AUTOSHUTTLE FEASIBILITY, FINANCIAL AND ENVIRONMENTAL ANALYSIS

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Abstract

The proposed transport system Autoshuttle integrates road and track guided traffic using and combining the specific advantages of each of these traffic modes. Conventional road vehicles are transported with their passengers and freight in individual cabins. The operational concept provides operation of the cabins without intermediate stops at almost constant travelling speed. During the journey convoys with low aerodynamic drag are formed in order to lower the energy consumption and increase traffic capacity. Approaching a station only those cabins that have reached their destination leave the convoy on a passive switch and decelerate on a brake track, while the other cabins close the gap in the convoy and travel on at the usual cruising speed. This paper describes the planning and economical aspects of a proposed commercial line along the motorway A3 in Germany between the cities of Duisburg and Cologne.

1 Introduction

The transport system Autoshuttle results from a consequent analysis of the user requirements and the frame conditions given by the state of the art, economy and environment.

According to the current traffic prediction [1] of the German Federal Ministry of Transport the traffic volume on roads will still increase. This refers to passenger and even more to freight transport. It results the well known situation on the motorways with daily tailbacks caused by high traffic density, accidents and construction work. Facing the predicted increase in traffic volume this situation becomes even more critical in the coming years, since upgrading the motorways in the most condensed areas is not possible or only with great expenditures. Expanding a motorway by an additional lane per direction is not possible in many locations. In some locations, expensive and not fully satisfying noise reduction measures or trench and tunnel construction is necessary.

Traffic guidance measures like for example electronic road signs or a traffic situation dependent road toll can level the traffic volume, whereas the effect is rather low. Although these new technologies have been considered in the traffic prognosis, the prognosis predicts scenarios with frequent tailbacks and considerable economical losses. As well, traffic transfer from road to rail using huge subventions is considered in the prognosis. However, rails will keep on having a low share of the total traffic and will therefore have a low effect on decreasing the motorway's tailbacks only.

The user requirements for a new means of transport are short door-to-door travelling times, low cost, high dependability, safety, flexibility and simple use. Target value of each mentioned aspect is the best value realised in any of the existing means of transport. Only if all these target values have been reached or improved upon, acceptance by the user and the entire population can be expected. Very good values in one or more criteria cannot compensate for bad values in other criteria.

Instead of setting up a concurrence to road traffic or trying to completely avoid road traffic, according to the requirements of the majority the unchanged road traffic vehicle is integrated in a very effective and environment friendly means of transport.

Individual transparent cabins transport road vehicles with their passengers and freight load, so that time consuming and uncomfortable transfer processes of passengers and freight from the road vehicle to another vehicle are avoided. During the journey, convoys with very low aerodynamical drag are formed, so that line capacity is increased, whereas energy consumption and transport expenses are lowered. Like on a motorway there are stations about every five kilometres. An individual cabin stops there only if its user announced a corresponding wish at any time before during the journey. This could be shortly before or at the beginning of the journey. Together with a constant travelling speed very low door-to-door travelling times are achieved. Track guidance and automated operation guarantee high levels of safety and reliability.

Preferably, Autoshuttle is built parallel to an existing motorway, since this yields the highest changeover rate from the road to Autoshuttle. At the motorway entries and exits there are Autoshuttle stations. Alternatively, Autoshuttle can be built at isolated locations like mountain ridge crossings in tunnels, which will profit from Autoshuttle’s safety, flexibility and environmental friendliness.

MAGLEV technology is well suited for Autoshuttle in combination with a long stator drive. The specific advantages of this concept are fully exploited:

- High control accuracy – realisation of the rendezvous-manoeuvre with a wayside control and safety system (see [2] and [6])

- Realisation of a passive switch – travelling direction on the switch is determined by the vehicle’s actuators only

- Very high traffic capacity combined with low specific space requirements – the high attraction and resultantly high traffic volume is achieved by the low convoy headways due to the rendezvous-manoeuvre and the passive switch together with an economically and ecologically advantageous uniform travelling speed of 180 km/h for passenger car convoys and lorry and bus convoys travelling on the same track

- Almost no noise emission due to the moderate travelling speed of 180 km/h and use of the MAGLEV system

- Simple vehicles – the long stator drive is mounted wayside, an ideal solution for a concept with many vehicles. The suspension system and the cabin construction are very simple, since the passengers use the comfort systems of the transported road vehicles

