power demand of metro systems is determined by the rolling stock features, the civil layout of tunnels and stations as well as by the way of operating the mechanical and electrical systems, including tunnel ventilation. Costs for traction power are influenced by vehicle design but equally by the choice of cross-sections and arrangement of shafts in the tunnel. Ventilation and cooling costs are caused by on-board systems of trains as well as by the equipment in tunnels and in stations. Thus, aero-thermal features of both, rolling stock and civil construction should be optimized together. During the design process, the above topics are commonly addressed separately. An overall system optimization covering for example rolling stock, civil design, track layout, tunnel ventilation and station ventilation is often missing. Awareness of rolling stock and infrastructure designers of the individual impact of the various factors affecting the energy demand of underground systems could be improved by more data for decision making. This paper aims at triggering more profound research work for a better understanding of the impact of the various design parameters on tunnel aerodynamics and the closely linked ventilation and cooling. Life-cycle costs would be reduced and a sustainable design shall be promoted.

1 Introduction

Transportation systems need to become faster, more frequent, more comfortable, safer and more economical. At the same time, our and future generations are facing constraints such as limited natural resources, required environmental protection,

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global warming and financial limitations. Conflicting demands are not new in engineering. However, the current diverging demands are rather fundamental. Every opportunity for improvement should be considered. Design and operation of transportation systems need to become more sustainable.

Sustainability has become a wide-ranging term that is applied to almost every aspect of life. In the context of engineering and design of transportation systems, the following design principles are in focus:

- Energy efficiency: develop processes/products which require less energy
- Long-term consideration: achieve quality and durability by longer-lasting and better-functioning systems considering the whole life-cycle of system
- Holistic view: improve in parts only if leading to an overall improvement
- Low-impact materials: use of small quantities of materials which require little energy to process and which have a low impact on the environment

These principles of sustainable design are a challenge for all technical systems. In the context of underground rail systems, the improvement of aerodynamic conditions is one key element to achieve an overall progress here.

In underground rail systems, aerodynamic phenomena affect both, the design of vehicles and of civil infrastructure. Particularly as the velocity and/or frequency of trains increase, the effects of tunnel aerodynamics on the design of tunnels and vehicles are becoming more important. In urban, heavy-duty underground systems or in tunnels of high-speed rail systems, several of the following aerodynamic phenomena need to be considered:

- Traction power requirements of trains
- Pressure loads on the vehicle, tunnel structure and equipment
- Pressure comfort and health limits related to pressure changes
- Micro-pressure waves and resulting noise (sonic boom, vibration)
- Loads due to air velocity acting on vehicle, tunnel structure and equipment
- Comfort and safety related to elevated flow velocities of air
- Air-exchange or climate in vehicle and tunnels/stations and related power demand of equipment in infrastructure

Aerodynamic issues (pressure, air velocity) are closely linked to the tunnel climate (air-exchange rate, temperature, humidity, air quality). This is important because many underground projects for urban transportation are located in warm and tropical regions of the world and tunnel aerodynamics allows improving the tunnel climate. In addition, the climate in very long tunnels becomes an important factor to assure system functionality. Therefore, aerodynamic issues have to be considered increasingly together with tunnel climate as well as ventilation and cooling of vehicles and tunnels including possible underground stations. The phenomena mentioned above have in common that all of them can be influenced by both, the design of the rolling stock and by the layout of the tunnels including possible underground stations. The interface of civil construction and of rolling stock offers the potential for optimization of the aero-thermal conditions.

2 Objectives

This paper shall present some challenges of sustainable design of underground rail systems at the interface of vehicle and tunnel aerodynamics. Examples are provided illustrating that the aero-thermal conditions of underground rail systems can be influenced simultaneously by both, the rolling stock and the civil design. Shortcomings of current projects shall be illustrated to motivate further research.

3 Aerodynamics Phenomena in Underground Rail and Metro Systems

The order of magnitude of pressure deviations from normal pressure in a high-speed rail tunnel may reach, for example, more than $+/-5$ kPa. Other pressure changes and air velocities might be created for the following reasons:

- *wind at portals*: Wind or storm may lead to substantial pressures acting on the air in the tunnel.
- *meteorological pressure differences*: Across tunnels connecting different valleys or mountain ridges substantial pressure difference might occur.
- *meteorological pressure changes*: The meteorological pressure in a region changes with time. During a year and even during a day the change of the meteorological pressure might be quite substantial, i.e. more than train-induced pressure fluctuations. However, the time scales of the changes are much larger (hours, days) than those of trains (seconds).
- *thermostatic pressure*: Temperature differences between the tunnel air and the outside may lead to pressure differences between portals.
- *tunnel ventilation*: The pressures created by fans may lead to considerable forces particularly acting on the walls of air ducts and shafts.

