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ELECTRIC ROAD VEHICLES – OVERVIEW, CONCEPTS AND RESEARCH AT REUTLINGEN UNIVERSITY

The paper details the architecture of fully electrified vehicles as well as their new electronic systems. Examples of up-to-date electrical passenger cars are given. A very important question, that is the environmental foot-print of electrical vehicles compared to conventional ones, is examined. A research project is introduced where a fleet of two-wheeled vehicles is available for day-to-day use. Research on vehicles, software for fleet management and battery range prediction is described.

В даній статті наведено докладні відомості щодо принципів роботи електрифікованих транспортних засобів, а також описано їх нові електричні системи. Показано приклади вже існуючих електричних пасажирських транспортних засобів. Розглянуто вплив електрифікованого транспорту на навколишнє середовище у порівнянні із звичайними видами транспорту. Наведено проект досліджень, у рамках якого існує парк двоколісних електрифікованих транспортних засобів для щоденного використання. Описано дослідження, безпосередньо пов'язані із електрифікованим транспортом, визначенням точного часу розряду батареї, а також програмним забезпеченням, що дозволяє керувати парком таких транспортних засобів.

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INTRODUCTION

Limited availability of natural resources and environmental problems caused by pollution have raised a global discussion concerning alternative technologies for locomotion. There are many studies available, ranging from vehicles with fully electrified powertrain up to systems using electrical energy for only partly supporting an internal conventional combustion engine. Battery-based electrical vehicles (BEVs) are examples for the first group, whilst hybrid electrical vehicles (HEV) can be categorized to the latter one. Plug-in hybrid vehicles (PHEV) have an exceptional position in this classification, because they provide two independent drive concepts. For short distances, driving power will solely be provided by an internal battery, which will be substituted by a conventional combustion engine generator, when battery capacity is close to deplete. Due to the enormous amount of technologies available on the market this study must be limited in its scope. The authors have chosen to focus their investigation only on BEVs. The idea of electrically powering an automobile is not new and has achieved its peak level in the beginning of the last century. It is quite interesting to note that during this time electric vehicles were seen in advantage compared to gasoline cars. In the early 19th century, they dominated the vehicle registration numbers with a ratio of 3:1 [1]. Figure 1 shows an interesting concept of an electric car, which was presented on 14th April 1900 at the automotive world exhibition in Paris. It was named after its designer Ferdinand Porsche who was employed at the machine factory Jakob Lohner & Co in Austria. Its front wheels were driven by two single hub motors. The power of the electrical motors was specified with each 2.5hp at 120rpm. A 44 cell battery with a capacity of 300Ah and a nominal voltage of 80V allowed a driving range of up to 50km at a maximum speed of 50km/h. The weight of the vehicle was specified with 1000kg, including the battery with 410kg. The vehicle was far ahead of its time and the principle of hub motors, which was also developed by Ferdinand Porsche, was later even used in space by the NASA to drive their moon vehicle. However, electric vehicles have never been mass produced mainly due to their limitations concerning driving range and missing infrastructure for recharging the batteries. In the past century, oil has been considered as a cheap and nearly unlimited source of energy. Further efforts in the development of improved electrical vehicles have therefore been neglected. Today this situation has changed dramatically. The global demand of oil is continuously increasing and political and economic issues do stroke fears of shortage. The



Figure 1: Lohner-Porsche battery driven electrical vehicle [2]

will be substituted by a conventional combustion engine generator, when battery capacity is close to deplete. Due to the enormous amount of technologies available on the market this study must be limited in its scope. The authors have chosen to focus their investigation only on BEVs. The idea of electrically powering an automobile is not new and has achieved its peak level in the beginning of the last century. It is quite interesting to note that during this time electric vehicles were seen in advantage compared to gasoline cars. In the early 19th century, they dominated the vehicle registration numbers with a ratio of 3:1 [1]. Figure 1 shows an interesting concept of an electric car, which was presented on 14th April 1900 at the automotive world exhibition in Paris. It was named after its designer Ferdinand Porsche who was employed at the machine factory Jakob Lohner & Co in Austria. Its front wheels were driven by two single hub motors. The power of the electrical motors was specified with each 2.5hp at 120rpm. A 44 cell battery with a capacity of 300Ah and a nominal voltage of 80V allowed a driving range of up to 50km at a maximum speed of 50km/h. The weight of the vehicle was specified with 1000kg, including the battery with 410kg. The vehicle was far ahead of its time and the principle of hub motors, which was also developed by Ferdinand Porsche, was later even used in space by the NASA to drive their moon vehicle. However, electric vehicles have never been mass produced mainly due to their limitations concerning driving range and missing infrastructure for recharging the batteries. In the past century, oil has been considered as a cheap and nearly unlimited source of energy. Further efforts in the development of improved electrical vehicles have therefore been neglected. Today this situation has changed dramatically. The global demand of oil is continuously increasing and political and economic issues do stroke fears of shortage. The