- Very low energy consumption – convoys formed by matching cabins with almost constant convoy cross section yield a very low air resistance and low additional energy consumption by use of a levitation and guidance configuration based on hybrid magnets in a transversal flux arrangement [2]

- Short door-to-door travelling times – due to very short times to reach the Autoshuttle station and to load the road vehicle as well as short times for unloading and reaching the final destination, Autoshuttle is at only 180 km/h fastest door-to-door means of mass transport in a wide range of journey lengths

Autoshuttle has been published in various media. A general survey on technology, usefulness and economy is given in [2], [3] and [4]. Safety aspects and approval aspects are dealt with in [5] and [6]. [7] describes details of the long stator synchronous drive. The present article gives a short overview on Autoshuttle in chapter 2 and a summary of a detailed application analysis for a commercial Autoshuttle line parallel to a motorway in Germany between Duisburg and Cologne in chapter 3.

2 Short Description of the Autoshuttle Concept

Figure 1 : Autoshuttle at the centre of a motorway

Figure 1 shows a convoy formed by MAGLEV-cabins for transport of passenger cars in the foreground. Oncoming is a convoy for lorries and buses. Passengers may stay seated in their vehicles. The MAGLEV-cabins are very simple. The plastic sides and the front upside hinged exit door are transparent. The rear two laterally hinged doors and the fuselage are opaque. Solar cells may be added to the roof. The front is streamlined. The rear part of the cabin extends over the rear doors at the circumference and is flexible at the tips. During the journey in a convoy the following cabin closes up directly to the end of the preceding cabin. Since the end part is congruent to the front end of the following cabin, the flexible tips of the front cabin touch the following cabin so that a streamlined, almost even transition between the cabins with constant cross-section is achieved between the cabins. The cabin sidings are hinged and can form lateral corridors with auxiliary doors, so that the passengers may leave the road vehicle or the cabin in extraordinary conditions. Further on, remote controlled ventilation windows are provided. There are cabins with a small cross-section for passenger cars – 2,20 m internal width and 1,70 m internal height – and cabins with a large cross-section for lorries and buses – 3,30 m internal width and 4,30 m internal height. Both types are provided in different lengths – from 3,60 m to 5,60 m internal length for cars, and from 6 m to 19 m internal length for lorries and buses. All types ride on the same track and form convoys with vehicles of an identical cross-section. The usual operating speed is 180 km/h (112 mph) for all convoys. The uniform speed yields an optimised line capacity.

Inside the cabin is a flat communication module movably mounted at the driver's side. The module moves towards the opened driver's window as soon as the driver moves something outside the window. At the communication module the driver enters the desired exit station by voice recognition or keyboard and pays by a credit card or via cellular phone. The type of the road vehicle is determined at the entrance station by a number plate identification system and an extract of the centralised road vehicle's register's databases. Fare is calculated with a table set up for each vehicle type including motor type. Fare is slightly lower than the averaged fuel cost when driving the road vehicle by its own means. The road vehicle's dimensions are determined by light beam detectors, so that a suitable cabin is ordered.

Furthermore, a fast exit button for exiting at the next station, an emergency call phone, a 12 V-supply for the road vehicle's equipment and a cabin ventilation and window remote control are provided. Since the cabin is always well ventilated the road vehicle may run the engine idle for operating the heating, air conditioning or other on-board equipment.

