Technologies for a modular vehicle concept used in passenger and goods transport.

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Current situation and challenges

At the beginning of the year 2019, vehicles with diesel internal combustion engines (Euro 4 or older) have been banned from entering the city of Stuttgart. This is the temporary climax of current efforts to address traffic-induced air pollution. More than 500 sanctions in several European cities try to ban private cars from cities. Most likely, a lot of today car-owners will switch to public transport in the future, thus increasing the issue with peak-times. During these phases (primarily commuting) the public transport is overstrained. During "off-peak"-phases equipment like busses operate very inefficient or stand idle in the operators' depot. New vehicle concepts are required to support the operators in on-peak-phases or revolutionize the transportation system completely.

However, not only the individual and public transport is affected by this transition, but also commercial traffic. This is in contrast to the steadily growing transport volume of goods. For instance, the market for parcel delivery grew by 96% from 2000 to 2017 [1]. New urban transportation systems to solve these issues are under development: e.g. new city hubs with truck swap bodies, more small electric vehicles, or freight bicycles for the last mile. There are several indicators showing that future vehicle concepts should combine automated urban delivery and people transportation; e.g. the European Commission is asking clearly for the new design of innovative shared, connected, cooperative and automated vehicle concepts for mobility of people and delivery of goods [2]. On a vehicle-level, some players in the automotive market have already presented scalable and modular vehicle concepts (Figure 1). These vehicle concepts as well as the corresponding business models to address urban traffic issues are discussed in [3].

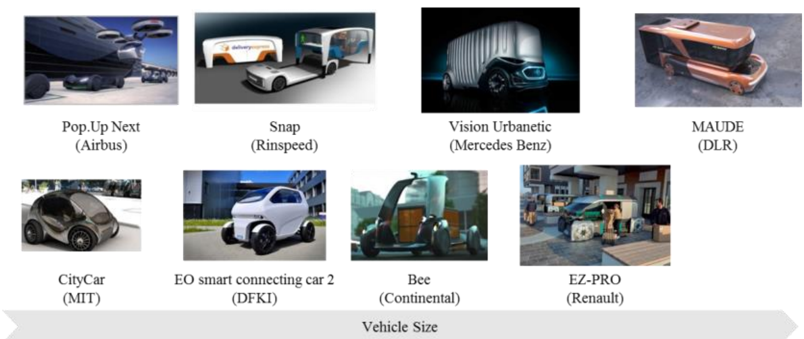

Figure 1: Vehicle concepts with scalable and modular structures
(source: own compilation based on [4]).

Figure 2 shows ideas for a better transport mode transition based on new on-the-road modular vehicle concept ideas. Our proposed vehicle concept, which is described in the following sections, follows the modular approach.

Figure 2: Vehicle concepts with different possibilities to separate driveboards and capsules (own visualization).

A novel on-the-road modular vehicle concept: MAUDE

The German Aerospace Center, Institute of Vehicle Concepts proposes a disruptive vehicle concept (MAUDE[1]) for transporting people and goods which is based on dynamic on-the-road modularization. Since it is designed for various applications, it offers answers for many areas of today's urban traffic. Our system is derived from a demand analysis to enable a successful business development in the urban transportation sector. The concept consists of an autonomous and electrified driveboard and separated capsules for the transportation of goods and people (Figure 3). Key functions have been designed more usable compared to other modular concepts (Figure 1): for instance, standardizable multi-purpose capsules or a driveboard-based lifting system. Other modular vehicle concepts are discussed in [3].

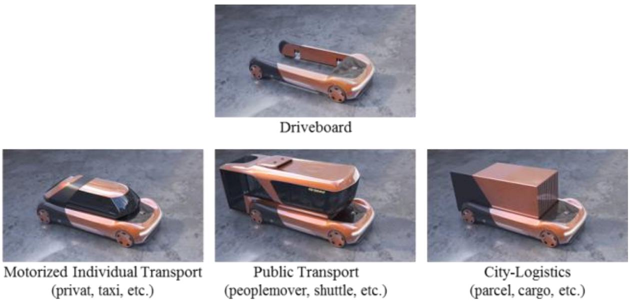

Figure 3: MAUDE – driveboard and capsules for various applications (own visualization).

