



# Project Report

## Alternative Transport Technologies for Megacities

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## List of Abbreviations

AC	Alternating current
BE	Battery electric
BEV	Battery electric vehicle
DC	Direct current
E-bike	Electric bike
FC	Fuel cell
FCE	Fuel cell electric
FCEV	Fuel cell electric vehicle
GVW	Gross vehicle weight
H <sub>2</sub>	Hydrogen
H <sub>2</sub> O	Water
LRT	Light rail transit
NEDC	New European driving cycle
O <sub>2</sub>	Oxygen
OEM	Original Equipment Manufacturer
pass.	passenger
pedelec	pedal electric cycle
pkm	Passenger kilometer
tkm	Ton kilometer



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# 1 Introduction

The United Nations have emphasized in their World Urbanization Prospects report that population growth and rapid urbanization are important trends in many regions around the world, and especially in developing countries (UN, 2014). These megatrends trigger among others increased urban transport, pollution and increased energy use for urban transport, in particular of fossil fuels, the latter being one of the significant contributors to climate change.

Each megacity, though, has its own characteristic transportation patterns and problems (Shah, 2014). There is a vast variety of city types differing amongst others in their spatial structure, existing traffic system, population density, cultural transport habits, and driving profiles. Other factors contributing to the uniqueness of cities are the economic power, the degree of (in)formality and political regulation and city planning schemes, all acting back on the shape of transport systems (Priester, Kenworthy et al., 2013). As a consequence, taking city-specific preconditions and requirements into account, there cannot be a “one-solution-fits-all” in terms of customized traffic systems. On the contrary, individual tailor-made solutions are needed.

This report shall support in enlightening the various options that exist for transport systems and in particular in terms of oil-independent vehicle concepts that are suitable for megacity contexts in the near future. More precisely, the aim is to compare and contrast - locally - emission-free individual and public land transport options (or vehicle concepts) that are suitable for megacity contexts, which are available on the market today or will likely be within the next 5 years. Investigated vehicle concepts are described in terms of their technical and economic characteristics using standardized key figures and comparing them among vehicle classes and drivetrain options.

Chapter 2 begins with a concise characterization of locally emission-free powertrain options, namely drivetrains for battery electric, fuel cell electric and overhead catenary vehicles on road and rail.

Based on the three powertrain options, Chapter 3 describes and characterizes individual and public transport vehicle options, namely two- and three-wheelers,



passenger cars, buses, light rail trains, metros, urban heavy rail and aerial ropeway systems. In addition, locally emission-free road freight transport options are described.

Data used in this report (e. g. on energy consumption, passenger capacity, prices) are a compilation of vehicle manufacturer data (simulation of test cycles), real life operator data. Furthermore, the DLR vehicle database is utilized, which is also mainly based on manufacturer data. Since there are large bandwidths of each characteristic based on the specific vehicle, operational profiles and the like, we give typical values and a lower and upper bound level.

## 2 Locally emission-free powertrains

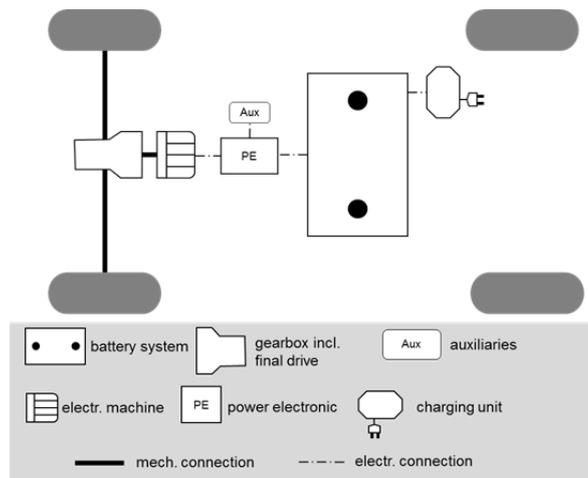
Currently, to achieve a locally emission-free land transport option, electric motors are utilized as a main powertrain. The electricity may be provided to the electric motor via several means either on or off-board:

- Battery electric powertrain: The electricity is generated off-board and stored on-board via electro-chemical energy storage units (see section 2.1),
- Catenary electric powertrain: The electricity is generated off-board and constantly supplied to the vehicle via an external catenary during driving (see section 2.2),
- Fuel cell electric powertrain: The electricity is generated on-board with a fuel cell via reaction of hydrogen and oxygen. For this application, an on-board hydrogen storage unit is needed (see section 2.3).

