SUPERBUS: USING AEROSPACE TECHNOLOGY TO MAKE HIGH SPEED TRANSPORT MORE SUSTAINABLE

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1. INTRODUCTION

The Superbus transport concept is being developed by Delft University of Technology in the Netherlands. It consists of a sustainable, high speed road driven vehicle for use in public transport, dedicated high speed infrastructure and advanced logistic support systems for its demand driven operation. The concept has been evaluated in the framework of the Dutch high speed connection between the West and the North of the country, the so-called Zuiderzee connection. In this evaluation procedure the Superbus was compared with other modes of high speed public transport. This paper describes the considerations which led to the start of the development of the Superbus transport concept, the Superbus transport concept itself, the assessment procedure used by the Dutch government to assess all possible modes of public transport on the Zuiderzee connection and will conclude by reporting some of the results. The focus of this paper will be on how aerospace technology contributes to the concept and has an impact on the sustainability.

2. CONSTANT DAILY TRAVEL BUDGET AND INCREASING SPEED

Empirical research has shown that on average world wide the daily travel time budget expressed in hours spent on traveling is constant. Schafer (1998) has shown that the average travel time budget is roughly one hour per day, independent of the gross domestic product per capita.
Figure 1: Daily travel time budget as a function of gross domestic product per capita (source: Schafer (1998))

For the Dutch situation the Central Bureau for Statistics keeps records of the travel behavior of the population. Figure 2 shows that based on their statistical data one can see that the assumption of a daily travel time budget of approximately one hour holds as well for the Dutch situation.

Apart from a small number of exceptions on average the gross domestic product per capita kept growing and is expected to grow in the future. This means that the average cost of a person on the move will grow as well. Therefore there will be a drive to maximize the transportation performance of transport systems. This means that the average speed in transport will show a tendency to go up as the GDP per capita increases. Combining this assumption with the constant daily travel times one could expect an increasing per capita travel volume (kilometers traveled) when the GDP per capita goes up. Empirical research has shown that this is indeed the case. Figure 3 shows this development.
Specific research into the surface travel only shows that there is a limit to this growth. At a certain moment the amount of kilometers traveled, reaches a limit. Figure 4 shows this for a number of developed countries and figure 5 for the Dutch situation. These figures show that there seems to be a limit in the growth of surface travel in developed countries.
To a certain extent this limit can be explained by the availability of space. Especially in densely populated countries the roads are more or less continuously filled with traffic jams. The Netherlands is one of the most densely populated countries of the World and at the same time has a high GDP per capita. Therefore it is likely that the Netherlands will be one of the first countries to meet these limits. The possibilities for growth in existing surface transport systems are limited. Basic economic laws say that when a good or service becomes scarce the price will go up. This means that the price of a kilometer traveled will become higher. On the other hand people will try to find alternative solutions. Over time this has been the case in transport as well. Victor and Schafer (1997) report that there is a continuous shift towards transportation modes with higher speeds. Figure 6 shows this effect
The solution man found for his mobility problems has been towards transportation modes with higher speeds. These high speed transportation modes require their own infrastructure like airports and high speed rail roads but man has shown to be able to realize them. Therefore the most likely future development is a shift towards more high speed transport.

3. TRENDS IN ENERGY NEEDED FOR TRANSPORT

Nowadays there is an increasing awareness that the energy consumption of the World’s population might have a detrimental influence on the climate. Especially
the use of fossil fuels is expected to contribute significantly to global warming and climate change. The energy used in transport forms a considerable part of the World’s energy consumption. It is therefore useful to consider what is the effect of the world wide trend of increasing speed in transport. Early research into this has been done by Gabrielli and Von Kármán (1950). They reported the specific resistance of vehicles as a function of their speeds. Specific resistance was expressed as the power required to propel the vehicle divided by its weight times speed. Figure 7 is a reproduction of their original diagram.