The typical magnitude of pressure changes of the above phenomena is smaller than those created by trains. Thus, the train-induced pressure fluctuations and resulting aerodynamic conditions are dominating in heavy-duty underground systems or in tunnels of high-speed rail systems.

The train-induced pressure fluctuations cause or affect the phenomena as listed in Table 1.

4 Measures to Control the Aero-Thermal Phenomena in Underground Systems

The aero-thermal phenomena mentioned above can be influenced and handled by a variety of measures. Several examples are given in Table 2.

Table 1 Major questions regarding aero-thermal phenomena in high-speed rail tunnels and/or heavy duty underground systems

Phenomena and examples of related questions	Location of impact	Stations (platform, mezzanine level	Other rooms (technical, social, vending offices)	Rail tunnel (incl. cross-passages, stairwells, shafts)	Vehicles
Traction power	How does a tunnel increase or affect the power demand of trains moving in a tunnel?				X
Pressure loads	What are the mechanical forces acting on the tunnel structure, the equipment in the tunnel, the vehicle, the load on freight trains, the passengers and staff?	X	X	X	X
Pressure comfort	How to avoid the unpleasant perception of pressure changes by hearing organs, i.e. aural discomfort?	X		X	X
Health limits	How to avoid harming pressure on hearing organs?	X		X	X
Micro-pressure waves	How to avoid the detonation-like, loud bang at portals upon train passage at opposite portal (sonic boom)?	X		X	
Loads due to air flow	What are the forces acting on signs/signals in a tunnel due to high air velocities?	X		X	X
Comfort and safety related to air flow	How to provide an acceptable, low velocity of air on the platform/access ways of an underground station?	X		X	X

(continued)

Table 1 (continued)

Phenomena and examples of related questions	Location of impact	Stations (platform, mezzanine level	Other rooms (technical, social, vending offices)	Rail tunnel (incl. cross-passages, stairwells, shafts)	Vehicles
Climate	How does heat release from vehicles and air-exchange influence the temperature, the humidity and the air-quality in a tunnel?	X	X	X	X
Ventilation of tunnel and related power consumption	How can tunnel ventilation (passive and mechanical) provide adequate temperature, humidity and air-quality? How does the vehicle and tunnel design increase or affect the power demand of the infrastructure?	X	X	X	X
Ventilation/air-conditioning of vehicle	How can train-bound HVAC-systems (passive and mechanical) provide adequate temperature, humidity and air-quality? (HVAC = heating, ventilation, air-conditioning)	X		X	X

Table 2 Examples of technical measures to cope with aerodynamic phenomena in tunnels

Phenomena	Examples of measures at vehicle	Examples of measures at tunnel
Traction power	• Apply aerodynamic streamlining	• Increase cross-sections (e.g. by single-tube, double-track tunnel)
	• Use advanced drive systems and components for control of traction power	• Introduce shafts
	• Implement light-weight construction	• Allow re-circulation of air within twin-tube systems (pressure relief ducts, no full-height platform screen doors)
		• Choose better vertical alignment
Pressure loads	• Apply aerodynamic streamlining	• Increase cross-sections of tunnels and particularly near portals
	• Implement robust design	• Introduce shafts/robust design
Pressure comfort/Health limits due to pressure	• Apply aerodynamic streamlining	• Increase cross-sections of tunnels, particularly near portals
	• Seal vehicles	• Introduce shafts
	• Implement passive or active pressure control at heating, ventilation and air-conditioning units (HVAC)	
Micro-pressure waves (sonic boom)	• Apply aerodynamic streamlining at train head and tail	• Design portals in favorable manner
		• Use active/passive measures to mitigate pressure waves inside of tunnel (portal design, damping of tunnel)
Loads due to air flow	• Apply aerodynamic streamlining	• Implement robust design
Comfort and safety related to air flow	• Apply aerodynamic streamlining	• Introduce pressure relief or draught relief shafts or shield-off platform region by baffle blades, locks, guide vanes, etc.
		• Create aerodynamic decoupling between platforms and trackway
		• Reduce open gap between vehicle and platform screen doors

(continued)

Table 2 (continued)

Phenomena	Examples of measures at vehicle	Examples of measures at tunnel
Climate and power for HVAC of tunnel/stations	• Apply aerodynamic shape	• Support natural ventilation
	• Release less heat, e.g. use regenerative breaking	• Support train-induced ventilation (e.g. by double-tube, single-track tunnels; platform screen doors)
	• Release heat such that efficient heat removal is possible (high enthalpy air at appropriate location)	• Remove heat in efficient manner by extracting air of high enthalpy
	• Use fire resistant materials or on-board fire extinguishing systems (i.e. relief requirements for tunnel ventilation)	• Use energy-efficient control schemes to provide ventilation according demands only
Climate and HVAC power of vehicle	• Reduce losses of cold-air during stops at stations	• Keep tunnel cool by preventing air re-circulation at portal/shaft
		• Allow for good air-quality by frequent air-exchange