### 2.1 Battery electric powertrain

A battery electric vehicle (BEV) utilizes an electric motor to convert electrical energy into mechanical energy and requires a battery for the energy storage. The battery is connected to electric motor via a DC/AC converter including a control system (Grunditz, 2014). Most of the BEVs have a gearbox with only one gear ratio (Lienkamp, 2014). If the vehicle has only one central electric motor, then a differential is needed similar to the conventional vehicles. The structure of a BEV with a central electric motor is presented schematically in Figure 1.

The battery is considered to be one of the most critical components of electrified vehicles due to its cost intensive nature (Özdemir and Hartmann, 2012; Redelbach, Özdemir et al., 2014). Furthermore, another drawback of the batteries compared to fossil liquid fuels is its lower energy density resulting in limited driving ranges combined with high volumes and masses of the energy storage system. Therefore, batteries (especially lithium-based ones) have been subject to tremendous research efforts in recent years and this trend is expected to continue in the following years (Wagner, Preschitschek et al., 2013) with improvements in costs, life expectancy and energy density.



**Figure 1: Schematic architecture of battery electric vehicles (BEV)**

Several quick battery charging strategies for battery electric road and rail vehicles beyond common conductive cable-based charging have emerged in recent years (some of which have already entered commercialization):

- Conductive quick charging
  - o This strategy is mainly designed for buses and trams. The charging at high power rates (200-500 kW) is performed at intermediate and turning points via extendable pantographs, a demonstration project for buses is for example in day-to-day use in Geneva, Switzerland (SAE Off-Highway Engineering Online, 2013).
- Inductive quick charging
  - o Several research and demonstration projects on inductive charging at traffic lights or even dynamically in-road-charging exist for passenger cars (EGVI, 2014; WiCh, 2014).
  - o For buses at intermediate stops and 10-30 minutes re-charging at turning points, several research, demonstration and commercialization projects are underway operating with a charging power of 50-200 kW (FTA, 2014b).
- Battery swapping stations
  - o China is operating robotic battery swapping stations for its urban battery electric buses in several cities since 2008 (Li, 2013).



- Battery car maker Tesla has installed a commercial battery swap station in California allowing a battery swap in about 3 minutes (Forbes, 2014).

Both inductive charging at stations and battery swap stations demand high infrastructural investments but enable a reduction of on-board battery capacity, weight and, thus, vehicle cost in turn (and allowing also an increase of passenger load).

Although battery-electric drivetrains could also be applied to rail applications, only road battery electric vehicles are considered in this study since external catenary systems are best suited to rail-bound urban mass rapid transit systems (see Chapter 3.2). The advantages of battery electric road vehicles compared to conventional internal combustion engine vehicles are summarized below:

- Zero local emissions
- Significant lower well-to-wheel greenhouse gas emissions possible (depending on the electricity generation)
- Lower variable costs (mainly fuel)
- Higher torque compared to internal combustion engine at low speed
- Lower vibrations and noise

However, battery electric road vehicles have also some drawbacks compared to internal combustion engine vehicles, which include:

- Limited driving range due to lower energy density
- Longer charging time
- Additional infrastructure requirement for charging points
- Higher purchase costs (at the moment)

## **2.2 Catenary electric powertrain**

Public transport systems, such as trams (light rail trains), metro, commuter train and trolley bus systems are operated on rail or road networks that are equipped with electric overhead wires or rigidly installed third rails alongside the track. The electric power is continuously transferred to the vehicle via the wire or third rail, usually direct current (DC) with 500 – 1500 V, and drawn by a current collector installed on the

vehicle. Sometimes, also alternate current (AC) systems with higher voltages are applied in commuter rail systems. Urban tram, metro and usually also commuter rail systems draw the electricity from an overhead catenary or a third rail. Road trolley buses operate with special current collectors under two overhead wires; one is to draw the current from the wire and the other to close the circuit.