![Figure 7: Specific resistance for various transport modes before 1950 (source: Yong et al (2005))](source: Yong et al (2005))

Gabrielli and Von Kármán discovered a lower limit in the specific resistance. Later this was called the Gabrielli – Kármán line. No vehicle was able to have a specific resistance/speed combination below this line. Only closely coupled combinations of vehicles like locomotives with a number of carriages or a series of cars were able to show a performance below this line. Over the years the performance of vehicles has improved. Yong et al. (2005) have shown that there is a trend in which vehicles are able to show the same performance in terms of speed but with a lower specific resistance. Figure 8 shows this development.
4. LESSONS TO BE LEARNT FROM AEROSPACE TECHNOLOGY

Aircraft by their nature are required to maximize the fuel efficiency. The reason for this is the compounding effect of having to take too much fuel on board. If the aircraft is not efficient enough it has to carry additional fuel. This additional fuel requires the aircraft structure to be able to carry this. This will make the structure larger and thus heavier. A more heavy aircraft requires more lift. The price to be paid for generating more lift is more drag. More drag requires more powerful engines. These more powerful engines are more heavy and consume more fuel. Thus again additional fuel has to be carried, etc.

In aircraft design two major areas can be distinguished in which this compounding effect can be counteracted. The first area is the weight of the aircraft. Minimizing the aircraft weight will reduce the lift required to lift the aircraft. Less lift results in less fuel required. The second area is the aerodynamic drag. By minimizing the aerodynamic drag the propulsive force can be minimized. This then results in less powerful and thus less heavy engines which consume less fuel.
Thus weight reduction and aerodynamic drag reduction are the two most important factors we have to consider. In land based vehicles the weight has its result on fuel consumption in two areas. The first one being the rolling friction and the second one being the energy needed to accelerate the vehicle. The rolling friction can be calculated using the following formula:

\[ D_{\text{rol}} = \mu \cdot W \]

where:
- \( D_{\text{rol}} \) = rolling drag
- \( \mu \) = coefficient of rolling friction
- \( W \) = weight of the vehicle

One can see that the rolling drag is directly proportional to the weight of the vehicle. Reducing the weight has a direct effect on the drag and thus the energy required as energy required equals the drag force times the distance covered. The coefficient of rolling friction in general can be considered to be independent of speed. Depending on the material of the tires and the surface on which the vehicle is running the value can vary.

The energy required to accelerate the vehicle is the integral of the force needed for acceleration times the distance covered. The following formula shows this:

\[ U_{\text{accel}} = \int F_{\text{accel}} \cdot ds \]

where:
- \( U_{\text{accel}} \) = acceleration energy
- \( F_{\text{accel}} \) = force needed for acceleration
- \( s \) = distance

The force needed for acceleration can be expressed as follows:

\[ F_{\text{accel}} = m \cdot a \]

where
- \( m \) = mass of the vehicle
- \( a \) = acceleration of the vehicle

One can see that the energy needed for acceleration is directly proportional to the mass of the vehicle. Reducing the mass has a direct influence on the energy needed to accelerate the vehicle.

The aerodynamic drag of a vehicle can be expressed with the following formula:
\[ D_{\text{aero}} = C_D \frac{1}{2} \rho v^2 S_f \]

where:
- \( D_{\text{aero}} \) = aerodynamic drag
- \( C_D \) = coefficient of aerodynamic drag
- \( \rho \) = density of the air
- \( v \) = speed
- \( S_f \) = frontal area

The aerodynamic drag of a vehicle can be influenced by its designer in several ways. By making the shape of the vehicle more aerodynamically smooth the coefficient of aerodynamic drag can be influenced. The better the shape the less the coefficient will become. Typical values for road based vehicles are given in by Hucho (1998). The drag coefficient of a standard city bus is 0.55. The drag coefficient of an advanced sports car can go down to 0.3 or below. Figure 9 gives an overview of typical values.

