Cost of supply and ventilation concepts in shield-driven tunnelling in due consideration of the engine type and drive technology

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Abstract. Supply logistics as a supporting sub-process of tunnel driving is significantly responsible for a smooth construction process and, thus, for the desired project success. The main task of supply logistics is to provide the required logistical goods for the tunnel-boring machine. Available are track-bound and tyre-bound systems, which are driven by conventional diesel engines or alternatively by hybrid or electric motors. A multitude of regulations set exhaust emission limits, which can only be met by sufficiently dimensioned ventilation. In particular, the use of diesel engines can result in high costs for ventilation, which must not be neglected for an economic optimization of the supply concept. In order to compare the economic efficiency of different systems, a calculation concept is presented, which shows possible economic, but also ecological and logistical advantages of the individual systems by quantifying relevant factors. The costs for the different types of vehicles are examined separately for chassis and drive train, as well as for ventilation. The information and results obtained with the calculation provide a basis for the decision-making process when choosing an optimal logistics concept. Due to the quantities of logistical goods involved, the focus is on supply logistics in shield tunnelling.

1. Introduction

In order to ensure an optimal construction process under consideration of existing constraints - in terms of costs, deadlines and quality - and complying with existing restrictions, construction logistics concepts focus primarily on the optimization of material and information flows to be handled [1]. The possible savings and optimization potential of construction logistics over the entire construction process are the main reasons for a more intense analysis of the subject. Above all, processes with a particularly high influence on the adherence to schedules and costs of a project take an important position in the context of project execution. Nevertheless, logistic plays a seemingly undervalued role in the construction industry - despite it's evident importance for project success – in particular compared to other branches of industry [1].

The aim of construction logistic concepts is optimizing the material and information flows [2]. Construction logistics can be broken down into the segments supply logistics, disposal logistics, information logistics and construction site logistics [3].

The focus of this paper is the development of a calculation concept for determining cost of supply logistics in shield tunneling. The concept is developed in a way that it can be applied to any project. The application is exemplarily shown for a tunnelling project.

2. Logistics as a sub-process in shield-driven tunnelling

The decision for a suitable supply concept depends on the type of tunnelling, the existing construction and the project-specific circumstances [4]. In shield tunneling, the logistical goods comprise in particular the tubbings, the annular gap mortar, pipes for extending the supply lines and personnel. The objective of all efforts is the undisturbed operation of these core processes. The supply of a shield machine with the required materials can be carried out either on trackless or track-bound systems. So-called multi-service vehicles (MSVs) are used as trackless systems. With regard to the drive train systems can be divided into diesel, electric or hybrid-driven systems. As a result of increasingly strict regulations in the context of occupational health and safety guidelines, the use of alternative drives has also gained importance for tunnel construction. In addition to the regulations for exhaust gas limit values, so-called workplace limit values were specified. In order to comply with these prescribed limits, active ventilation is required in the tunnel during the construction period. Alternative drive concepts with hybrid or purely electric drives can significantly reduce exhaust gases and pollutants in the tunnel, which has an impact on the dimensioning of the ventilation system. This can save cost for the operation of the ventilation system, especially with increasing tunnel length.

3. Calculation methodology

In the following, a methodology based on physical principles is developed which allows different concepts for the supply of shield machines to be evaluated in terms of economic efficiency by quantifying all relevant factors. The total cost for supply logistics consist of various components. For each of those components a methodology for calculating the cost is presented below. On the first level, the cost can be divided into cost of supply vehicles and cost for ventilation. The second level breaks down the supply vehicle cost into explicit vehicle cost and fuel cost. The ventilation cost can be further divided into infrastructure cost, which consist of the cost for ducts, clamps and fans, and energy cost. All components are developed separately for the variants shown in Table 2:

Table 1: Variations of concepts.

	Trackbound	**Trackless**
Diesel- driven	Diesel-trackbound	Diesel-trackless
Hybrid- driven	Hybrid- trackbound	Hybrid- trackless
Electric drive	Elektro-trackbound	Elektro trackless

Since the underlying calculation steps are based on physical principles - and thus independent of a specific project - this model can be used to simulate the supply logistics for any tunnel construction project and to predict the cost taking into account all relevant influencing project-specific conditions.