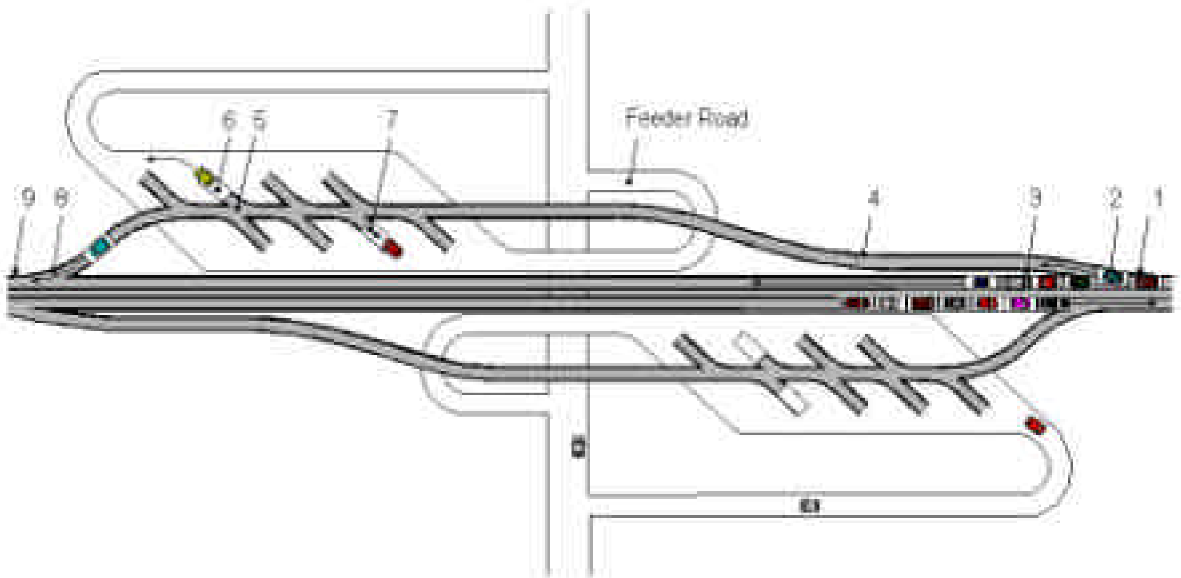


Figure 2 : Simplified sketch of a station

Figure 2 shows a simplified sketch of a station from above. Stations are located as densely as motorway exits along the line, i. e. each 5 km (3 m). Via a passive switch 1 an exiting cabin 2 leaves the convoy 3. (operation of the passive switch is described below) On an approximately 1.2 km (0.75 m) long braking track 4 the vehicle decelerates, turns to the right on another switch 5 and stops in an exiting bay 6 where the road vehicle leaves the cabin through the front door. Thereafter the cabin moves backwards towards an entering bay 7 where another road vehicle enters. As soon as the convoy 3 has reached a reference position on the main track, the freshly loaded cabin accelerates, switches on to the main track 8 via a passive switch 9 and is swiftly caught up by the convoy 3 on reaching the operating speed. Those who don't want to exit will pass the station at full speed. Averaged speed therefore is close to 180 km/h (112 mph). The car convoys follow each other in a 2 minutes sequence, lorry and bus convoys in a 6 minutes sequence. Frequency is diminished during night-time. Coupling of the vehicle principally is not necessary, however simple engaging couplers which uncouple on lateral motion are provided. The convoy 3 needs not to be extended when a cabin leaves the convoy 3 at the passive switch.

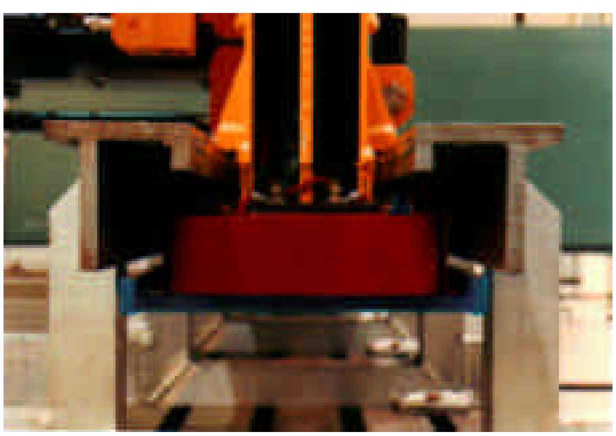


Figure 3 : Levitation and guidance system

The levitation bogies of the cabins enter between the two rails at each side and engage from beneath the rails, see figure 3. Magnetic circuits are formed through the controlled hybrid permanent and electromagnets with minimised energy consumption and the rails. The configuration of the levitation system enables the levitation function even when one rail per side is omitted. This is the case at some parts of the passive switch. Additionally, lateral movement control magnets are provided, which are short-term activated when entering a non-moving switch. For example cabins turning to the left activate the control of the additional lateral movement control magnets. The cabin travels contact-free controlled by its on-board magnet in the desired direction through the passive switch.