![Figure 9: Typical values of aerodynamic drag coefficients of road vehicles (source: Hucho (1998))](image)

The density of the air decreases with increasing altitude. In aircraft the designer can choose the cruise altitude and thereby determining the density of the air. In designing road vehicles this is not a design parameter. For the time being the speed is considered to be an input parameter. The speed is a requirement based on the transport performance the people want to achieve. One could argue that reducing the speed is one way to reduce energy consumption. However the past has shown that the is a continuous demand for an increasing speed. The design challenge for the future therefore will be to increase the speed of vehicle while simultaneously reduce the energy consumption. The last design parameter is the
frontal area $S_f$. By reducing the frontal area the aerodynamic drag and thus the energy consumption can be reduced.

The lessons learnt from aviation boil down to the fact that the vehicles should be as light as possible, have a streamlined outer shape and have frontal area as low as possible.

5. THE IMPORTANCE OF INFRASTRUCTURE IN OVERALL ENERGY CONSUMPTION

When one decides to develop new transport connections one always has to take care of the necessary infrastructure. This holds for all types of transport. Road based transport systems require roads; rail based transport systems require rail roads and air based transport systems require airports. The building of this infrastructure requires energy. When one makes an assessment of the energy usage of a transport system one often limits oneself to the direct energy consumption. This is the energy used for the vehicles itself. Next to this direct energy usage the indirect energy usage has to be taken into account. The indirect energy usage is the energy used for building and maintaining all the necessary infrastructure to make it possible for the vehicles to perform their primary task, e.g. transporting persons or freight.

The overall energy usage of a transport system is the combination of the direct and indirect energy usage over the complete lifespan of the transport system. Bos (1998) has shown that the amount of energy needed for building and maintaining the necessary infrastructure can form a considerable part of the overall energy usage of the complete transport system. When one considers expanding existing transport systems or developing new transport systems this energy usage therefore has to be taken into account. This leads to the conclusion that when one decides to expand existing transport systems or develop new ones those ones which require a simple infrastructure may be favored from an energy point of view.

Next to the energy needed to build and maintain the necessary infrastructure the aspect of impact on the environment has to be taken into account. Especially in densely populated areas additional infrastructure is hard to place and often meets resistance of the population because it spoils the view. A term like “pollution of the horizon” is often used as an argument to try to stop building new infrastructure. Taking this into account the challenge for the designers should be to minimize the environmental impact of new infrastructure. This could also influence the choice for the type of transport system to be chosen.
6. CURRENT SITUATION IN VEHICLE DESIGN AND CHALLENGES FOR THE FUTURE

Van den Brink and Van Wee (2001) have shown that the car-fleet specific fuel consumption has not shown any decrease anymore since 1990. Although the engine specific fuel consumption still is decreasing the fleet performance does not improve anymore. The reason for this is that the improvements in engine performance cannot match the increasing mass and thus increasing fuel consumption of the average car. The reason for this being the additional mass the designers put in the cars because of comfort and safety requirements as well as the trend to buy larger cars with increasing wealth. Unless regulations on this will change it is not expected that this will improve. Van Kampen (2003) has shown that the average weight of all road vehicles has gone up. This not only holds for passenger cars but also for commercial vehicles like buses and trucks. He concludes that since 1985 the average weight of cars has gone up by 12%, that of buses by 14% and that of trucks by 27%. As the reason for this he quotes the increase in comfort as well as the increase in safety.

One can define a weight efficiency of a vehicle as the ratio between the empty weight of the vehicle and the so-called payload. The payload is the cargo and/or passengers carried by the vehicle. Table 1 gives an overview of this ratio for a number of vehicles. The smaller the ratio the better the performance of the type of vehicle is.

Table 1: approximate values for weight efficiency of vehicles

<table>
<thead>
<tr>
<th>Type of vehicle</th>
<th>( \frac{W_{\text{empty}}}{W_{\text{payload}}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bicycle</td>
<td>0.3</td>
</tr>
<tr>
<td>Bus</td>
<td>3</td>
</tr>
<tr>
<td>Car – average</td>
<td>3 - 12</td>
</tr>
<tr>
<td>Car – luxury</td>
<td>8 - 27</td>
</tr>
<tr>
<td>Subsonic aircraft</td>
<td>4 (70% utilization)</td>
</tr>
<tr>
<td>Light rail</td>
<td>8 (70% utilization)</td>
</tr>
<tr>
<td>Intercity train</td>
<td>10 (70% utilization)</td>
</tr>
</tbody>
</table>

The table shows that bicycles and buses are the most weight efficient types of vehicles. The trend in rail transport to make use of light rail concepts will not lead to weight efficient transport. Although the rolling friction will be less than that of road vehicles the energy needed for acceleration plays a significant role in the overall energy consumption.