3.1. Supply vehicle cost

To calculate the vehicle cost the required number of vehicles must be known, which depends on the speed of excavation and the cycle time. The definition of the cycle time is as follows:

The cycle time describes the time required by the supply unit to be loaded at the tubbing storage facility, to travel to the tunnel machine (TM), to be unloaded there and to travel the distance back to the tubbing storage facility.

Hence, the cycle time can be determined by the tunnel length and the vehicle speed. The speed is given by a speed profile for trackless and track-bound vehicles depending on the gradient and weight. Therefore, the tunnel must be divided into sections of equal gradient. Here, a separation must be made between outward and return journeys due to the gradient and the mass of the vehicle. The time t_n required for the individual sections can be calculated as follows:

$$t_n = \frac{s_n}{v_n} \tag{1}$$

t_n = time of section n

s_n = length of section n
v_n = speed of section n

To calculate the time for the total distance to be covered, all sections n and the time t_{VE} for the individual supply sub-processes are added. After loading the tubbings, the mortar box is filled (t_{load}). The time for driving the vehicle into the TM must also be taken into account (t_{TM}). Unloading of the segments and the mortar box are done simultaneously (t_{unload}). After this, the driver of the MSV has to change the driver's cab (t_{change}); this process does not exist for track-bound concepts.

$$t_{VE} = t_{load} + t_{TM} + t_{unload} + t_{change} \tag{2}$$

The cycle time t_c can be calculated by adding up the individual sections and the individual subprocesses:

$$t_c = \sum_{i=1}^{n} t_n + t_{VE} \tag{3}$$

The number of vehicles required is determined by the cycle time t_c and the time t_V to set a tubbing and advance a drilling stroke. This results from the advance rate and the width of the tubbing:

$$t_V = t_{tubbing} + v_{advance\ rate}/b_{tubbing} \tag{4}$$

Finally, the number of required vehicles N is

$$N = t_c/t_V \tag{5}$$

As the tunnel length continues to increase over the entire project duration, more vehicles will be needed as the project progresses. One advantage of track-bound vehicles is already obvious: by attaching wagons, no extra vehicles need to be provided for the transport of staff and pipes. In case of using trackless systems, an additional vehicle must be used for pipes and lines, as well as two vehicles for transporting staff members. Regardless of the system, another vehicle is required as a rescue vehicle. It should be noted that cost for power supply are not affected, since the transport power consumption is not significant compared to TM.

3.2. Supply vehicle – fuel costs
To calculate fuel costs, the energy required to move a vehicle needs to be known. This is a purely physical quantity required to compensate for the driving resistance which can be calculated as follows:

$$F_{FW} = F_{Luft} + F_{Roll} + F_{Steig} + F_B \tag{6}$$

$F_{FW} = vehicle\ resistance\ [N]$
$F_{Luft} = air\ resistance\ [N]$
$F_{Roll} = rolling\ resistance\ [N]$
$F_{Steig} = climbing\ resistance\ [N]$
$F_B = acceleration\ resistance\ [N]$

The required energy is independent of the drive technology. The various drive technologies differ only in their efficiency and in the ability of recuperating the energy released. The air resistance increases with the square of the vehicle speed. Due to the low vehicle speed in the scenario considered here, the proportion of air resistance is negligibly small and can be neglected. Since the vehicles assumedly will usually not start off in the steepest (decisive) section, the acceleration resistance is also neglected. The remaining driving resistances is:

$$F_{roll} = c_{Roll} \cdot m \cdot g \cdot \cos \alpha \tag{7}$$

$F_{roll} = rolling\ resistance\ [N]$
$c_{Roll} = rolling\ resistance\ coefficient\ [-]$
$\quad = 0,014 - 0,02$ for trackless systems and $0,001 - 0,002$ for trackbound systems
$m = vehicle\ mass\ (incl.load)\ [kg]$
$g = gravity = 9,81\ \left[{m}/{s^2}\right]$
$\alpha = pitch\ angle\ [rad]$

$$F_{steig} = m \cdot g \cdot \sin \alpha \tag{8}$$

$F_{steig} = climbing\ resistance\ [N]$
$m = vehicle\ mass\ (incl.load)\ [kg]$
$g = gravity = 9,81\ \left[{m}/{s^2}\right]$
$\alpha = pitch\ angle\ [rad]$