Table 2 indicates several ways to influence the aerodynamic conditions in underground systems and to control the impact of tunnel aerodynamics on vehicles. Some of the examples exhibit inherent design conflicts. On the one hand, for example, choosing a double-tube, single-track tunnel is of advantage with respect to controlled air-exchange, heat removal and climate control in heavy-duty underground systems or in very long rail tunnels. Due to the piston effect of trains, warm air is being carried out of the tunnel system in an efficient manner due to mono-directional traffic. On the other hand, single-tube, double-track tunnels are preferable regarding other aerodynamic phenomena. In comparison to double-tube tunnels, these offer a larger free cross-sectional area. Larger cross-sections lead to smaller pressure forces, better pressure comfort (ignoring oncoming traffic), reduced traction power demand and better suppression of non-acceptable micro-pressure waves.

In summary, a design might be good for the tunnel aerodynamics but might be bad for the climate or other system features. Therefore, all aero-thermal phenomena have to be taken into account and further, possibly conflicting demands need to be considered:

- safety (for example related to fire/smoke control)
- operational and maintenance flexibility
- reliability and availability of system
- systems harmonization with other parts of network

- environmental protection
- cost efficiency

Obviously, there is a wide range of possible perspectives and scopes to influence and/or to cope with aerodynamic phenomena in tunnels. The focus here is on the particular interface of civil construction and rolling stock. Some examples of possible aerodynamics optimization at the interface of rolling stock and civil construction shall be addressed.

5 Life-Cycle Costs of System Balancing Between Vehicle and Tunnel and Between Construction and Operation

Sustainable investment goes along with reaching the required system performance while keeping lowest life-cycle costs. Reduced life cycle costs are a prerequisite for sustainable design.

Figure 1 shows examples of improving the aerodynamic conditions in a tunnel with respect to pressure comfort, i.e. reduced pressure fluctuations inside trains:

- pressure relief shafts at tunnels
- streamlined trains with active pressure control inside coaches.

The relief shafts create partial reflections of the pressure waves. This weakens the pressure waves without the need to increase the free cross-sectional area of the tunnel (see [1, 2]). For certain project settings it might be a reasonable opportunity to improve the pressure comfort by using shafts and keeping the free cross-sectional tunnel area comparatively small (e.g. at tunnels of short and medium length; trains with no or limited sealing; small overburden and/or cut-and-cover tunnels; no residential area in immediate vicinity of shaft for noise reasons). Aerodynamic streamlining of trains is beneficial for various other aerodynamic reasons (less traction power, reducing pressure fluctuations, reduced micro-pressure waves, improved cross-wind stability).

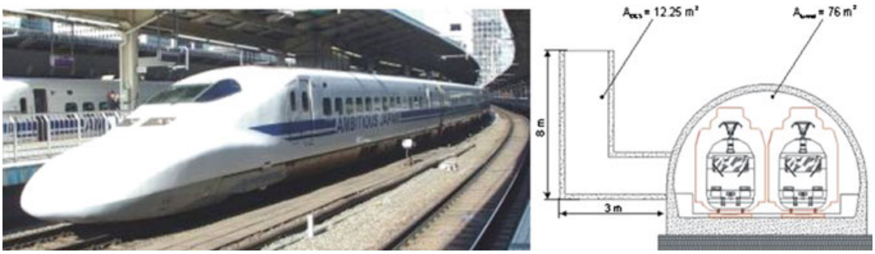

Fig. 1 Aerodynamically streamlined Shinkansen 700 with active pressurization system of cabin (*left*) and shaft to improve pressure comfort in a tunnel (*right*)

Table 3 Balancing expenditures between construction and operation and trains and tunnels

Expenditures	Rolling stock	Tunnel
	Measure:	Measure:
	• Apply aerodynamic streamlining	• Increase cross-sections of tunnels, e.g. near portals
	• Seal vehicles	• Introduce shafts or open cross-connections between adjacent tunnels
	• Implement passive or active pressure control of A/C units	
Investment/construction costs	• Costs for raw materials and construction, e.g., for a more robust vehicle structure, measures for sealing, space requirements for streamlining and pressure control	• Costs for raw materials and construction
		• Costs for land and space for shafts
Operation and replacement costs	• Maintenance costs of additional equipment and sealing	• Costs for operation of additional infrastructure (cleaning, regular refurbishment, handling of vandalism, safety, security, etc.)
	• Traction power costs due to additional weight of vehicle	
	• Costs due to reduced space for commercial utilization due to streamlining of train ends, larger HVAC units, etc.	