The challenge for the future will be to address four issues simultaneously. Firstly the passengers would like to see the speed go up. Secondly the amount of energy consumed must be reduced. Thirdly the total energy supply must become sustainable. In trying to meet these challenges one could make use of the lessons learnt from aviation. Fourthly the impact of the necessary infrastructure
has to be taken into account. This holds both for the energy required to build and maintain is as well as for the environmental impact it will have.

7. THE SUPERBUS TRANSPORT CONCEPT

Currently Delft University of Technology (DUT) in the Netherlands is investigating a new transport concept that might be able to meet some of the challenges mentioned in the previous section.

7.1 Innovative aspects of the concept: vehicle, infrastructure and logistics

The Superbus transport concept has four main aspects: (1) the vehicle, (2) the infrastructure, (3) the logistics and (4) the combination of these three in a transport system. The innovative character of the Superbus concept primarily can be found in a smart combination of existing technologies. The technologies themselves are not new but the combination in one vehicle is. The Superbus technology is based on a combination of aerospace technology and information and communication technology (ICT). The aerospace technology can be found in a refined aerodynamic shape and a light weight structure. Secondly the use of infrastructure is innovative. Superbus will partly make use of its own dedicated lightweight infrastructure for high speeds but will also use existing roads where it will obey the current speed limits. Thirdly the (non-existence of a) time table is innovative: the logistics will be demand driven and highly ICT supported. Finally the combination of these aspects is innovative. The concept also allows or probably even needs evolutionary growth. One can start simply using existing infrastructure and gradually extend the system, it is not limited by the requirement of a fully completed new infrastructure.

![Figure 10: Artist impression of the Superbus](image-url)
7.2 The Superbus vehicle

Superbus aims to be an innovative and sustainable road driven high speed vehicle for public transport. The typical design range of the vehicle is 30 to 200 km. The concept was invented in 2004 by prof. Wubbo Ockels of the Faculty of Aerospace Engineering of Delft University of Technology (DUT) in the Netherlands. The concept consists of an advanced vehicle capable of driving 250 km/h, a dedicated light weight infrastructure called Super track and the application of ICT for logistics, handling, comfort and safety. The Superbus itself will be an electrically driven vehicle with a seating capacity of 20 to 30 passengers. With respect to its size it complies with current regulations for buses, no longer than 15 m, no wider than 2.55 m. The height is however limited to 1.7 m which reduces frontal area and therefore the aerodynamic drag and energy consumption. Passengers will board the vehicle like they do in normal car via doors on the side of the vehicle. For this the vehicle body will be raised by 35 cm. By means of a combination of streamlining and a relatively small frontal area the power required for this vehicle at 250 km/h is comparable with that of a normal bus at a speed of 100 km/h. By refining the outer shape of the vehicle the noise production will be minimized. The limits the usage of noise screens. The concept has been described in Ockels and Melkert (2004) and Melkert (2006a).

![Figure 11: Side view of the Superbus vehicle](image)

7.3 Infrastructure

Since the Superbus drives on rubber tires and meets current regulations with respect to sizes it can reach inner cities as well as local roads and highways. Where the Superbus will use its high speed dedicated infrastructure will be required from a safety point of view and because of regulations. The Superbus is a relatively lightweight vehicle (axle loading less than 3 tonnes) and the high speed infrastructure will exclusively be used by similar vehicles. That means a relatively simple and light weight infrastructure will be sufficient. This high speed infrastructure has been named Super track. It for instance could exist of a relatively simple concrete structure. This simple structure requires a minimum energy use in building and maintenance. Next to that the environmental impact is minimized since it requires no overhead wires, no deep foundation and a minimal usage of noise screens.
7.4 Logistics