Due to the influence of the load and the gradient, the tunnel also needs to be divided into individual sections for the calculation of fuel costs. If the speed and vehicle load are known, the time required for covering the total length of the individual section can be calculated, based on these considerations: The daily advance of the machine consists of several drilling strokes. For each drilling stroke, the TM is to be supplied with a tubbing and other materials. Consequently, one trip of the supply train is necessary for each drilling stroke. The distance to cover is not constant, however, increases with each drilling stroke by the length of the drilling stroke or by the daily advance each day.

If the corresponding driving resistance is known (equation (6)), the power and the resulting energy required for the individual sections can be calculated. Since the process is a translational motion, the ZUGHAKENLEISTUNG("pulling power") must be calculated. This is the maximum power available after subtracting all losses at the towing device and is a frequently used characteristic value for towing vehicles in rail and road traffic. It is calculated as:

$$P_n = F_{W,n} \cdot v_n \tag{9}$$

For starting and braking as well as speed changes, the acceleration energy also needs to be taken into account:

$$E_{acc} = {1}/{2} \cdot m \cdot v_n^2 \tag{10}$$

As a first step, the model calculates the physical energy (E_{ideal}) required to move a vehicle with a known weight and payload for a given distance using the equations shown above:

$$E_{ideal} = E_{acc} + P_n \cdot t_n \tag{11}$$

Then, the required total energy is weighted by the corresponding efficiency values and cumulated over all sections. Finally calculating the fuel quantity for the diesel drives, the specific fuel consumption of the installed unit is used, leading to cost on the basis of an exemplary diesel price of1.00 €/l at the considered construction site.

3.3. Ventilation – energy cost
A physical model representing the ventilation system is being developed, which can be used to calculate the maximum pressure and the maximum amount of air that needs to be delivered (figure 1).
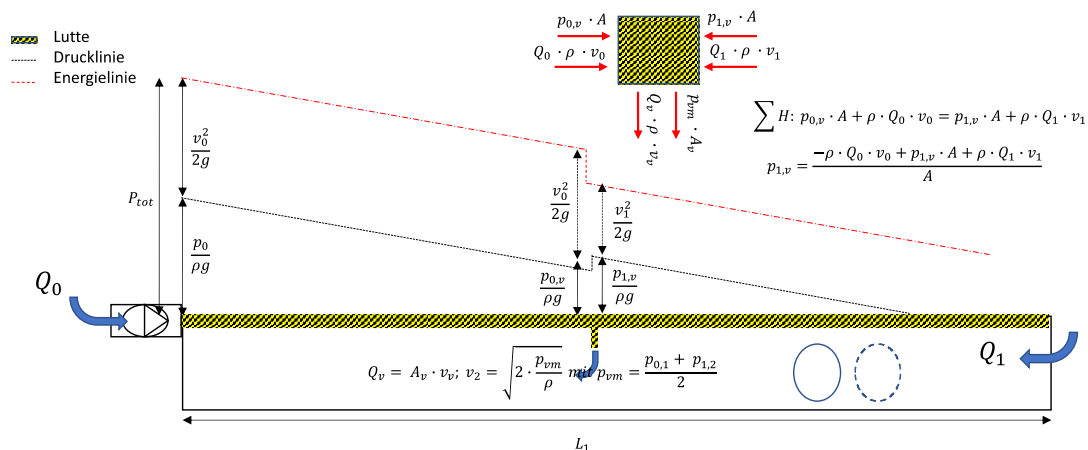
Figure 1: model of the ventilation system

The tunnel ventilation is based on pipe hydraulics. The duct is regarded as a pipe and the fans as a pump. The decisive factor for the required fan power is the total pressure present. This can be calculated for ideal, frictionless flows using the Bernoulli principle. In real flows, internal friction is given by the viscosity of the fluid, which leads to thermal losses which need to be taken into account via a corresponding loss height h_v. The total pressure at the fan is calculated by the Bernoulli equation extended by the loss height:

$$P_{tot} = \frac{1}{2}v_1^2 \cdot \rho + p_1 + \frac{1}{2}v_1^2 \cdot \rho \cdot (\lambda \cdot \frac{L_1}{d} + \Sigma \zeta_{i,1}) \tag{12}$$