Table 3 provides an example of the task to properly balance costs. The example deals with achieving pressure comfort inside of high-speed trains. Expenditures are possible:

- for measures at rolling stock and/or for measure at tunnels
- during construction and/or during operation

In order to minimize life-cycle costs in the context of pressure comfort, several aspects have to be considered to balance measures at vehicles and tunnels. Spending on tunnels such as larger cross-section and/or shafts becomes preferable for the following boundary conditions:

- small share of high-speed tunnels within whole rail network
- high frequency of trains
- expected strong increase in future energy costs

- emphasis on simple, reliable systems with high availability
- measure beneficial for other aerodynamic purposes as well, such as limiting traction power demand and suppression of micro-pressure waves
- in case of shafts: combination of measure with other functions possible, e.g., emergency exit, access to technical rooms, smoke control during fire emergency, etc.
- in case of shafts: small overburden of tunnel and sufficient distance to residential areas

Spending on vehicles becomes preferable if the above boundary conditions are less dominating. In addition, measures to improve aerodynamic streamlining of trains will lead in most cases to smaller pressure fluctuations in tunnels. Therefore, reducing aerodynamic drag and friction to reduce energy consumption, to improve cross-wind stability, to reduce creation of critical micro-pressure waves will improve pressure comfort as well.

Expenses for construction costs should be preferred in contrast to operation costs in case of expected strong increase in future energy costs and expected strong increase in future maintenance costs. The above example on pressure comfort shows that various boundary conditions need to be considered. Optimization from a technical or physical point of view might not be feasible for operational or legal reasons. Responsibilities regarding balancing of costs for underground systems and optimization of life-cycle costs and sustainability are illustrated simplified in Fig. 2.

Figure 2 shows that optimizing life-cycle costs requires co-ordinated activities of the involved parties. On the one hand, the potential of possible optimization is limited for the following unchangeable reasons:

- boundary conditions for design of tunnels and stations (space limitations especially in urban areas, geo-technical constraints, access and operational demands, etc.)
- high-level restrains (norms, laws, safety and availability requirements, network-wide or manufacturer-wide standards, etc.)
- uncertainties with respect to future developments (customer demands, costs for electricity, future vehicle/drives and further technology, etc.)

On the other hand, the potential for improvements is not fully exploited yet. The awareness of designers and decision-makers could be improved. Knowledge about

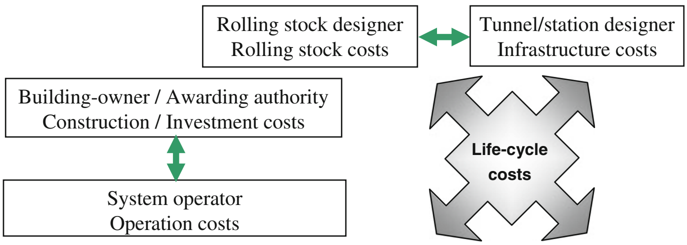

Fig. 2 Responsibilities regarding allocation and balancing of costs of underground systems

mutual dependencies of design parameters of vehicles and infrastructure and their consequences for system emergency consumption and life-cycle costs are limited. In typical projects, time and resources are missing elaborate and optimize a more sustainable design. Easy accessible, best-practice recommendations and more data as basis of decision-making would be beneficial. Selected case studies would allow to present opportunities and lead to more sound design decisions.

6 Choosing Appropriate Measures for Improvements

In Table 4, selected examples are provided in order to highlight the challenge of balancing measures at vehicle with measures at tunnels/stations and the task to balance costs between construction and operation. Table 4 is of qualitative nature only. For application in projects, data and a quantitative analysis on the sensitivity of the different measures are needed.

7 Selected Examples of Measures

Three further examples regarding the challenge of choosing appropriate measures for improving the aerodynamic conditions in underground rail systems shall be presented:

- Choice of free-cross-sectional area: Consequences for life cycle costs
- Provision of pressure relief between tubes: Balancing costs for traction power and for tunnel cooling
- Definition air exchange in tunnel: Balancing measures for control of temperature in vehicles and tunnels

7.1 Adapting the Free-cross-sectional Area of Tunnel

Figure 3 shows the power requirements for a passenger train passing through the Swiss Gotthard Base Tunnel at 250 km/h (GBT; operational in 2017). The figure illustrates:

- Aerodynamic resistance is a major contributor to the power consumption of the trains, both, on open track and in the tunnel.
- In the tunnel the aerodynamic resistance leads to significantly higher power requirements than on the open track particularly at high velocity (in example of Fig. 3 by a factor of 3 more than on open track).