[1] Modular, Autonomous, Updateable, Disruptive, Electric

The main USP of the MAUDE concept is the interface between the capsules and the driveboard in form of a U with an integrated lifting system, which reduces the costs for the capsules and avoids expensive infrastructure – this is a major distinction to existing concepts which include the lifting system in the capsules or use handling robots. However, this results in a sophisticated packaging, because the driveboard's space is very limited. Our approach offers the possibility of depositing and exchanging capsules on the ground without a lifting unit integrated in the infrastructure or in the capsules. This allows for effective and fast loading of cargo capsules on ground-level, e.g. with a trolley, which is especially useful for urban operation. The rear opening of the driveboard's structure offers the further advantage that capsules with different lengths can be transported with the MAUDE concept.

For the capsules a variety of different designs is possible: capsules for the transportation of passengers, parcels, waste, construction tools, etc. [3]. The people capsules must have their own distributed energy storage for the supply of heating, air conditioning, electronics, lighting, etc. As the passenger pods mounted on the side are designed with overhang, pods also have advanced vehicle sensors for autonomous driving on board. Simple cargo capsules come without an overhang, but can be built very easily and inexpensively without further electronics, similar to an ISO-Container.

The following sections will give an overview to the key topics of the MAUDE vehicle concept, form structural design, drivetrain, and possible automation concepts.

Structural design of the vehicle concept

By separating the driveboard from the capsules, the necessary requirements plays an essential role to define and optimize different levels of modularization as well as to design the concept for loading and unloading (possible variations: laterally, from behind, from the front, from above) but also for getting in and out of persons (possible variations: from behind, from front, from the side).

These further functionalities of the vehicle concept lead in particular to additional weight which has to be compensated in order to realize the necessary payload and axle loads (Figure 4). When comparing a conventional vehicle with a battery electric, autonomous vehicle, the additional weight e.g. for the energy storage and additional features for automatization reduces the payload. If the modularization is added, the payload drops again. This additional weight due to the modularization must be countered with intelligent and economical lightweight construction.

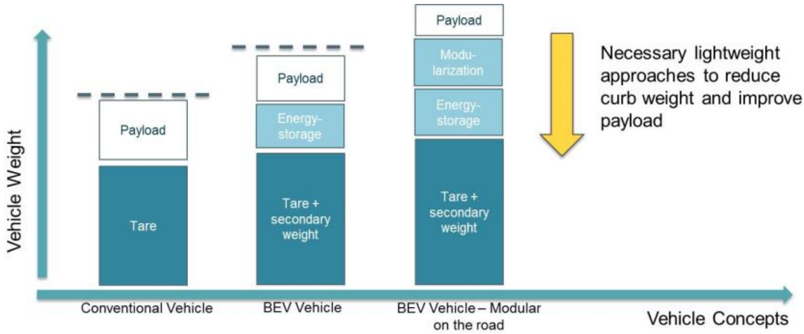

Figure 4: Necessary lightweight construction to ensure the necessary payload, axle loads and resource conservation [5].

In order to analyze the necessary load paths, which are effective for different vehicle concepts and package specifications, structural optimization procedures were used. This is essential to derive mechanical interfaces and load carrier points of the driveboard and capsules in detail (Figure 5). Based on simulation results (e.g. structure optimization in relation to vehicle torsion and bending), the first concept designs for a selected driveboard were implemented and analyzed (Figure 6).

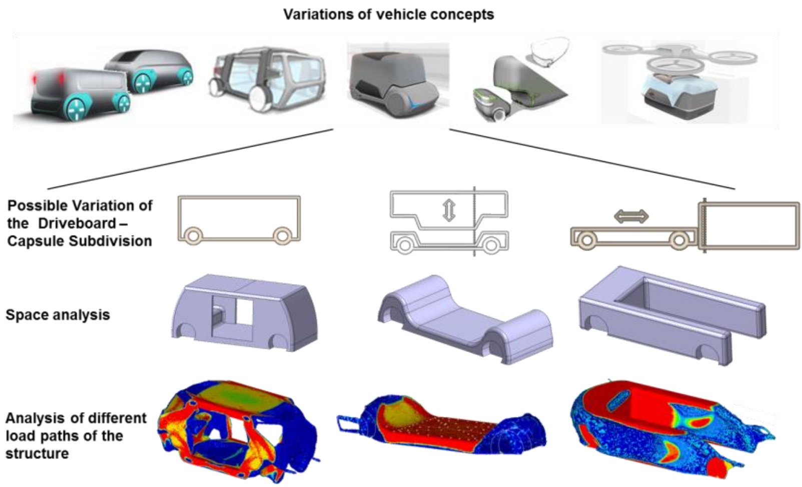

Figure 5: Load path analyzes for different requirements and package specifications [5].