$\lambda = coefficient\ of\ friction\ = 0,015 [-]$
$d = diameter\ of\ the\ duct\ [m]$
$L = lenght\ of\ the\ duct\ [m]$
$\zeta = loss\ coefficient = 0,7 [-]$

The speed v can be calculated by the volume flow Q and the cross-sectional area A:

$$v = \frac{Q}{A} \tag{13}$$

The principle of linear momentum can be used to determine the pressure as shown in figure 1:

$$P_1 = \frac{p_2 \cdot A + \rho \cdot Q \cdot v_2 - \rho \cdot Q \cdot v_1}{A} \tag{14}$$

In this model, as a simplification atmospheric pressure conditions are assumed to prevail at the exit point in the tunnel. In fact, however, a certain overpressure is generated by the ventilation at the tunnel face, which is reduced along the tunnel axis to the portal. In relation to the pressure within the ducts this is negligible due to the low flow velocities along the tunnel axis.

The required power of a fan can be calculated as follows:

$$N_V = \frac{p_{tot} \cdot Q}{\eta_M \cdot \eta_V\ 10^3} \tag{15}$$

$N_V = required\ power\ of\ the\ fan\ [kW]$
$Q = required\ air\ to\ be\ transported\ \left[\frac{m}{s}\right]$

$p_{vent} = total\ pressure\ at\ the\ fan\ [Pa]$

$\eta_M = motor\ efficiency$

$\eta_V = fan\ efficiency$

As can be seen from the formulae, the required capacity is strongly dependent on the volume of air to be transported. This is precisely determined by various regulations of the individual countries, which needs to be taken into account when dimensioning the ventilation system. According to figure 1 loss due to leakage in the ducts must also be added to the required fresh air volumes. The loss quantity is calculated using the Toricelli's law and the mean hydrostatic pressure. Since this in turn depends on the volume of air to be transported, it is necessary to iterate. Figure 2 shows a summary of the used calculations to determine the required power for a fan:

Calculation of the power of the fan				
		Diesel	Hybrid	Electic
Section 2	Q2 [m³/s]	87,00	51,00	35,00
	v_2 [m/s]	17,72	10,39	7,13
	λ*L/D [-]	42,00	42,00	42,00
	v_2^2 *ρ/2 [kg/s²m]	188,47	64,77	30,50
$=v_2^2$ *ρ/2*(λ*L/D+Σζ)	p2 [Pa]	7.981,85	2.742,87	1.291,82
Loss	Pvm	7.490,56	2.574,05	1.212,31
=square root of (2*pv/ρ)	v_A	111,73	65,50	44,95
	Q_A	65,82	38,58	26,48
Section 1				
	Q_1 [m³/s]	152,82	89,58	61,48
	v1 [m/s]	31,13	18,25	12,52
	v_1^2 *ρ/2 [kg/s²m]	581,50	199,83	94,11
$=(P_v*A+ρ*Q_2*v_2-ρ*Q_1*v_1)/A$	P_1 [Pa]	7.195,79	2.472,75	1.164,60
$=P_1+v_2^2$ *ρ/2*(λ*L/D+Σζ)	P_{0S} [Pa]	31.822,34	10.935,38	5.150,27
$=v_1^2$ *ρ/2	P_{0D} [Pa]	581,50	199,83	94,11
	P_{0tot} [Pa]	32.403,84	11.135,21	5.244,38
	L [kW]	**6.189,79**	**1.246,89**	**403,02**

Figure 2: used equations to determine the power of a fan

The necessary energy [kWh] can be calculated by multiplying the excavation time [h] required for the section under consideration by the power [kW] required along the section.

3.4. Ventilation – infrastructure costs

The number and size of the fans are based on the required power. The total length of the ducts required is derived from the tunnel length. Accordingly, the number of required clamps can also be calculated.