As an additional mechanical safety device vertical guidance rails are mounted at the passive switch in the centre of either the straight and deviating branch. Centred under the cabin at the front end is a guidance pin, which is laterally moveable by about 10 cm. The cabin approaching the passive switch in diverting direction fixes the intended direction before the braking distance before the passive switch is reached by activating the additional lateral motion magnet as described above and by additionally moving the guidance pin in the desired direction. The pin is latched at the end position. Emergency brake is applied on failure. The guidance pin travels contact-free laterally along the guidance rails. Erroneous guidance is not possible even on magnet failure by this engaging mechanical safety device.

Autoshuttle has a long-stator-linear-synchronous-drive with iron-free stator. In track sections, where cabins have to move with a short distance between each other at different speeds, motor sections reach short lengths down to 3 m. Each of the short motor sections is fed by an power interverter, disposing a pole position sensor and stator current control. The motor has a simple configuration and reaches high efficiencies due to the low power demand of the convoys at constant speed and due to the short motor sections during the accelerated motion.

A control centre surveys control of the operation. Communication between the cabins and the control centre takes place by radio or high frequency leaking cable in the track bed. The control centre receives the following information from the cabins:

- cabin-id
- position
- desired exit station
- information related to the received fare
- emergency and failure information

The cabins receive the following information from the control centre:

- indication concerning the direction to be chosen at the next non-moving point
- specific fare of the transported road vehicle
- communication with the emergency phone

The control centre controls operation by processing the information received by the vehicles in corresponding direction commands for the cabins. The track bears Hall-sensors detecting the presence of cabins. If the sensors detect that a vehicle remains behind its intended position, all following cabins, which could come into a conflicting position with this cabin will brake after a tolerance interval. The control centre calculates track occupancy after the passage of a non-moving point according to the direction indication to the cabins issued earlier. Indications of desired exit stations are used for the co-ordination of the necessary empty runs for dispatching the necessary number of cabins at each station. Additionally, a daytime and calendar-dependent forecast program is used for this purpose. In order to save energy, empty runs start only together with loaded runs whenever possible.

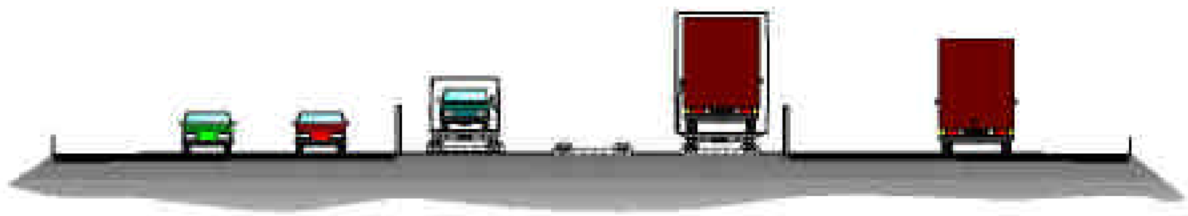
Energy consumption has been determined using a formula for theoretical determination of rail vehicle air drag and alternatively using existing air drag field data from the Transrapid MAGLEV for aerodynamic similarity calculations. With all additional consumptions like on board energy supply, empty runs, different journey phases and the station's energy needs, comparison values were determined. An average passenger car transported by Autoshuttle uses the equivalent primary energy to 2.3 l Diesel per 100 km or 104 mpg. A 40 tons lorry uses 13 l Diesel per 100 km or 18 mpg.

Related to the measurements of the Transrapid TR 07 MAGLEV-vehicle a noise emission of a convoy at 180 km/h (112 mph) of less than 74 dB in 25 m distance can be expected. Subjective noise perception is very positive. With the usual convoy frequencies of 80/h and passing durations of 4 s, this yields the low averaged value 61 dB in 25 m distance, making noise reduction measures generally obsolete. Autoshuttle may therefore be built through populated quarters without causing unacceptable noise annoyance.

3 Commercial Line Example Duisburg-Cologne

A suitable first application is the German motorway A3 between Duisburg Breitscheid Intersection and Cologne Königsforst. This is a 56 km (35 m) long section currently characterised by a very high traffic volume with almost daily tailbacks. Current data of the German Federal Ministry of Transport predict an increase of more than 15% in passenger traffic and more than 50% in freight traffic until 2015. Adding further lanes to the currently six to eight lane motorway is very problematic due to close residential areas and the existing noise limitation laws.