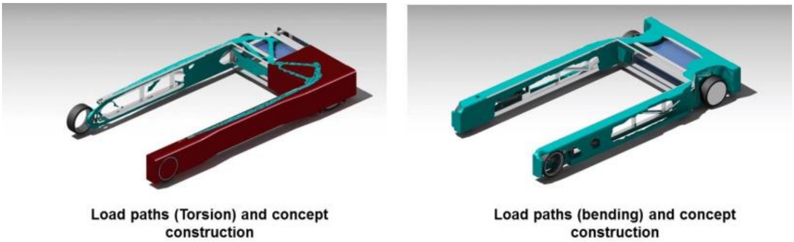

Figure 6: Structural analyzes and concept designs for different load assumptions (excerpt; own visualization).

Requirements and concepts for the drive system

An urban, modular-on-the road vehicle concept is a unique solution and requires a closer look to the driveline design. The following figure based on an initial MAUDE study gives a first overview with (1) rear wheel with suspension, (2) front wheel drive and (3) battery:

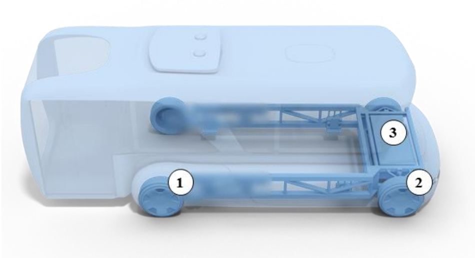

Figure 7: Driveline components (own visualization).

There are some important restrictions which have to be considered. The performance of the drives of a driveboard could be low compared to usual conventional vehicles in this size. A “Sprinter size” MAUDE application has a drive with 2*45 kW and 1600 Nm at the wheel and allows a max speed of 70 km/h and a grad ability of 20% and 6% at 60km/h. Based on the planned use cases [3], these are fully sufficient values. The urban application defines the max speed of about 70km/h (with 8% grade) and max. 20% grade should be sufficient for urban regions (e.g. garage ramps). Usual values above of 40% and more are defined as not relevant for the application (no rutted lanes or no start at road curbside).

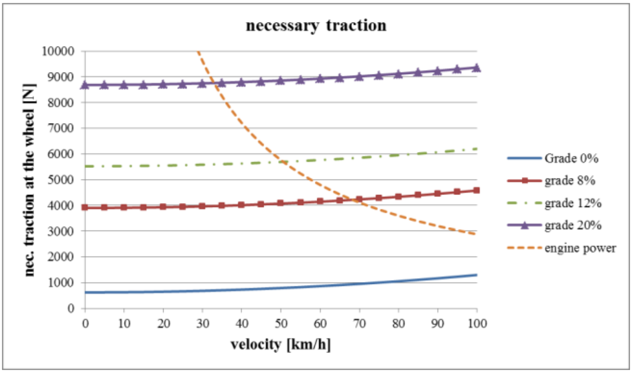

Figure 8: Requirements for the powertrain (own visualization).

Battery and energy management

The new modular design opens new opportunities for the energy management. As shown in the schematic Figure 9, the MAUDE concept uses capsules with own batteries. To increase the usability the stand by time for charging of the driveboard should be as low as possible. A usual approach is the use of high power chargers with the known disadvantages of installed power, reduced battery lifetime, or costs. We follow a new way and equip some of the capsules with an own battery systems.

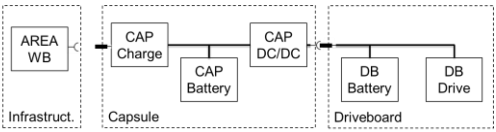

Figure 9: Energy Supply concept (own visualization).