electrification of the automobile is considered as the most promising technology for our mobile future. However, there are still major (technological) challenges, e.g., in terms of maximizing range anxiety, battery costs, charging time and the construction of a sustainable energy supply.

STATE OF THE ART IN ELECTRIC MOBILITY

Architecture of E-cars

The basic architecture of an electrical passenger car is presented in **Ошибка! Источник ссылки не найден.** Of course, there are possible variations of this architecture but the presented structure seems to be quite common. First of all, the conventional combustion engine is replaced by one or more electrical motors which are directly driving the wheels. Neither manual nor automatic shift gear boxes are in use. The motors get their electrical energy from high voltage batteries or battery packs via power electronic inverters, which are or should be able to recover electrical energy during deceleration phases. For the high voltage electrical components and wires in a car, particular safety

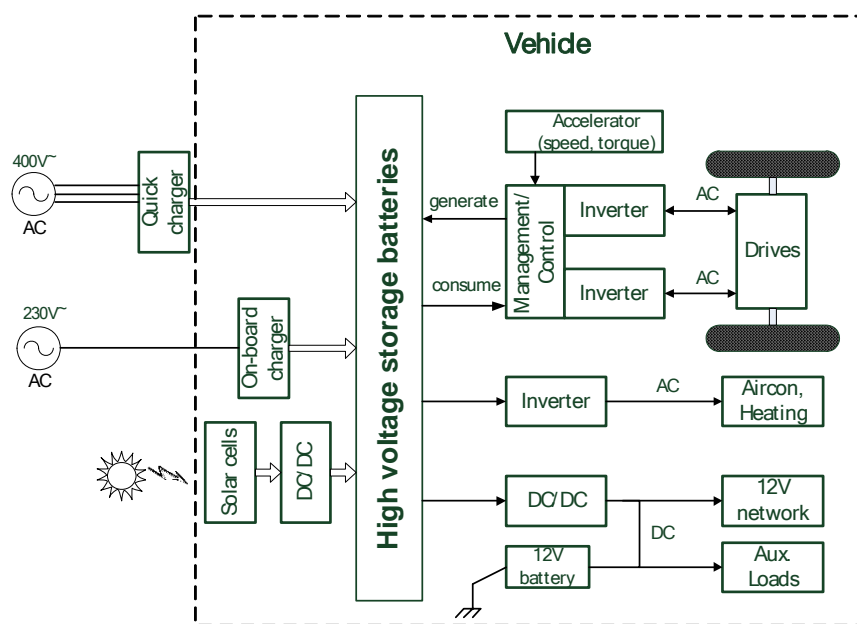


Figure 1: Components of an electrical vehicle

measures are to be implemented. Besides the high voltage components and wire network, there is still a common low voltage (12V) DC system and wire network (because of safety reasons), which supplies all the well-known common electrical components and systems of the car. Some components will have to be implemented in a different way compared to a conventional vehicle, in particular the heating and air conditioning(HVAC) system as well as the break force amplifier. Conventional cars make use of the thermal energy of a combustion engine for heating and the air-conditioning system is mechanically driven by the motor. In e-cars, heating and air conditioning will have to be implemented electrically (consuming energy out of the high voltage battery). For charging the batteries there are the following concepts: Standard charging of the high voltage battery from conventional 230V supply is usually done via an on-board electronic charger system. Quick charging from 400V AC might require external electronic chargers. In future both charger types might be able to transfer energy back from the vehicle's battery into the power grid. Therefore in future, electric vehicles may play an important role in intelligent power distribution and storage concepts. Charging of the low voltage battery is done by transferring energy from the high voltage battery via an electronic DC/DC converter. An interesting but not yet decided question will be whether it will make sense to equip standard e-cars with solar cells. In this case, an additional DC/DC