Table 4 Measures at tunnel/station and rolling stock to influence aero-thermal conditions

Major impact on (XX major impact, X slight impact, – no impact)	Traction power	Pressure loads	Pressure comfort/ Health	Micro-pressure waves	Loads due to air flow	Comfort and safety of air flow	Tunnel climate and HVAC	Vehicle climate and HVAC
Measures								
Measures at vehicle (selected examples only)								
Aerodynamic shaping	XX	XX	XX	XX	XX	X	–	–
Regenerative braking	XX	–	–	–	–	–	XX	X
Energy efficient design of drives and HVAC system with reduction of heat release	XX	–	–	–	–	–	XX	XX
Light-weight structures	XX	–	–	–	–	–	X	X
Passive/active pressure control of passenger compartments	–	–	X	–	–	–	–	X
Fire resistant material	–	–	–	–	–	–	XX	–
On-board fire extinguishing systems	X	–	–	–	–	–	XX	–
Measures at tunnel/station								
Choice of tunnel free cross-section al area	XX	XX	XX	XX	XX	XX	XX	X
Shape of portal, i.e. gradual change of cross-section	–	X	X	XX	–	–	–	–
Alignment of portals of double-tube systems	–	–	–	–	–	–	XX	–
Number, location, features of pressure relief shafts	X	XX	XX	X	X	–	–	–
Number, location, features of draught relief shafts	X	X	X	X	X	X	XX	

(continued)

Table 4 (continued)

Major impact on (XX major impact, X slight impact, – no impact) Measures	Traction power	Pressure loads	Pressure comfort/ Health	Micro-pressure waves	Loads due to air flow	Comfort and safety of air flow	Tunnel climate and HVAC	Vehicle climate and HVAC
Adjustment friction and damping characteristic of tunnel	X	X	X	XX	X	X	–	–
Open doors of cross-passages/crossovers	XX	X	X	X	X	X	X	X
Optimized overtrack exhaust (OTE) and under-platform exhaust (UPE)—more efficient removal of heat from vehicle	–	–	–	–	–	–	XX	XX
Vertical alignment to reduce traction power for acceleration and losses due to breaking	X	–	–	–	–	–	X	X
Full-height platform screen doors	X	–	–	–	–	XX	XX	X
Design of gaps at stations with platform screen-doors	–	–	–	–	–	X	X	X
Release of heat from technical equipment in tunnel	–	–	–	–	–	–	XX	XX
Avoidance of unnecessary heat ingress at portals/stations	–	–	–	–	–	–	XX	XX
Support natural or train-induced ventilation (shafts, openings)	X	X	X	–	–	–	XX	XX

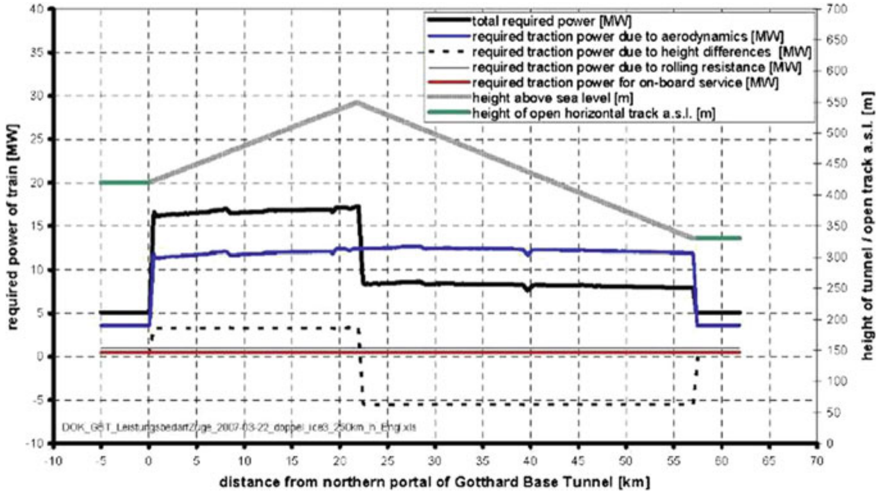

Fig. 3 Required power of high-speed passenger train for run from north to south through Gotthard Base Tunnel at 250 km/h with train length of approx. 400 m

Despite the inherent higher aerodynamic resistance in tunnel, the GBT is an example of saving energy by tunnel infrastructure. Simulations have been made comparing the existing shorter Gotthard tunnel and its access ramps with the new longer and lower Gotthard Base Tunnel (GBT). It was found that the expected 300 trains a day with a share of about 15 % of passenger trains will consume 20–30 % less power using the new and wider GBT (including energy for operation of the tunnel). At the same time, travel times are reduced by 40 % for passenger trains (81 min rather than 138 min for reference journey) and by 25 % for freight trains (145 min rather than 190 min for reference journey) [7].