In recent years, overhead catenary trucks for goods transport on roads have been in discussion (den Boer, Aarnik et al., 2013), but no such system has until now begun to enter commercial service in an urban environment. Furthermore, as overhead catenary trucks are not expected to be in service in the megacities in the near future (about 5 years), they are not considered in this study.

In general, overhead catenary systems can be distinguished by transport application as presented in Table 1.

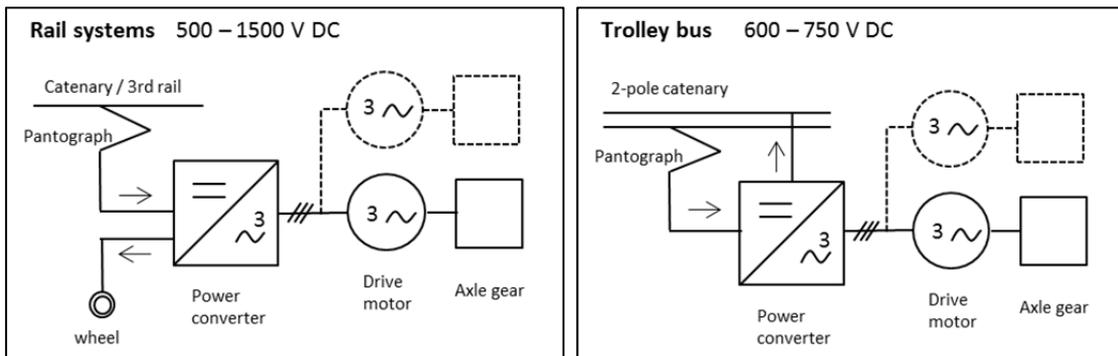
**Table 1: Overhead catenary and third rail systems in urban public transport applications**

Transport Applications	Energy Supply System	Typical Voltage Levels
Tram/Light Rail	Overhead Catenary	500-750 V DC
Metro		750-1500 V DC
Commuter Train		0.75-1.5 kV DC or 15/25 kV AC
Metro, Commuter Train	Third Rail	750-1500 V DC
Trolley bus	Overhead Catenary (two poles)	600-750 V DC

Source: DLR vehicle database

Depending on the network layout and the type of vehicles the voltage level in cities is usually in the range of 500 – 1500 V DC, some suburban commuter trains operate also on alternating current with 15 kV, 16.7 Hz or 25 kV, 50 Hz. In some networks, recuperation of braking energy is possible.

In modern catenary vehicles, the DC current drawn from the catenary is converted by power electronics to a three-phase current with variable frequency and voltage that feeds the drive motors. Between drive motor and axle, a gear translates torque and speed required for the transmission. Figure 2 shows schematic drivetrain topologies of rail and trolleybus catenary vehicles (the latter with 2-pole catenary systems).



**Figure 2: Schematic architecture of rail and road bound catenary vehicles**

Vehicles drawing traction electricity continuously from a catenary are advantageous over battery electric and fuel cell vehicles in terms of the following aspects:

- the traction energy is continuously drawn from an external current wire making expensive and heavy vehicle on-board storage systems unnecessary,
- there is no need to refuel (as with fuel cell hydrogen vehicles) or to recharge (as with battery electric vehicles) and, thus, the operating range, within network borders, is not limited,
- high vehicle efficiency levels (80-90 %),
- proven and well-known system on infrastructure and vehicle level for decades,
- especially useful for highly frequented public transport networks.

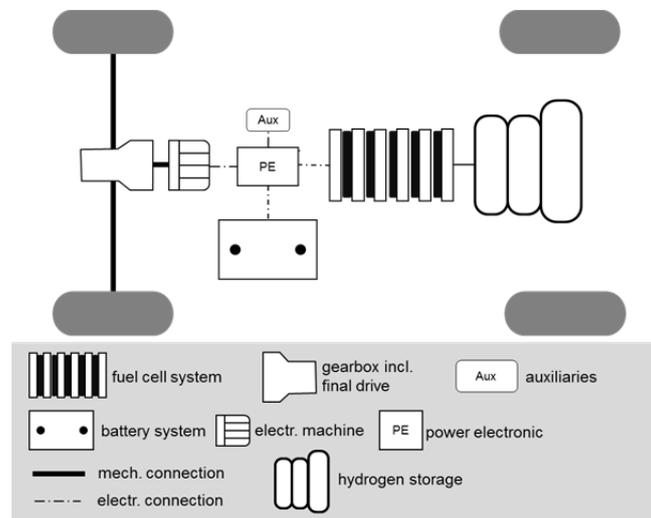
In certain cases, however, overhead electrification may not prove advantageous over operation with battery electric and fuel cell vehicles. Some drawbacks of catenary electrification include:

- visual intrusion through overhead wire network, undesired especially in historically valuable city areas,
- high capital expenditure for wayside energy infrastructure that may not pay off in case of low line-capacity utilization,
- vehicles are bound to the fixed catenary network,
- application restricted to public transport systems, the system is not useable for passenger cars.

### 2.3 Fuel cell electric powertrain

In contrary to the vehicle architectures described above, fuel cell (hybrid) electric vehicles provide traction power by using a fuel cell as energy converter of chemical energy (mostly hydrogen) into electrical energy based on ionic catalytic breakdown of the molecular fuel at the anode. Figure 3 illustrates an exemplary fuel cell powertrain with a central electric motor. Key elements of this system are the hydrogen storage and fuel cell system.

There are several possibilities to store hydrogen on board such as in liquid form, compressed under high pressure or via physical and chemical compounds (Eichseder and Klell, 2012). State of the art is the compressed hydrogen storage under 350 and 700 bar using composite materials for the tanks, which prevents hydrogen diffusion and ensures safety. The 700 bar technology allows a higher energy storage capacity compared to the 350 bar storage. Energy losses due to compression amounts to approximately 15 % of the energy content of hydrogen, which is significantly less than hydrogen being stored in liquid form (30-40 % losses) (Ferrari, Offinger et al., 2012).

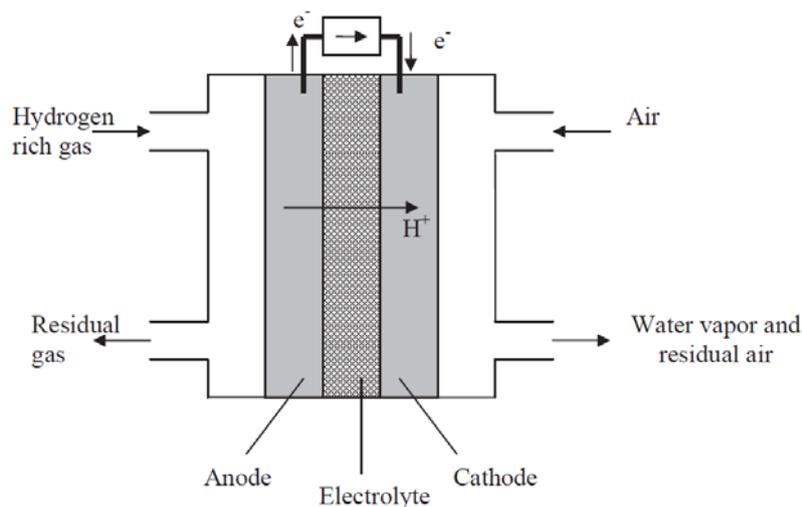


**Figure 3: Schematic architecture of fuel cell electric vehicles (FCEV)**

There are several fuel cell types, however, in this study only the proton exchange membrane (PEM, see in Figure 4 taken from Özdemir, 2012) is considered as this type is most suitable for automotive applications due to advantageous current-over-voltage characteristics, the flexibility to react on rapid load changes and the fast warm-up time

(Mench, 2008; Baehr and Kabelac, 2012). In PEM systems, a thin plastic membrane is used as electrolyte. The reactants are hydrogen ( $H_2$ ) at the anode and oxygen ( $O_2$ ) at the cathode. Final product of the reaction at the cathode is water ( $H_2O$ ).

The fuel cell is connected to an electric motor via a DC/AC converter including a control system. A small battery is required for most of the fuel cell applications mainly in order to (1) supply peak powers, (2) regenerate the breaking energy, (3) allow a downsizing of the fuel cell system and (4) provide the load at the start during the heating-up period of the fuel cell stack (Schaltz, Khaligh et al., 2009).