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converter is necessary to charge either the high or the low voltage battery. Excursion: So called range extenders in a special type of hybrid vehicles are combustion engines which drive an electrical generator in order to charge the high voltage battery in case of shortage of electrical energy. As the range extender does not directly drive the wheels, it can run at fixed rotational speed and an optimal set of parameters. A closer look to the high voltage battery reveals different possible types. Lead-based high voltage batteries are mostly out of use because of their very limited life-time and number of charging cycles, as well as very high weight. Other possible types are Redox-flow-batteries and ZEBRA batteries. Currently in most e-cars different types of Li-ion batteries (lithium-based batteries) are used. Common to lithium-based batteries is that the whole system consists of a huge number (stack) of cells. Since lithium-based batteries may by no means be over-charged, a safe and intelligent battery management and charging system, often taking into account the parameters of single cells or at least of subsets of cells, is essential. A closer look to the electrical drives of the car shows that mostly AC motors are in use. This can be either a single motor for all driven wheels, or so called hub-based motors (each driven wheel has its own motor). Therefore one or more DC/AC converters are necessary in combination with intelligent management and control units. The electronic converters are switched frequency inverters whose basic functionality and architecture are well-known from other intelligent controlled AC drive applications (like AC servo drives in automation systems and machines). The energy efficiency ratio of the power inverters are of extreme importance, as there is a continuous energy flow forth and back between high voltage battery and motor(s). Efficiency rates of 95% or better are envisaged. As Figure 2 shows, besides the high power drive inverters, quite an additional number of DC/DC, AC/DC and DC/AC converters can be found in electrical vehicles. Power electronics are therefore a major field of development and source of value generation in e-cars.

Examples of modern electric vehicles

Most car producers are working on the development of electrical vehicles to supplement their product portfolio. However, only a few are already commercially available on the market. Figure 3 shows two examples from entirely different vehicle categories. Table 1 opposes their specifications.



Figure 3: Examples of electrical vehicles; (a) Mitsubishi i-MiEV, (b) Tesla Roadster

Table 1

Technical data [6], [7]

	Mitsubishi i-MiEV	Tesla Roadster
Acceleration 0-100km/h [s]	15.9	3.9
Battery [V/Ah]	330/48	375/150
Empty weight [kg]	1,110	1,235
Maximum speed [km/h]	130	201
Power [kW]	49	215
Price (excl. VAT) [€]	~29,000	~84,000
Range [km]	150	394
Torque [Nm]	180	370

Ecological balance.

Electric vehicles are considered as promising alternative since they do not produce any tailpipe emissions during operation. However, they may cause additional power grid load, green-house gases and pollutions for the generation of electricity required for battery charging. Electric vehicles do therefore increase electric power use. However, if managed correctly, that power can be fully provided using the power plants we have available today [3], [4]. General predictions of CO₂ emissions for BEVs, which determine the environmental impact, are considered impossible due to the variation of each country's energy mix. An electrical vehicle may be only operated emission free, when the electricity is produced by renewable sources. Another source of pollutants is the production of the vehicle components. However, latter ones are only little in meaning during the whole life cycle of the vehicle. The authors will therefore not further consider them. Literature points out that one electric vehicle increases the electricity consumption of a household in industrialized countries by about 50% [3]. Introducing a large number of electrical vehicles therefore induces new challenges concerning the infrastructure of charging stations as well as the power grid. The total amount of energy E_{tot} required to move a vehicle can be expressed with equation (1).

$$E_{tot} = \frac{E_{res}}{\eta_{trans} \eta_{motor} \eta_{fuel}} \quad (1)$$

with E_{res} : Mechanical efficiency to move the vehicle [MJ/km],

η_{trans} : Transmission efficiency,

η_{motor} : Electric motor efficiency,

η_{fuel} : Fuel efficiency.

In terms of an BEV, the fuel supply efficiency can be further expressed with equation (2)

$$\eta_{fuel} = \eta_{charging} \eta_{grid} \eta_{power} \eta_{res} \quad (2)$$

with: $\eta_{charging}$: Efficiency of charging and discharging the battery,

η_{grid} : Efficiency of the electrical distribution grid,

η_{power} : Efficiency of the power plant,

η_{res} : Efficiency of mining or farming of energy resources.