4. Case Study of an Exemplary Project

The example used here is a twin-tube tunnel of length 8,200 m per tube, where tire-bound vehicles were used. Official market prices were obtained to quantify the vehicle costs in order to obtain significant results. For not used variants, offers from various companies were available. For vehicle cost, a buy-back option after the end of the project of 20% for track-bound and 35% for tire-bound vehicles was taken into account according to the offers. The prices of the MSVs and the track-bound vehicles also include a fixed flat rate for wear and tear and maintenance.

For the determination of the energy costs 150 m long sections of the ducts are selected. With a tunneling speed of 20 m/d, this results in a duration of 180 h. With a known electrical power price, which is 0.19 €/kWh for the project under consideration, the aeration costs can finally be determined. For all variants, a diameter of the ducts of 2.5 m was assumed.

For the calculation of the infrastructure costs, the prices for the fans were estimated at €100,000 for the diesel variant, €75,000 for the hybrid variant, and €50,000 for the electric variant, according to information from a company. The price for the ducts was estimated at 17,23 €/m and for the clamps at 32,54 € per piece.

Considering the total cost of the supply concept (see figure 3), it can be noted that the fuel cost and the infrastructure cost of tunnel ventilation are playing a minor role. The vehicle cost are by far making up the largest part.
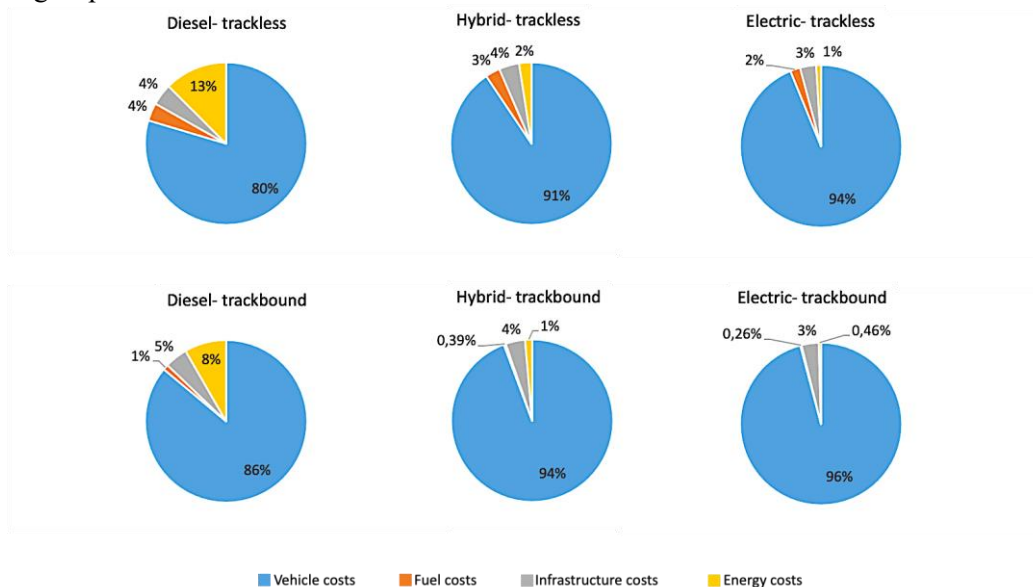

Figure 3: Results for the different systems

Due to the lower speeds and transport capacities, more vehicles are required for tire-bound systems as the tunnel length increases (from approx. 4,200 m, six vehicles for tire-bound and four vehicles for track-bound systems). That is why the vehicle cost for tire-bound systems increase faster than for track-bound systems as the tunnel length increases. This also results in an increasing exhaust gas production and thus an increased amount of fresh air required. Using alternative drives, energy cost increase not that much with rising tunnel length.

Alternative drives produce far fewer exhaust gases, which is why the dimensioning of the ventilation concept is approx. 25 % - 50 % lower, depending on the drive type. E.g., using diesel-powered MSVs, leads to energy cost for the reference project of approx. 13 % of the total costs, while using MSVs with an electric drive, they only account for a share of approx. 1 %. However, the higher initial investment cost of alternative drives are not compensated just by their lower energy and fuel cost. As conventional drives are significantly less expensive to purchase, they are the best choice from a cost-oriented point of view - despite higher operating costs - for the reference project in the case of track-bound concepts up to a tunnel length of approx. 7,600 meters. For track-bound concepts, the use of alternative drive concepts would only be profitable for a tunnel length of more than approx. 7,300 m. In terms of cost, tire-bound concepts are to be preferred to track-bound concepts with conventional drive up to a tunnel length of approx. 4,600 m (figure 4).