The Superbus logistics is based on a demand driven transport. Demand driven transport has been applied and investigated several times. Terminology often used for these type of systems is Demand Responsive Transport (DRT). Other terms used are dial-a-ride or dial-a-bus. Enoch et al. (2000) give an extensive overview based on 74 examples. Many applications can be found in the transport of elderly and disabled people in rural areas. Evers (2005; 2006) also gives an overview of applications realised. He concludes that a cost effective operation requires some combination of demand in one vehicle. This poses problems for the operator since he will not always be able to combine demand either because the demand itself is too small or the system cannot match supply and demand fast enough. Mageean and Nelson (2003) conclude that dial-a-ride systems are often confronted with high costs, a lack of flexibility in route planning and an inability to handle high traffic flows. They argue that these downsides can be overcome using information and communication technology (ICT). In the framework of the European programs SAMPO (System for Advanced Management of Public Transport Operations) and SAMPLUS (System for Advanced Management of Public Transport Operations Plus) they developed a telematics-based DRT system (Nelson and Magean, 1998). They conclude that the wide use of ICT has a beneficial effect on the operation.

In the Superbus system wide use of ICT for the combination of supply and demand will be used. Still, sufficient demand will be a key issue for the cost-effective operation of the system. Only connecting rural areas with each other will not lead to a cost-effective operation. In the Superbus system customers could indicate their wishes via internet or SMS. A central server would couple these demands to the available vehicles and make the customer one or more offers. Where there would be a constant demand a constant supply, a fixed schedule could be offered.

7.5 Combination of aspects and possibilities for evolutionary growth

The combination of three different areas of innovation is innovative in itself: vehicle technology, infrastructure and logistics have been combined in this concept. Next to that Superbus also offers the possibility of an evolutionary growth. In a railway system the vehicles can only start driving when the complete dedicated infrastructure has been completed. The Superbus logistic concept allows to start right away using existing infrastructure and gradually extending it with new dedicated infrastructure. For other aspects like logistics this holds as well. However, one has to take care that the average speed is high enough to beat other existing transport systems. In areas with frequent traffic jams this requires the usage of the hard shoulder or dedicated lanes during rush hours. The Netherlands have existing legislation in place allowing this.
Due to the fact that the vehicles drive on rubber tires, they can use existing infrastructure although in that case its speed will be limited to current speed limits. The high speed infrastructure can be built gradually and over time the average speed of the vehicles during a trip can increase over the years. Depending on the success of the concept and the available budgets a phased extension of the high speed infrastructure can be realised. This approach has financial benefits because it saves interest and reduces the risks compared to constructing all new infrastructure in one go.

The economic life span of a Superbus vehicle is estimated at 3 to 4 years (Melkert, 2006b). This economic life span has been estimated based on the life span of conventional buses. Their life span is based on a number of kilometres driven. This number has been used for the Superbus as well. Since the production of kilometres per unit of time is relatively high the life span is relatively short. In practice this will mean that some part of the vehicle, like drive train will have reached their technical end of life while some other parts like the chassis could be used for longer periods. For the time being it is assumed that the whole vehicle has to be replaced after reaching the number of kilometres set. This conservative approach increases the vehicle costs for a service but it also allows replacing vehicles by more modern ones relatively easy. This makes it possible to technologically innovate continuously. In this way the speed on the high speed infrastructure can be increased in smaller steps over time. For instance the system could start at a speed of 150 km/h and gradually move towards the target speed of 250 km/h.

7.6 Sustainability aspects of the concept

In developing the Superbus transport concept sustainability has been used as one of the boundary conditions. In that way the four challenges for the future mentioned in one of the previous sections can be met. The vehicle is designed such that energy use is minimized. A refined aerodynamic shape and a light weight structure make it possible to both increase the speed and limit the energy usage. Figure 12 shows a comparison with other high speed transport modes where energy usage is expressed in terms of energy consumption per seat-kilometre.
The propulsion system used will be a full electric system based on the use of four electric motors and a battery pack to store the energy. This has two advantages. Firstly electric motors have efficiencies well over 90% where internal combustion engines have efficiencies between 20 and 35% depending on the operating condition. Secondly the use electricity makes the system compliant for us with sustainable means of energy conversion. The necessary electricity can be generated by means like solar panels, wind turbines, etc.