Figure 4 graphically compares different types of vehicles according to their CO₂ emissions. Equations (1) and (2) have been separated according to their Well-to-Tank (WtT) and Tank-to-Wheel (TtW) emissions. The sum of WtT and TtW therefore equals again the Well-to-Wheel (WtW) performance, including all energy relevant steps beginning with the extraction of the energy resource up to the physical movement of the vehicle. Figure 4 shows that electric vehicles are in average cleaner than other vehicles during operation. A car using conventional gasoline emits in average more than twice as much CO₂. It is assumed that BEVs even get cleaner over time, because the proportion of renewable energy sources is supposed to rise in future. Figure 4 can however only be considered as indicative, since it assumes averaged values of CO₂ intensity for electricity production

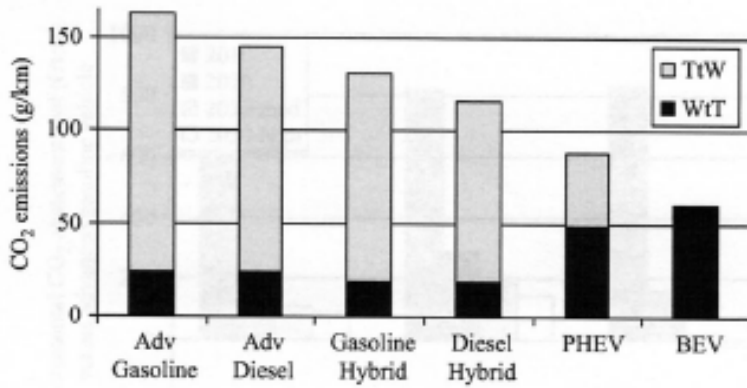


Figure 4: Well-to-Wheel CO₂ emissions [4]

within Europe. The European country with the lowest CO₂ rate emits 54g CO₂ per kWh, whilst the country with the highest CO₂ emissions produces 1,333g CO₂ per kWh [4]. Literature points out that a two-wheeler BEV in France causes about 5g CO₂/km while the same vehicle in India would pollute the environment with about 35g CO₂/km [5]. France derives nearly 80% of its power capacity from nuclear plants which is in contrast to India, whose power generation is extremely CO₂ intensive.

ELECTRIC MOBILITY PROJECT AT REUTLINGEN UNIVERSITY

Electric mobility is considered to be one of the most significant concepts for future locomotion. It is therefore important to introduce this technology to students in an early stage.

Background. The opening of the Robert Bosch Center for power electronics (RBZ), which is located off-campus, has been the reason for introducing electric two-wheelers at Reutlingen University (RU), allowing internal staff and student exchange. The RBZ is situated in the suburbs of Reutlingen, meaning a distance of about 8km to the main campus. This is shown in Figure 5.

The route between the RBZ and RU incorporates high traffic density, including plural traffic lights and many stop and go cycles. A vehicle with a conventional combustion engine would likely consume a high amount of fuel. Reutlingen University has therefore introduced a fleet of electric two-wheelers as an environmental friendly alternative.

Infrastructure. The fleet consists of two different types of two-wheelers, electric scooters and electric bikes (Pedelecs), whereas five vehicles are available of each group. Electric scooters, manufactured by the regional manufacturer Gesellschaft für umweltbewusste Fortbewegung (GUF), offered the best performance.

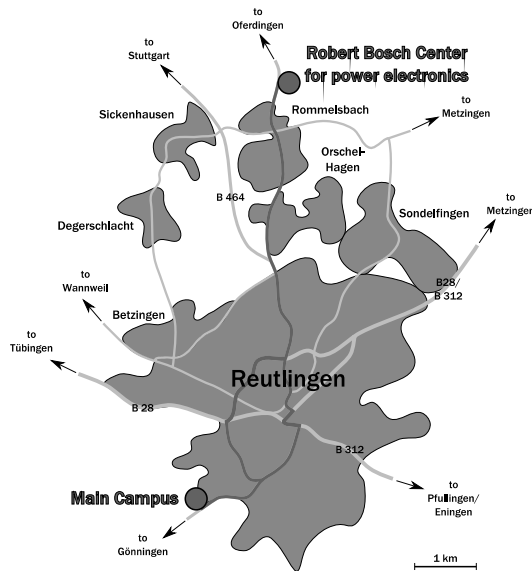


Figure 5. Map of Reutlingen showing the locations of RU and RBZ

Their engines support pedaling up to a velocity of 25km/h. In Germany, no driver's license is required to drive with Pedelects and they are also permitted on bicycle lanes. A helmet is recommended but is however not a legal prerequisite.