The differences between tire- and track-based concepts in regard to the energy cost turn out to be significant, amounting to 28.9 % for the diesel variant, 13.9 % for the hybrid variant and only 12.1 % for the electric variant of the energy cost of the tire-bound counterparts. The reason for a higher monetary efficiency of track-bound systems is their higher transport performance as well as the rolling resistance of rail wheels and rubber tires, which is about a magnitude lower.

It should be noted that the vehicle cost are not including wages for drivers. Due to the higher number of vehicles required for trackless systems, it can be assumed that track-bound systems are better solution from an economic point of view. In addition, the maintenance costs for trackless vehicles are higher than those for track-bound concepts.
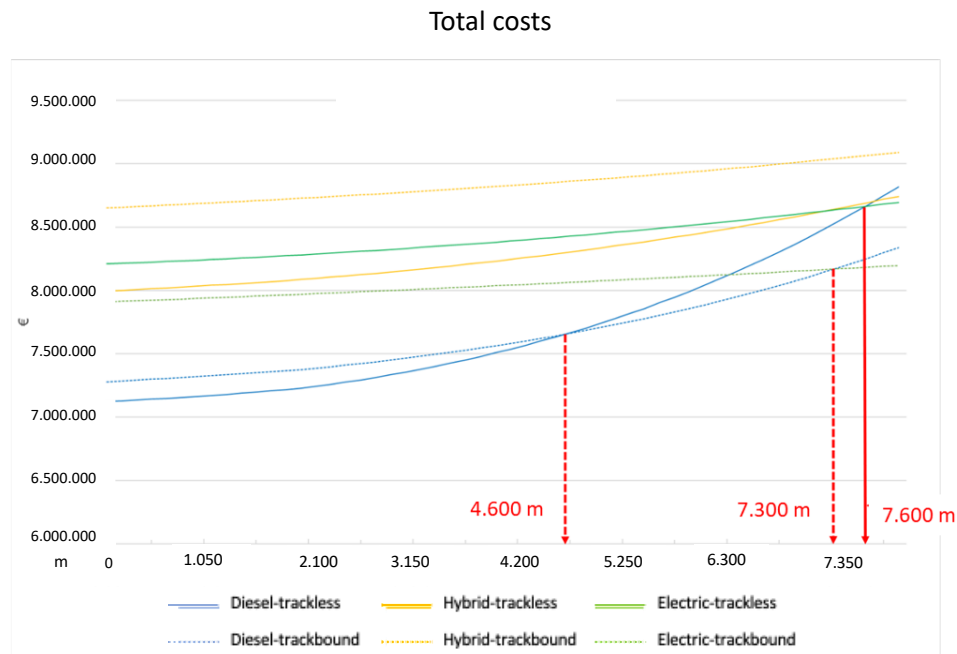
Figure 4: Total costs of the different concepts

5. Conclusion

The evaluation of the logistics costs showed that the initial investment costs of the vehicles account for the largest share of the total costs. As the tunnel length increases, the remaining cost items become increasingly important, but the vehicle cost remain decisive.

Whereas the initial investment costs for the vehicles and for the infrastructure of the ventilation are linear with increasing tunnel length, the operating costs have a strongly exponential character. As the number of vehicles increases - and so the difference in the exhaust gas production increases - the operation costs of diesel and hybrid-driven systems rise much faster. The increase in costs over the length of the tunnel is much more exponential for diesel drives.

Generally speaking, the costs of tire-bound concepts rise more sharply over the length of the tunnel than those of track-bound concepts. The reason for this is the strong increase in ventilation costs (which account for the majority of aeration costs) and fuel costs for tire-bound concepts due to the lower transport capacity and the lower driving resistance.

The energy costs linked to the tunnel ventilation can be drastically lowered by using alternative drives. Here, alternative drive concepts offer great saving potentials. For example, the use of hybrid-driven systems in the example project presented here results in a cost saving of approx. 81% in the energy cost of tunnel ventilation.

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