For a generic tunnel, the influence of the free cross-sectional area on investment costs and the costs for traction power are shown in Fig. 4.

Increasing the free cross-sectional area of the tunnel reduces traction power and increases the costs for construction. Figure 4 indicates that for given boundary conditions an optimal tunnel size exists. Figure 5 highlights the impact of the costs for energy and the train velocity and for a certain train frequency on the optimal cross-sectional area of the tunnel. Increased energy costs lead to larger optimal tunnel cross-section.

First generation high-speed tunnels were mostly built as single-tube, double-track systems. The current trend of building more twin-tube, single-track rather than single-tube, double-track tunnels leads to reducing the free cross-sectional area from about 80–50 m^2 for typical European high-speed rail tunnels (see Fig. 6). According to Figs. 4 and 5, this change may lead to sub-optimal cross-sections in terms of tunnel aerodynamics and life-cycle costs. The aerodynamics, rather than the kinetic envelope of trains or the tunneling method might become the determining factor for the size of tunnels of high-speed rail connections. Considering other beneficial aero-

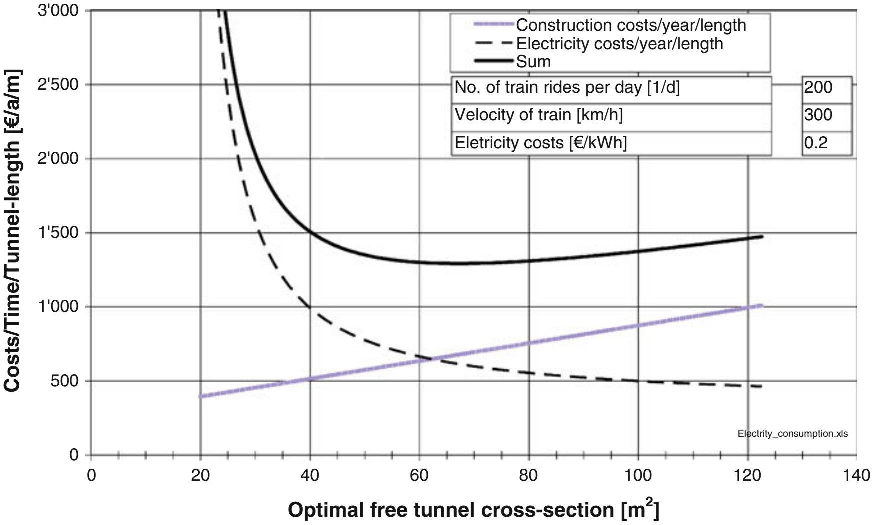

Fig. 4 Specific investment and operation costs for a rail tunnel for different sizes of cross-sectional areas; illustration of principal relationship only

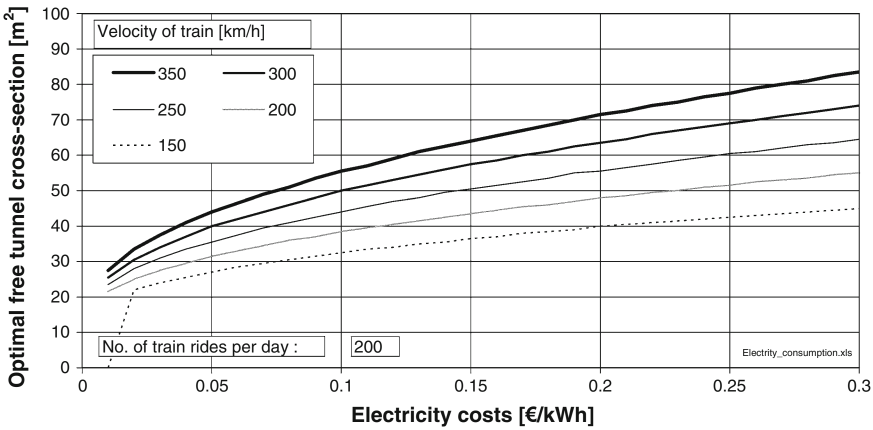

Fig. 5 Optimal size of cross-sectional area of tunnel depending on costs for electrical power; illustration of principal relationship only

dynamic aspects of large cross-sections (pressure comfort, micro-pressure waves, traction power, smoke control), the choice of new high-speed tunnel systems should be evaluated with care.

Apart from reducing energy consumption, improvements may allow to reduce the required maximum traction power to be installed (for example with respect to number of locomotives) power supply of rail network. Alternatively, maximum allowable train length or train weight can be adapted.