3.1 Civil Engineering



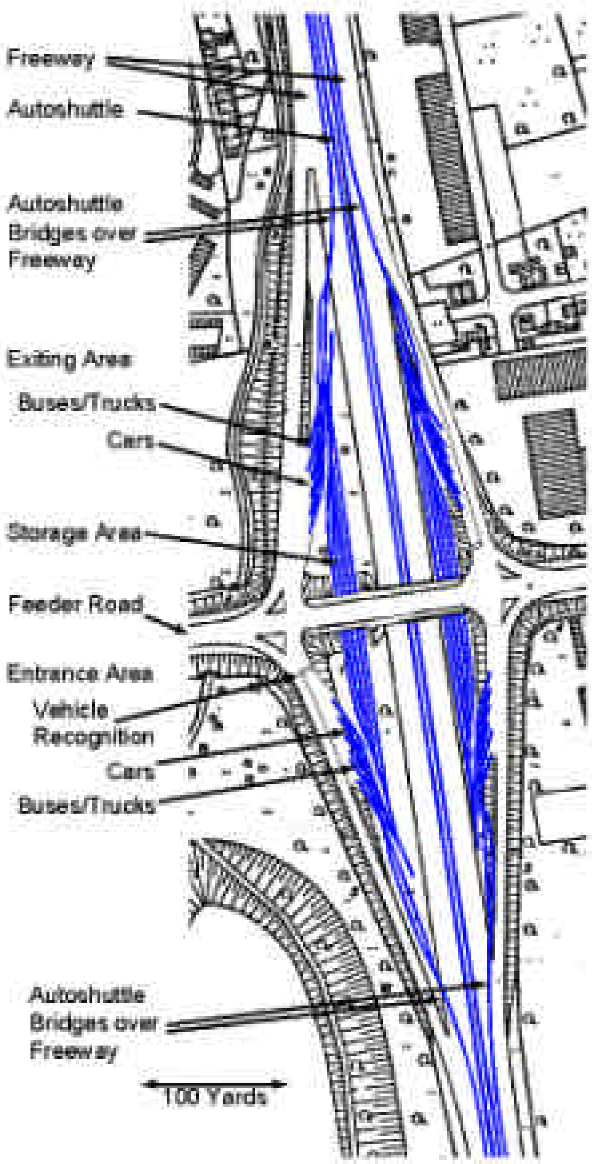


Figure 4 (above) : Cross-section of a motorway with Autoshuttle at the centre

The Autoshuttle main tracks will be built at the centre of the motorway, which will be reduced from a six to a four lane motorway in most sections. This is sufficient for the remaining conventional traffic, since the total traffic capacity of Autoshuttle plus remaining motorway lanes is far higher than before construction of Autoshuttle. Figure 4 shows a cross-section of the motorway A3 in the section Cologne-Leverkusen with two Autoshuttle main tracks and a braking track. The lateral limits of the right-of-way have not been affected.

The Autoshuttle stations are located at the entrances and exits of the existing motorway. Road vehicles approaching from a feeder road can directly enter an Autoshuttle cabin without using the motorway. Figure 5 shows the realistic configuration of the Autoshuttle station at the Leverkusen entrance and exit. Approximately 1.2 kilometre (0.75 m) before the station a braking track switches out of the main track in either direction. There are three tracks at the centre of the motorway in these sections, see figure 4. The last section of the brake track is built as a bridge leading the brake track from the centre of the motorway to the area between the motorway and its ramps towards the feeder road. The Autoshuttle bridges have short ramps because the cabin speed is under 70 km/h (44 mph) on them. Curvature radius is 250 m (800 ft.). The braking track leads to a two track waiting section, which then leads to the exit bays.

to manage a high traffic volume of road vehicles entering or leaving the motorway. It has been determined by a combination of practical studies measuring the average times for road vehicles to enter a garage and a theoretical study calculating the necessary delays for the cabin movements on the adjacent tracks including door opening and closing times that six entrance and six exit bays are sufficient in either direction of the station in order to meet the loading and unloading demands during the peak traffic volume periods. For example, 650 passenger cars can be loaded or unloaded per hour in either direction. This is sufficient even for a changeover rate from the motorway as high as 70% using a maximum hourly rate of 7500 vehicles per hour as predicted in [9]. The percentage of exiting and entering vehicle is 12%. Unloading has similar conditions. The configuration of Autoshuttle with individual cabins, which are loaded and unloaded in forward direction shows a very high loading and unloading capacity.