**Figure 4: Components of PEM fuel cell**

Although FCEVs could also be used for rail applications, only road vehicles are considered in this study. The advantages of fuel cell electric road vehicles are summarized below:

- Zero local emissions
- Lower well-to-wheel greenhouse gas emissions compared to internal combustion engine vehicles possible (depending on the hydrogen generation path)
- High efficiency of the fuel cell compared to internal combustion engine particularly at low temperatures
- Lower vibrations and noise compared to conventional vehicles
- Higher range of operation compared to BEV



- Significant shorter refueling times than recharging times for BEV

However, fuel cell electric road vehicles have also some drawbacks, which include:

- Higher purchase costs (even higher than BEVs)
- Requirement to build a hydrogen infrastructure
- High purity requirements and high costs of hydrogen as fuel
- Durability and long-term performance of fuel cell stack especially for transient operation

## 3 Locally emission-free vehicles for megacities

In this chapter, the powertrain types described in Chapter 2 are linked to different road and rail bound vehicle types relevant for megacities. The vehicle concepts are subdivided into individual passenger transport, public passenger transport and road freight transport means.

### 3.1 Individual passenger transport

The individual passenger transport is subdivided into two sections: two- and three-wheelers (see chapter 3.1.1) and passenger cars (see chapter 0).

#### 3.1.1 Two- and three-wheelers

##### *Pedelecs and E-bikes*

Pedelecs (pedal electric cycle) have an electric motor up to 250 W and the cyclist is supported by the electric motor only if he/she is also cycling and the speed is less than 25 km/h. E-bikes (also called pedelec 45 or S-pedelec) are equipped with an electric motor with up to 500 W, which supports the cyclist up to 45 km/h. Additionally, the e-bike cyclist may drive only electrically up to 20 km/h (ADFC, 2014)<sup>1</sup>.

The characteristics of pedelecs and e-bikes are presented in Table 2. The average speed without stops for pedelecs and e-bikes is about 18 km/h. The energy for supporting the cyclist is stored in the battery and the electric driving range is typically between 30 and 60 km, depending on the battery capacity. The average electricity consumption is about 1 kWh per 100 km bicycle ride. Retail prices of pedelecs and e-bikes (only from Chinese suppliers) are between 400 and 2,000 US \$, with an average value of 700 US \$.

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<sup>1</sup> The maximum wattage or limits for supporting the cyclist are valid for Germany and may vary by country and jurisdiction.

**Table 2: Techno-economic characteristics of pedelecs/e-bikes**

	Unit	Default values and Ranges
<b>Technical factors</b>	Capacity (Passenger seats)	1 (1-2)
	Speed (max)	50 <sup>a</sup>
	Speed (average)	18 (14-22 <sup>b</sup> )
	Range	30-60
	Tank to wheel energy consumption	1,03
<b>Economic factors</b>	Vehicle price	700 (400-2000 <sup>b</sup> )
	Life expectancy	15,000
	Life time of battery	3-5 300-1000
a) Suggested maximum speed for a stable mechanical design b) w/o stops c) Chinese suppliers only		

Sources: Duce, 2011; Elektrofahrrad.net, 2012; Go\_Pedelec, 2012; Mohan, Jayasree et al., 2013; ADFC, 2014; Schleinitz, Franke-Bartholdt et al., 2014; Alibaba, 2015

***Electric scooters and electric motorbikes***

Electric scooters (a motorbike with a step-through frame) and motorbikes are two-wheeled vehicles<sup>2</sup> powered by electricity, by electricity and gasoline (hybrid) or by hydrogen (fuel cell). The focus lies on battery electric scooters and motorbikes in this section.

In 2013, about 12 million e-scooters were sold worldwide, of which 9.4 million were sold in China alone (Navigant, 2014). There, the majority of e-scooters are equipped with cheap lead-acid batteries. Exported e-scooters, on the other hand, have lithium ion and in some cases nickel metal hydride batteries (Wei and Benjamin, 2012).