Use-case investigations show, that the number of capsules is much higher than the number of driveboards (1/3 … 1/10 depending on application) [3]. The capsule could be charged in the infrastructure in hubs or at customer site with low power and sufficient time, so charging infrastructure cost are low. During normal operation the driveboard can drive with capsules without batteries, so driving range is limited by driveboard battery capacity. During the day the overall operational control manages several transport tasks with capsules with battery. In this case the driveboard battery will be charged via a converter by the capsule battery. Typical capsules with batteries could be e.g. passenger capsules or refrigerator goods capsules. In these both examples there is an additional energy demand for the use case, heating and cooling for cabin climate or cooling of goods.

This new system and the different combinations of driveboards and capsules have some more design parameters which have to be defined. For the additional degree of freedom new design rules have to be defined. Based on vehicle size and usual vehicle design parameters known from existing EVs, the energy consumption will be appr. 30 kWh/100km (Table 1). With the assumption of an overall average speed of 25 km/h (a typical urban bus line during week day has an av. speed of about 15-20 km/h) a daily distance of 600 km at 24/7 operation is possible. For autonomous vehicles with this maximum utilization, battery size and charging during operation are very free to design. A quite suitable battery size for the driveboard will be an 8h shift operation with a capacity of 60kWh. The necessary energy of 180kWh for a whole day operation will cause to large battery sizes for the driveboard, so for a full 24h autonomous operation, the disposition of capsules during the day operation has to be managed in this way that during a shift a capsule with a battery has to be operated. Depending on the use-case and capsule type different capsule design configurations are possible.

Table 1: Initial battery design estimates.

DB: Specification, Performance		
Energy consumption	30	kWh/100km
Average speed	25	km/h
Average power	7,5	kW
DB: One battery load		
Battery Capacity	60	kWh
Range	200	km
Operating time	8	h
System: Daily energy, range		
Energy/day	180	kWh
Range/day	600	km
CAP: Battery v1		
Battery capacity	60	kWh
DC/DC - Power	20	kW
No C * Operating time	3 * 3	h
CAP: Battery v2		
Battery capacity	60	kWh
DC/DC - Power	60	kW
No C * Operating time	3 * 1	h

The simplified table shows the impact: e.g. for a passenger capsule which will be used in an on-peak public transport operation, the operating time will be presumed 3h and during this time the Driveboard-battery (DB-Battery) has to be charged with 60kWh in the related shift. So Capsule-Battery (CAP-Battery) will be 60kWh+x (x for 3h cabin operation, climatisation, etc.) and installed DCDC Inverter Power is only 20 kW for continuous and effective charging of the DB-Battery. Operational estimates show that for some longer PT on-peak shift passenger capsules could be sufficient but might be critical for night operation, so some of the goods capsules have to be equipped with a CAP-Battery. The table CAP-Battery V2 shows the simple difference. Goods capsules in general have a much lower operation time in the DB e.g. on the way from hub to customer. With the exemplarily assumption of 2-way delivery a 30 min driving the energy for the 3rd shift has to be transferred from CAP-Battery to DB-Battery in one hour resulting in a DCDC Inverter Power of 60 kW.

As shown in the chapter above, the wheels will carry in coupled state and max. payload the biggest share of the load. So normally the rear wheels of a vehicle could be equipped with twin wheels. However, the concept in Figure 7 does not allow a large wheelset due to the limited width of the alongside stage. Considering a further specification point, the available space in the rear wheel section is very limited. An integration of an electrical drive is very challenging.

The location of the heavy driveboard battery of the vehicle (Figure 7) could be disposed in the head of the driveboard. There are several reasons for this position. A packaging in the stage in general is possible but only with an ineffective and expensive subdivision in modules. The place in front has the big advantage of load on the front axle and, more important, reduces the load of the critical rear wheels and allows a bigger overhang at the back.

These design discussion shows the complexity of the overall energy system design. It depends very strong on the use-cases and has to be designed individually for each city application. However counter-arguments are known. It is obvious, that the overall system capacity is higher than the quick charging solution, but the first business model calculations show a cost advantage for the capsule battery solution for highest utilization. Furthermore a positive impact on lifetime of the battery is expected. Experience with 24h operation of battery systems in autonomous vehicles does not exist worldwide. So relative continues operation without temperature spikes (during quick charging) is positive for the lifetime of each technical system.

Automation of the vehicle concept: first considerations and deriving of research questions

Urban, on-the-road modular vehicle concepts are basically designed for full autonomous operation. The driveboard itself is more a robot without a driver workplace or seat and the capsules are also not equipped with a steering wheel etc. According to SAE Standards the concept will be designed for SAE 5 level.