Fig. 6 Portal of tunnel Richthof of German high-speed rail line Hanover-Wuerzburg and of Loetschberg Base Tunnel; cross-sectional area of tunnels approx. 82 and 45 m^2, respectively

7.2 Pressure Relief Between Tubes

In very long tunnels, the piston effect of trains is required for air-exchange and temperature control of the tunnel. Twin-tube, single-track tunnels lead to an efficient air-exchange. Simultaneously, these tunnel systems lead to an increased traction power demand. Introducing cross-openings between the tubes allows reducing the tractive effort, since air in front of the train is pushed into to the parallel tube and re-enters the tube behind the train. Figure 7 shows the resulting reduced demand for traction power for a 20-km-long rail tunnel.

Based on the above principle to reduce the maximum power demand, pressure relief ducts were installed in Channel tunnel between France and England (see Fig. 8). The decision was made after construction works had already started and rolling stock specified. The traction power consumption, the maximum required power of trains

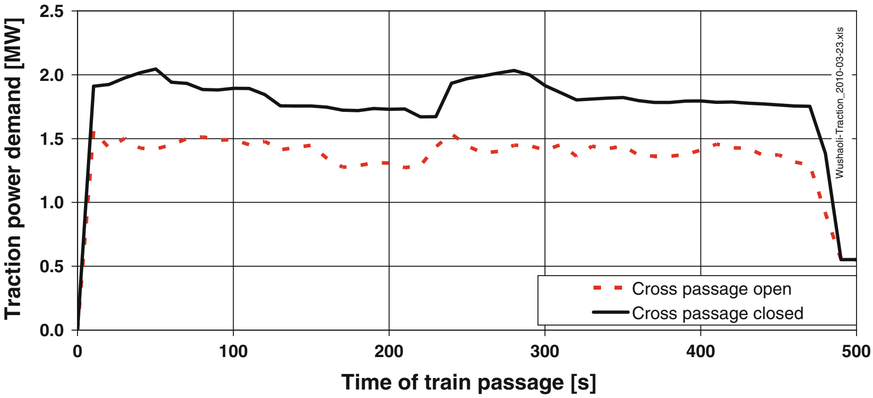

Fig. 7 Traction power demand in a 20 Km long twin-tube, single-track tunnel with open and closed cross-passages at same train speed

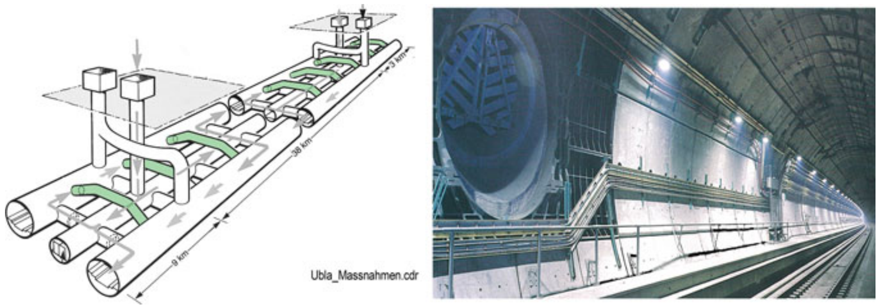

Fig. 8 Pressure relief ducts in Channel Tunnel to reduce traction power demand of trains (spacing of 500 m)

(particularly of shuttle trains) and the requirements for power supply in the tunnel were reduced by pressure relief ducts (see [4]).

However, the resulting re-circulation of air reduced the air-exchange and increased the expected temperatures in the tunnel. In order to control the temperature and in order to compensate the effect of internal re-circulation of air, a dry-cooling system became introduced (cooling pipes, refrigeration plants), i.e. aerodynamic improvements for trains caused substantial investments for a cooling system. Today's experience shows that the cooling system is not necessary. Very likely, a holistic design approach with adapted design specifications for rolling stock, power supply and tunnel design, had avoided the requirement for the cooling system in the first place

7.3 Air Exchange in Tunnel

In warm climate and/or in heavy duty underground systems, the heat release from trains due to braking and air-conditioning of coaches needs to be removed. During normal mode of operation, excessive temperatures might be noted particularly at stations [6]. This is for the following reasons:

- Prior to the stop at the station, the resistor grids and bogies heat up due to breaking.
- Air-conditioning units release heat at a certain location for an extended period of time.
- The piston-effect of the train decays.

Similarly, during congested mode of operation with short-time stops of trains in tunnels, the resulting built-up of heat in the tunnels needs to be handled by forced longitudinal ventilation of the tunnel.

In underground systems with full-height platform screen doors, the trackway space and the platform region are essentially decoupled. As a consequence, the tunnels do not need to be cooled down to the temperature which is expected on the platform for comfort reasons.