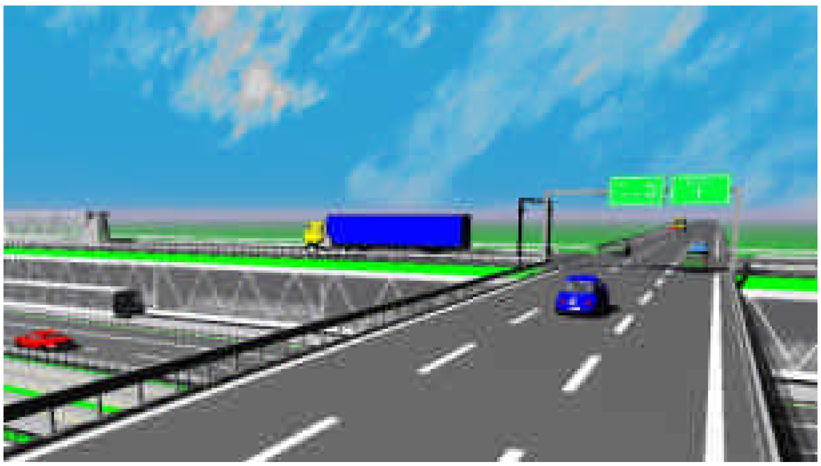


Figure 6 : Access to the Autoshuttle station

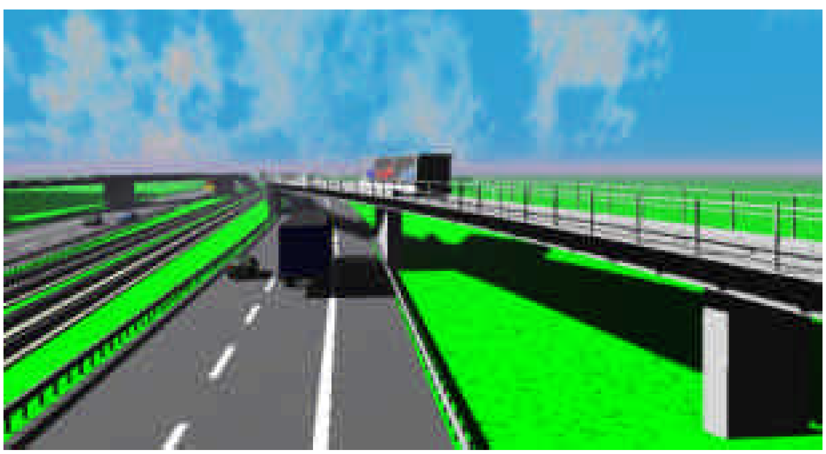


Figure 7 : Crossing the motoway towards the main line

Immediately after leaving the cabins the road vehicles reach the original ramp and get on the feeder road without any further delay. The empty cabins travel backwards out of the unloading bay, cross the access track and travel on a reversing track back to the beginning of the station. There they reverse on a stub end track and switch to the left on an adjacent switch leading to the storage yard. The beginning of the yard is in a downward slope. As shown in figure 6, the yard tracks with stored empty cabins lead in a bore under the feeder road. The tracks rise towards the entrance area on the other side of the feeder road. Cabins of each type, i. e. both cross-section types and each available length in either cross-section move via the stub end track towards the waiting track directly in front of the loading bays. On arrival and detection of a road vehicle it is then a matter of a few seconds until a convenient cabin has stopped in the bay which is signalled to the road vehicle driver and has its rear doors open. After loading, the cabin drives to one of the two parallel waiting tracks for small respectively large cross-section. When a corresponding convoy has passed the reference position on the main track, the starting cabin or small convoy accelerates, crosses over to the centre of the motorway on a bridge, see figure 7, and switches to the main track. 1400 meters behind the starting position the cabins are caught up by the through convoy.

The first and the last station of the Autoshuttle line is much larger than the shown Leverkusen station since the main traffic on the motorway has to be loaded respectively unloaded. These stations have 30 bays in each direction. Hourly loading capacity reaches for example 3270 passenger cars. When the Autoshuttle line will be extended over these end points, the former end station will become smaller. Returning loops are located at the end points and at intermediate motorway intersections at Hilden and Leverkusen.