Table 2 technically compares the vehicles. Figure 6 shows the electric two wheelers at RU.

The operation of electric two-wheelers simplifies the availability of 230V charging infrastructure. This makes it possible to use standard household installations for battery charging.

Special care must be taken in terms of outdoor installations, since they require additional protection against environmental conditions and vandalism. For this reason a special charging station will be installed on campus. The feeding-in of renewable energy sources will however not be considered at this stage.

Table 2

Comparison of the two-wheelers' technical data

	GUF GECO2	Centurion E-Fire
Type	Electric scooter	Electric bike/Pedelec
Motor power [W]	2,500	250
Battery voltage [V]	48	36
Battery capacity [Ah]	45 (lead) 34.5 (lithium)	8
Charging time [h]	6	1.5 (quick charge) 8 (normal charge)
Maximum velocity [km/h]	45	Not specified; Pedal support up to 25
Maximum range [km]	60	145
Weight [kg]	130 (lead battery) 85 (lithium battery)	22
Price (excl. VAT) [€]	~2,300 (lead battery) ~4,100 (lithium battery)	~2,200
Type of driving license	EU class M	None

The allocation of two-wheelers to the users and the terms of condition are defined by a concept, which will be briefly introduced in the following section. According to German law, every user has to wear at least a helmet when using an electric scooter, which will be provided by RU (RU recommends wearing additional safety equipment). Furthermore the electric scooters have to be insured against third party liability and against theft.



(a)

(b)

Figure 6. Electric two-wheelers at Reutlingen University; (a) Electric scooter, (b) Pedelec

Before renting out a vehicle for the first time, prospective users are required to sign a user agreement and to provide a valid driver's license (in terms of electric scooters). After that, a user account will be activated which allows for registering on the software portal and enables vehicle booking (see chapter 0). It also monitors the user's profile. Bookings can also be done via internet. With each rental process, the user has to sign a confirmation. Simultaneously, data such as user number, specific vehicle and mileage will be acquired. Due to limited battery capacities, the permitted-driving range has to be correlated to the rental time. Users are allowed to book the vehicles half-day (8 am to 1 pm or 1 pm to 6 pm) or full-day (8 am to 6 pm). In case of issuing a two-wheeler half-day, users are allowed to drive 20 km. Otherwise they may drive the vehicle until the battery is empty. In this way, time-consuming charging during the day and the resulting unavailability of the vehicles shall be avoided.

Software for running a fleet of electric vehicles

Currently the School of Engineering carries out research on two software projects.

Fleet management software

The fleet management software is realized as a database client, which receives its data from a MySQL database specially developed for this project. It helps the operator to carry out the essential fleet management routines which are listed below:

- User and vehicle administration,
- Vehicle rental and booking,
- Maintenance and incident recording,
- Representation of statistical information.

For these purposes, the database model consists of five entities (user, vehicle, transaction, incident and downtime), whose attributes represent the required information. Since the attributes are the same, rentals and bookings can be both understood as transactions. The software client grants a password protected access for different users, in order to protect important information from being unintentionally deleted or altered. There are three user groups with different access rights: Administrator, staff member and normal user. Information concerning users and vehicles are available to administrators and staff members only. Bookings and rentals can only be done by ad-

ministrators or staff members. A normal user who wants to apply for a vehicle can leave a request for a certain type of vehicle and if there is a vehicle available it will be booked automatically.