Compared to today’s autonomous movers our concept likes to follow an unconventional way not only in the design but also in the field of automation. We try to find an optimum for the location of the “automation control” between vehicle and infrastructure. Nearly all of the autonomous vehicles which have been demonstrated up to now have vehicle control system for operation and safety on different layers mainly installed in the vehicle. This usual approach results in a huge number of vehicle sensors and very high computation power in the vehicle. Considering the evolutionary development during the last years, integrating more and more ADAS (Advanced Driver Assistance Systems), and existing safety standards, this is a reasonable way established carmakers have to go. However, some applications have been presented where the vehicle control is managed within the infrastructure. Bosch has already demonstrated its valet parking based on infrastructure supervision and only using simple vehicles sensors and actuators [6].

There are different drivers to follow within our automation concept. Based on geometrical reasons it is appropriate to mount a variety of sensor at the top or in upper corners of the vehicle to get the best picture of the surrounding situation. However, we have analyzed from a business case of view, that most necessary components should be placed in the driveboard and not in the capsules. The business model estimates have led to the conclusion that the capsules should be as cost-effective as possible due to the much higher number of capsules compared to the driveboards. Driveboard with sensors is close to 100% operation rate while capsules only 5-20% depending on use-case. So, only very cheap commodity sensors should be allowed.

A further aspect for specifying automation control in the infrastructure is the unsymmetrical design. We use different capsule sizes: long capsules for passenger transport (side entrance) and goods transport are allowed to protrude the driveboard. As Figure 10 shows, the driveboard with the long capsule (1) has a surrounding sensor view (2) but a sensor shadow at the back (3).

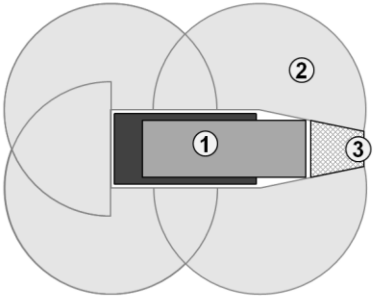

Figure 10: Driveboard and capsule with sensor view (own visualization).

In normal forward operation this is usually not critical but for maneuvers like reverse driving and unloading the automation needs sufficient sensors for control and safety. Thus, it could be a possibility to install hubs, where the vehicle has to park backwards as smart zones (Figure 11). The MAUDE vehicle (1) drives for loading and unloading in a smart zone (2) where e.g. several cameras (3) are used for control.

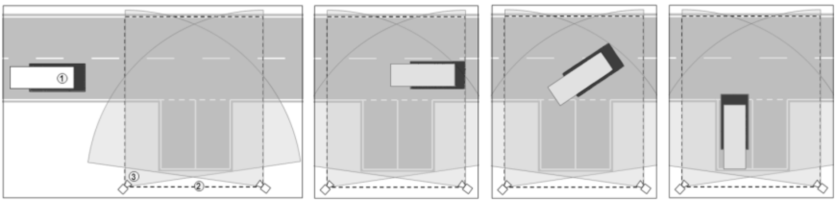

Figure 11 Traffic Sequence Chart – Unloading in smart zone (own visualization).

The general discussion of "Autonomous Control" installed in the vehicle and / or in the infrastructure is ongoing. The research question is: Which are the advantages and disadvantages for solutions with focus on vehicle or infrastructure support for urban automated driving. In our specific on-the-road modular approach it is very important to determine how many (if any) sensors need to be installed in the capsules. The best and cost optimized solution is still open and has to be investigated in further research.

Summary

This paper shows a new highly on-the-road modular vehicle concept. Based on demand analyses and inquires with different user groups, we have specified the vehicle and done a first conceptual analysis. We discussed generally the impact of modularity on the weight of the overall vehicle and outlined a lightweight design approach. A load path analysis shows the stress of components compared to other vehicle concepts. The urban driving performance results in a very moderate design of the powertrain. The unique approach with a split battery in driveboard and capsule allows a real 24/7 operation of the driveboard. Furthermore, we discussed different automation concepts. This specific on-the-road modular approach is unique and has been evolved by the German Aerospace Center, Institute of Vehicle Concepts. Further conceptual work will be continued together with additional research partners.

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