Next to the energy consumption for building and maintaining the infrastructure is minimized because of the simplicity. The design philosophy of the concept is such that all the intelligence will be placed in the vehicle and therefore the infrastructure will not require extensive safety measures to be built in. Next to that the dedicated high speed infrastructure is limited in size and purpose designed for light weight vehicles. It thus requires no heavy and energy intensive infrastructure.

### 7.7 Superbus and the Zuiderzee connection

A new concept brings new chances but also many uncertainties. In that sense a unique chance was given to the concept mid 2005. The Superbus concept was given the opportunity to take part in the second assessment of the Zuiderzee connection in the Netherlands (Verkeer en Waterstaat, 2006a). The intention of the Zuiderzee connection is to connect the densely populated Western part of the country, Amsterdam and its surroundings, with the more rural parts of the country in the North, the province of Groningen. Figure 13 visualises the possible new connection.
This connection is already under consideration since the end of the 20th century. Recently the second Cost and Benefit Analysis (CBA) for the Zuiderzee connection has been published (Ecorys, 2006). This new assessment was needed in order to help the decision making process. One of the important changes with respect to the earlier CBAs of the Zuiderzee connection was the addition of a new transport alternative, the Superbus concept.

The majority of Parliament asked the Minister of Transport and Public Works to officially add the Superbus to the list of possible alternatives being investigated for this connection. Other alternatives under consideration were a magnetic levitation train, a high speed train and upgrades of existing rail road connections. This has given DUT a unique opportunity to bring this concept to the test in a relatively early stage of its development. It must be taken into consideration that DUT is to be considered the developer of the concept, not an interest group or a company who has an interest in the implementation of the concept. DUT will never start the production of Superbus vehicles or start a public transport service with Superbuses. Therefore DUT played a neutral role in this assessment of the Zuiderzee connection. During the assessment the other alternatives were optimized as far as possible. This could be done because an earlier CBA performed in 2000 had shown both strong and weak points (NEI, 2000). For the first assessment reference is made to Van Wee et al. (2003). For Superbus such an optimization was not possible since the concept is in an early stage of its development.

After finalizing the structure vision the government concluded that in comparison with the other transport alternatives the Superbus performed best with respect to costs of infrastructure, environmental impact and the amount of passengers transported (Verkeer en Waterstaat 2006a and 2006b). It therefore decided to
invest in a research and development program for the Superbus transport concept.

7.8 Superbus development overview

Although not directly necessary for the assessment of the Superbus concept in the framework of the Zuiderzee connection it is useful to give an overview of the development of the concept. The concept was invented in 2004. The development started with an assessment of the feasibility of the Superbus at the conceptual level. This has been done by means of interviewing 35 experts from industry and universities. They were presented the concept and asked for their opinion and suggestions for improvement. This resulted in a report called “dossier Superbus” (Ockels and Melkert, 2004). In this report the authors concluded that the concept in principle is feasible. The improvement suggestions of the experts have been used for further development.

DUT is now building a full scale experimental demonstration vehicle. It is intended to have this vehicle ready in 2008 and show it to a world wide public during the 2008 Beijing Olympics. With this demonstration vehicle it is the intention to show the technical feasibility of the vehicle itself. This is done because experience has shown that many people have the tendency to react in a sceptical way when confronted with a new innovative concept. If one takes the time to study the concept more thoroughly normally scepticism reduces. However experience has taught that people can only be convinced when they are able to touch and feel the product.

8. CONCLUSION

Passenger transport in the future has to meet a combination of challenges: higher speed, less energy consumption, move towards sustainability and have an infrastructure with minimal environmental impact. The Superbus transport concept might be able to contribute in meeting these challenges. Aerospace technologies like light weight structures and refined aerodynamic design of the outer shape of the vehicle play a major role in this.

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