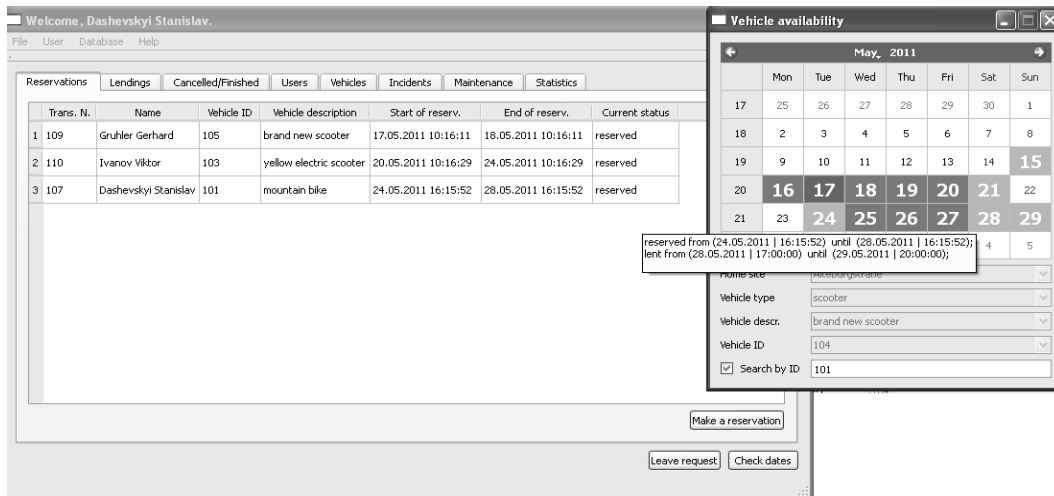


Figure 7: Reservation window

The reservation window is shown in Figure 7. There is a list of existing bookings on the left and a “Vehicle availability” widget on the right, which allows the operator to get an overview of booked, rented out or broken vehicles. The widget also shows if a vehicle has been issued for the whole day or only for a half day. As the layout of the other windows is similar, the reservation window shall be considered as representative. In order to gather information about the availability and reliability of the vehicles, the software provides the ability to store records concerning incidents and maintenance activities. If a maintenance period and a reservation period overlap, the booking is cancelled and the user is asked to request another vehicle. In order to evaluate the users’ behavior, the software offers an opportunity to show various statistical information such as vehicle demand, vehicle type demand, covered distances, maintenance intervals, incidents, etc.

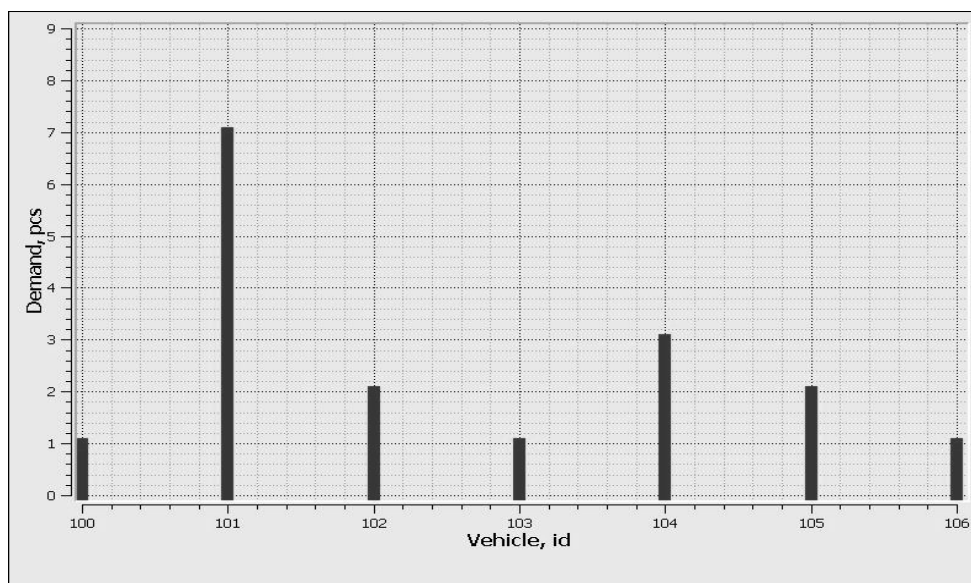


Figure 8: Example for statistic evaluation

Figure 8 shows an exemplary overview of the vehicle demand. Here, the chart shows the number of already finished bookings for each vehicle. The statistical functions come along with the MySQL queries, so that there are no further entities in the database model needed.

Intelligent range prediction

The scope of the second project is the development of an intelligent system for range estimation of electric two-wheelers. Currently, it is difficult for a user to predict the remaining driving range of the battery. Usually, a two-wheeler only provides a display of little accuracy to indicate the battery voltage level. This only allows poor performance in estimating battery capacity and does not visually display any nonlinear discharge of the battery. Latter effect dominates on hilly tracks. The higher the driving load the less the battery voltage. To solve these problems, the range prediction shall be supported by GPS data (elevation, velocity, acceleration) of a driven route. This is shown in Figure 9.