The techno-economic characteristics of battery e-scooters are presented in Table 3. Mainly, there are two types of e-scooters (Hero-Electric, 2015). These are high range e-scooters with about 70 km range and 25 km/h maximum speed, and high speed e-scooters with about 50 km range and 45 km/h maximum speed. Retail prices of e-

<sup>2</sup> There are also three-wheeled electric motorcycles/scooters on the market, but not as commonly used.

scooters are between 370 and 860 US \$ which are valid for Indian suppliers. The prices in EU are significantly higher.

**Table 3: Techno-economic characteristics of battery electric scooters**

		Unit	Default values and Ranges
Technical factors	Capacity (Passenger)	Cap/vehicle	1 (1-3)
	Speed (max)	km/h	45 (25-60)
	Range	km	50 (40-80)
	Tank to wheel energy consumption	kWh/100 vkm	2.5 (2.1-3.0)
Economic factors	Vehicle price	US\$	650 <sup>a</sup> (370-860)
	Life time of vehicle	km	50,000
	Life time of battery	a (years) cycles	2-6 (350 <sup>b</sup> -1000 <sup>c</sup> )

a) E-scooters from India. E-scooters offered in Europe might have significantly different (about 2,000 US \$) prices than the ones listed above (**Unu-Motors, 2015**).

b) Lead-acid

c) Lithium-Ion

Sources: Duce, 2011; emco, 2012; Hero-Electric, 2015; Wlinenews, 2015; Widmer and Gauch, 2008

Recently, there have been several efforts to develop a fuel cell scooter (IKA, 2008). One model available on the market (APFCT, 2015) is reported to have an electrical range of 62 km in city driving conditions. The prices for 10 scooters including hydrogen recharger is about 350,000 US \$, which is significantly higher than the battery electric scooters (APFCT, 2015). However, it should be noted that with the increasing number of production, the production costs might decrease significantly. Furthermore, the main advantage of the fuel cell scooters compared to battery electric scooters is the significantly shorter refueling time.

The characteristics of electric motorbikes are presented in Table 4. Motorbikes have significantly higher maximum speeds (about 170 km/h) and ranges (190 km) compared to scooters. Consequently, the prices of motorbikes are also substantially higher with an average price of about 18,000 US \$. Estimated life time of the motorbike is between 97,000 and 121,000 km and the battery life time is about 1,200 cycles (see Table 4).

**Table 4: Techno-economic characteristics of battery electric motorbikes**

	Unit	Default values and Ranges
<b>Technical factors</b>	Capacity (Passenger) Cap/vehicle	1
	Speed (max) km/h	170 (150-240 <sup>b</sup> )
	Range km	190 (50-300)
	Tank to wheel energy consumption kWh/100 vkm	4.5-5.0
<b>Economic factors</b>	Vehicle price US\$	18,000 (9,900-39,000)
	Life time of vehicle km	97,000 – 121,000
	Life time of battery cycles	1,200

a) The range and the (tank to wheel) energy consumption values are referring to the statements of manufacturers, which are mostly based on standardized driving cycles. The energy consumption for real driving conditions might be significantly higher than the standardized driving cycles.

b) A single electric motorcycle model with a maximum speed of 350 km/h is not considered here.

Sources: Chester and Horvath, 2009; Energica, 2015; Johammer, 2015; LightningMotorcycle, 2015; ZeroMotorcycles, 2015b; ZeroMotorcycles, 2015a; ZeroMotorcycles, 2015c

### ***Auto Rickshaw (electric)***

Electric Auto Rickshaws are usually three-wheeled vehicles (also called tricycles or tuk tuks) with a cabin used for public transport, which is substituting basically a taxi (Hickman, 2011). Although many rickshaws are men-powered, more than eight million only in India (Sarmah, 2010), there are also rickshaws with conventional combustion engines. Recently, there are several available models on the market that are equipped with a battery and an electric motor.

The techno-economic characteristics of battery electric rickshaws are presented in Table 5. Passenger capacities of rickshaws from India vary between 4+1 and 7+1, where most of the models are built for 5 passengers + 1 driver. The average maximum speed and range are 35 km/h and 80 km respectively. In Mumbai (India), a rickshaw is operated on average 10 hours per day and travels 105 km on average (Shlaes and

Mani, 2013). Therefore, many rickshaw drivers need higher ranges than the average electric rickshaw range of 80 km. The prices of e-rickshaws are between 410 and 2,000 US \$ which are valid for Indian and Chinese wholesale suppliers (prices for at least 10 e-rickshaws for most of the suppliers).