Fig. 9 Heat extraction at station by overtrack exhaust (OTE, *top*) and under-platform exhaust (UPE, *bottom*) along the station trackway (*left* Station trackway along platform, *right* station model [5])

Heat removal from tunnel and stations is achieved and supported by:

- Shafts at stations and in tunnels utilizing the train-induced piston effect and natural draft
- Portal and cross-over design of twin-tube, double-track systems
- Overtrack exhaust (OTE) along the trackway at the stations (see Fig. 9)
- Underplatform exhaust (UPE) along the trackway at the stations (see Fig. 9)

Thus, balancing the measures to control the temperature in vehicles and tunnels is the challenge. The following examples show a variety of measures:

(A) Reduce energy consumption of vehicle:

- reduce tractive requirements by tunnel design
  - provide larger cross-section for less aerodynamic resistance
  - introduce shafts/openings for less aerodynamic resistance
  - implement improved vertical track alignment (slopes for supporting acceleration and
  - braking near stations)
- reduce traction and power, demands by vehicle design
  - design lighter trains and better streamlined trains
  - utilize more efficient drives and adapted signaling systems
  - use more efficient regenerative breaking, i.e. reduce amount of heat dissipated to tunnel air
  - use more efficient on-board services

(B) Reduce energy consumption of infrastructure:

- reduce the energy effort to remove heat
  - allow for natural ventilation
  - allow for efficient train-induced ventilation
  - use energy-efficient control strategies of tunnel ventilation and platform cooling

  – increase efficiency of heat removal from train by better adapted interface of UPE and OTE to trains at stations

- reduce energy consumption for vehicle (see A)

Vehicle and infrastructure designers the mutual impact of measures is often not quantifiable. Three examples may illustrate typical design question:

1. To which extend shafts should be increased in size and how should they be arranged in order to allow for less powerful HVAC systems on trains?
2. Where should exhaust air from air-conditioning units of trains be released?
3. To which extend warm air from condenser units from trains can be redirected to the extraction points of under-platform exhaust (UPE)? How can the UPE be optimized to extract more efficiently heat from trains?

The location of the train air-conditioning unit has an impact on the tunnel air temperature and the tunnel ventilation requirements. During a train stoppage, the heat will accumulate in the annular space along the train and the warmer less dense air will rise and collect along the tunnel ceiling. Ceiling mounted A/C units aggravate the problem because the heat discharged by the upstream A/C units cascades along the train in the upper regions of the annulus and can make the condenser intake temperature of the downstream A/C units about 7° C (12° F) higher than the average tunnel air temperature at the same location, even with the operation of the tunnel ventilation system (see [3]). In comparison, underneath train A/C units can reduce the airflow requirement to ventilate the tunnel during congested operation due to the stratification effect and, in turn, reduce the associated civil provision.

It would be beneficial to elaborate a better data basis of the relationships. This would allow to direct investments in the most reasonable manner. So far, the improved energy efficiency has mainly been achieved by advanced drive systems and components for traction through the acquisition of new rolling stock, but this improvement is off set increasingly by demanding requirements from the customer in terms of overall travel comfort, escalators, HVAC systems, etc.

8 Proposal for Future Work and Objectives of Design Optimization

Many parameters determine the aerodynamics and resulting climate of an underground system. Many factors can be modified to create a better passenger environment, improved performance and reduced operational costs. Therefore, a basis of decision-making is needed to improve an underground system.

A set of best-practice-recommendations and checklists would be beneficial to support designers. The basis of decision-making should be improved to allow for sustainable design. In order to advance, research should follow the following objectives:

- Create awareness of interrelationships
- Illustrate sensitivity and impact of design parameter and measures by case studies
- Show systems limitations
- Provide key cost data for vehicles and infrastructure as basis for life-cycle cost analysis and as basis for decision making
- Issue check-lists and present best-practice recommendations
- Motivate improvement of rail tunnels and metro systems design in the context of life-cycle costs and energy demand

Most likely, the proposal will not yield “a technical revolution”. However, spending more research in system integration may lead to a set of cost-efficient improvements and optimization. Design decisions would be based on more sound knowledge.

9 Conclusions

Aerodynamic conditions in underground rails systems and the related climate can be influenced by both, measures at rolling stock or at the infrastructure. Improvements of aero-thermal conditions require adaptation at the interface of rolling stock and infrastructure and balance of investments for rolling stock and infrastructure. The design and analysis of underground systems is a complex process, requiring thoughtful consideration of both technical advantages and limitations of various alternatives, as well as the cost implications and long-term sustainability. Key design parameters are often set without consideration of the aero-thermal aspects or consequences for ventilation of vehicles and tunnels. For improved design, information about the relationship between the major design parameters is needed. Cost data is required for design optimization. Best-practice recommendations are needed to allow improvements. Progress is expected not by one “big thing”, but as a result of hundreds of little things.

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