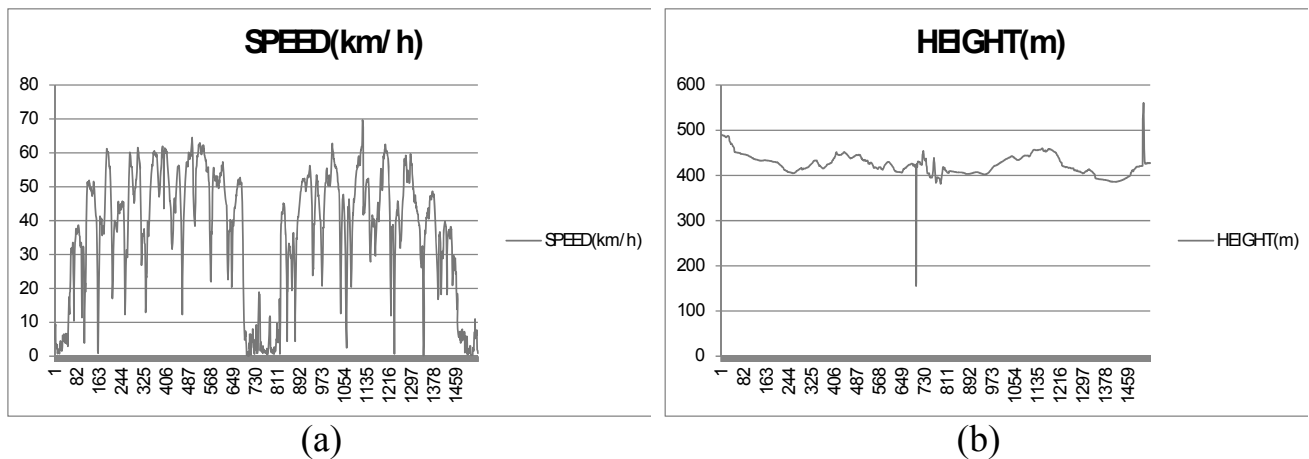


Figure 9. GPS Profile of the route between the main campus and the RBZ; (a) Speed profile, (b) Elevation profile

This supersedes any technical modifications of the vehicle, once the system characteristics (power consumption and battery characteristics) have been determined. Generally, those parameters are known by the vehicle manufacturer and can be directly put into the predictive system. Therefore a data logger (based on an Arduino microcontroller evaluation board) will be used to monitor battery voltage and current consumption. In combination with the GPS data, this information can be used to determine the system characteristics. In future, the microcontroller board shall be extended by a GPS receiver in order to have all the required functionality combined within one device.

RESULTS, CONCLUSION

Recently, electrical vehicles have been enjoying more and more popularity. Additionally, the range of available products has been continuously increasing. This especially applies to Pedeles which have been branded as auxiliary tool for the elderly. Continuous improvements in technology (such as novel drive concepts and advances in power electronics) have raised the public opinion of these products towards modern and agile tools for locomotion. This situation is however different for electric scooters. There are many systems available, which differ in technology, quality and

marketability. Concerning the technical specification, there is hardly any long term experience available yet and OEM knowledge can often only be considered as indicative. It is therefore important to verify the available information with respect to real-world operating situations. First testings of the electric scooter have shown the need of a precise range prediction. The hilly roads in Reutlingen lead to a high power consumption which results, especially while driving with partially discharged batteries, in a considerable breakdown of the battery voltage. This pretends an almost empty battery, although its capacity is still sufficient for driving several kilometers. An additional problem is the charger's lack of protection against environmental influences, which does not allow for outdoor charging.

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КОМП'ЮТЕРНА СИСТЕМА КОНТРОЛЮ ТЕХНІЧНОГО СТАНУ ГАЗОПЕРЕКАЧУВАЛЬНИХ АГРЕГАТІВ

Зроблено обґрунтування вибору методу розбиття просторів показників технічних станів окремих вузлів газоперекачувальних агрегатів на класи із застосуванням штучних нейронних мереж, удосконалено метод побудови меж між класами, розроблено відповідне програмне забезпечення, яке інтегроване в існуючу систему контролю та управління газоперекачувальними агрегатами природного газу.

Сделано обоснование выбора метода разбиения пространств показателей технических состояний отдельных узлов газоперекачивающих агрегатов на классы с применением искусственных нейронных сетей, усовершенствован метод построения границ между классами, разра-