Autoshuttle can be build almost entirely on the existing motorway right-of-way and on lost areas between motorway and ramps or within intersections. Contrarily to the conventional concept of upgrading the motorway, Autoshuttle yields almost without need of new areas a far higher traffic capacity, average speed and drastically diminishes negative effects like accidents, noise, jams, energy consumption and further emissions.

3.2 Construction Strategy

In order to minimise constraints to the motorway traffic during the Autoshuttle line's construction, some of the intermediate stations will be omitted in the first commercial operation phases. Because of the long-distance journeys which already use Autoshuttle then, the missing intermediate stations are build with lesser impact on the then reduced conventional traffic. It is economical to start operation on very short sections of the order of 15 km (9 m) already, to which further sections will be added consecutively.

3.3 Financing

Building costs and operation costs as well as the revenues were predicted for the line Duisburg-Cologne. In case of doubt due to low accuracy of the data available, conservative estimations were used. The result of this analysis shall be used for the following determination if the Autoshuttle line Duisburg-Cologne can be built and operated without subsidies. All sums are indicated in Million Euro at price level 2002.

3.3.1 Construction Costs

The construction costs were predicted based on a detailed analysis of infrastructure construction projects of the German Railways Deutsche Bahn AG. Track construction with sleepers as well as dams and cuts are very similar to classical railway lines. The load is lower however at about 4 tons per meter. Long stator drive, energy supply and operation system are based on cost indications for the former Transrapid line project Hamburg – Berlin [8]. Costs for some of the cabin's components like for example magnets could be determined very accurately. Other components were estimated based on road vehicle components due to similar production lots and construction methods. The following table shows a summary of the building costs. The line capacity is sufficient for the traffic volume as predicted and described in the following chapters.

Construction Costs	**Mio.Euro**
195 km track inclusive 1300 passive switches	103
58 bridges over roads	99
29 bores under roads	28
Long stator cable for 195 km track	47
Land purchase	26
Energy supply components	298
Buildings	65
Operation system	59
Planning, miscellaneous	79
1.862 cabins à 65.000.- Euro for a small and 570.000.- Euro for a large cabin	289
Sum	**1.093**

According to the construction strategy described in chapter 3.2 the line starts commercial operation in partial completion states two years before the final completion. Revenues from this period will be used for the financing of the last section, which will get into commercial operation four years after start of the line's construction. At an interest rate of 7,5% and a credit period of 25 years this yields annual capital costs of 112 Mio. Euro. Deduction will be financed entirely by profits as described below.

3.3.2 Revenues

The Autoshuttle line will be built and operated privately without any subsidies. Revenues result only from fares paid by road vehicle users which use Autoshuttle instead of the parallel motorway. Further attracted traffic can be expected but will not be considered in the following analysis. Traffic volume on the parallel motorway was determined based on [1] and [9]. Precondition for large revenues is a high acceptance among potential users. A preliminary acceptance survey (see [2], annex A8) shows that Autoshuttle with its features

- transport of road vehicles in cabins on dense traffic motorways
- fast
- safe, reliable and cheap

corresponds to the requirements of a very high percentage of travellers. The first and third topic listed is almost always accomplished by Autoshuttle. For very short journeys however, the total travelling time is not attractive due to the time losses connected to loading and unloading, so that only low acceptance of changing over to Autoshuttle can be expected for such journeys. Starting from this the changeover rate from the motorway to Autoshuttle has been predicted based on a road vehicle, daytime and journey length dependent analysis. Input data is:

- A comparison of total travelling times when using the motorway or alternatively Autoshuttle
- A changeover resistance towards Autoshuttle, which limits the percentage of Autoshuttle users even in the case of an advantageous Autoshuttle total travelling time
- A certain dislike of using the motorway during rush hours due to the tailback risk and during bad weather periods due to the increased accident risk

For the time dependent traffic volume on the examined motorway section the daytime and weekday dependent characteristics according to [9] were used. The distribution of the journey length on the motorway has been estimated as almost even with a small maximum at 35 km (22 m). Changeover rate mainly depends on the distance travelled on the motorway for each journey considered. For distances up to 6 km (4 m) the changeover rate is zero. During night hours the changeover rate for passenger cars reaches only 36% even for the longest journey, i. e. 56 km (35 m). Further noise reduction laws would result in an increase here however. In the other extreme, the changeover rate reaches 59% for passenger cars during the rush-hour on the longest journey. The corresponding value is 79% for lorries and buses. They have a total travelling time of 24 minutes for the 56 km (35 m) from entering the station including all waiting times until the exit from the final station. This stands against averaged 45 minutes when travelling the same distance on the motorway. Summarising, the prediction shows that 32% of all journeys will change over to Autoshuttle. Since mainly long distance journey will be attracted, this value represents 40% of the vehicle-kilometre travelled on the motorway. The percentage of lorries and buses is 28% and thus much higher than on the parallel motorway, where it is 14,4%. The remaining four-lane motorway will be used during peak hour by 1550 vehicles per lane and hour, thus somewhat less than currently so that the perturbation tendency will be diminished. Using the Autoshuttle fare model as indicated above “5% cheaper than the fuel cost and - if applicable - additionally the heavy weight tax ”, revenues of 183 Mio. Euro result. 62% of the revenue result from lorries and buses.

3.3.3 Operational Costs

The following table shows the annual operational costs. Deduction will be described in the text below.

Operational Costs per Year	**Mio.Euro**
Staff costs for 178 employees	10
Material costs for maintenance	14
Energy costs at 0,06 Euro/kWh	12
Insurances	5
Sum	**41**

The low running costs of the cabins result from their simple construction with very few rotating or hinged parts. Furthermore, it is very cost efficient for the operator to offer transport volume for road vehicles instead of seating capacity for passengers. Specific energy costs are very low due to the convoy operation with low aerodynamic drag per cabin at 180 km/h only and the minimised acceleration and brake phases.

3.3.4 Net Result

The Autoshuttle construction and operation company is profitable from the first year of operation on the full line on and achieves a profit of 23 Mio. Euro before taxes. This will increase in the following years due to constant capital cost and increasing revenues which are higher than the operational costs. Even if only 27% of the journeys, representing 33% of the road vehicle kilometres change over to Autoshuttle, full cost coverage is achieved. The predicted changeover rate is 24% higher than this value. Deduction can therefore be financed by profits. Even if only 27% of the journeys change over, deduction can be financed before end of the credit period by profits which in this case start in the second year of full line operation. If in later stages long Autoshuttle lines will be connected to a complete network, the changeover rate further increases, since mainly long distance journeys are attracted by Autoshuttle. Even lines with lower traffic volumes can be built and operated without subsidies.

The selected fare model partially offers extremely low costs for the user. The most economical Volkswagen Lupo or Audi A3 diesel compact cars would travel for example from Berlin to Frankfurt am Main for 13 Euro, the distance being 520 km (323 m). Door-to-door travelling time would be slightly more than 3 hours. In reality, most users would have to bear further costs when travelling on the parallel motorway like for example tyre use, mileage-dependent workshop costs and the mileage-dependent reselling value loss. Together with the fuel cost this sums for the example mentioned up to 26 Euro. (see [2], annex 9) The preliminary survey in [2], annex 8 shows that a very high percentage of the potential Autoshuttle users would accept if these additional costs were considered in the determination of Autoshuttle fares. Therefore, higher fares as used in above chapters are probably acceptable.

4 Conclusion

Construction of an Autoshuttle line results in a means of transport with very

- high safety
- low door-to-door travelling times
- high traffic capacity
- high reliability
- low energy consumption
- low noise emission
- low space requirements which can flexibly adapted to the circumstances

and therefore fulfils all criteria of a new means of transport. With a sample commercial line from Duisburg to Cologne it can be shown that even with pessimistic assumptions construction and operation is feasible without subsidies. Due to the excellent Autoshuttle features a high acceptance level results among the users and the line residents, since this means of transport has many intermediate stops which will offer a high speed service. Additionally, Autoshuttle will result in a drastic reduction of the motorway's traffic density and the corresponding nuisances. Because Autoshuttle can attract a high traffic volume even when construction starts in mutually isolated short lines at the most critical spots, a network can be built extending over lower traffic density sections in an subsidise-free way using reinvestments of the profits from the first lines. Thus, Autoshuttle solves one of the most urgent transport problems in a feasible manner.

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