**Table 5: Techno-economic characteristics of battery electric rickshaw**

		Unit	Default values and Ranges
Technical factors	Capacity (Passenger)	Cap/vehicle	5+1 (4-7)+1
	Speed (max)	km/h	35 (20-50)
	Range	km	80 (40-150)
	Tank to wheel energy consumption	kWh/100km	8 (6-10)
Economic factors	Vehicle price	US\$ <sub>2010</sub>	850 (410 – 2,000)
	Life time of vehicle	a (years)	15 <sup>a</sup>
	Life time of battery	cycles	650

a) The survey results in this study show that the age of auto rickshaws in Mumbai are between 6 months and 15 years, with an average age of the fleet of 5.5 years. There are some political efforts to restrict the age of rickshaws with 16 years (Shlaes and Mani, 2013)

Sources: Shlaes and Mani, 2013; Baba, 2015; Brokers-Union, 2015; CeeonIndia, 2015; Devante, 2015; Hebei-Xingbang, 2015; Shandong-Mulan, 2015; Suzhou-Jade-Peacock, 2015; Tara, 2015; Vaahak, 2015; Zhejiang-Tosheen, 2015

Furthermore, there are also some efforts to introduce hydrogen as a fuel for rickshaws. One demonstration project in New Delhi introduced rickshaws with hydrogen fuel utilized in conventional engines in order to reduce local emissions (Villatico, Das et al., 2010). Another study analyzed the energy consumption of fuel cell rickshaws (Mallouh, Denman et al., 2010). However, the same study concludes that fuel cell rickshaws are an unrealistic option due to their high investment and operating costs compared to the conventional auto rickshaws. Therefore, this technology option is not considered further in this study.

### 3.1.2 Passenger cars

In this study, passenger cars are classified according to the European market car classification system (EU, 1999). Among the different segments, mini car (A), small car (B), and medium car (C) segments are mainly considered in this study as they are the most relevant ones for Megacities. The segments and corresponding (conventional) passenger cars available in the market are presented in Table 6.

**Table 6: European car market classification system with brand and model examples (European focus)**

Segment	Brand and model examples
<b>Mini car (A)</b>	Smart fortwo, Citroën C1, Ford Ka, Opel Agila, Toyota Aygo, VW up!
<b>Small car (B)</b>	Ford Fiesta, Renault Clio, VW Polo, Opel Corsa, Peugeot 208, Toyota Yaris
<b>Medium car (C)</b>	VW Golf, Ford Focus, Opel Astra, Škoda Octavia, Peugeot 308, Toyota Corolla, Honda Civic, Renault Megane
<b>Large car (D)</b>	BMW 3 series, VW Passat, Audi A4, Mercedes C Class, Opel/Vauxhall Insignia, Peugeot 508
<b>Executive car (E)</b>	BMW 5 series, Mercedes E class, Audi A6, Volvo V70
<b>Luxury car (F)</b>	Mercedes S Class, BMW 7 series, Audi A8,
<b>Sport coupes (S)</b>	Mercedes SLK, Audi TT, Porsche 911, BMW 6 series
<b>Multi-purpose car (M)</b>	Fiat 500L, Nissan Note, Opel Meriva, Citroen C4 Picasso, VW Sharan, VW Transporter
<b>Sport utility car (J)</b>	Renault Captur, Peugeot 2008, Nissan Qashqai, VW Tiguan, BMW X5, Range Rover, Audi Q7

Average passenger car speed in megacities depends on the traffic situation in the city itself rather than on the vehicle segment. Average vehicle speed at town centers in Germany is 39 km/h (Rumbolz, 2013). However, figures for average speed in megacities vary between 7 and 28 km/h and are, thus, significantly lower (Bangkok 7 km/h (Hayashi, 2010); Manila 7 km/h; Jakarta 9 km/h; Tokyo 16km/h; Los Angeles 26 km/h; New York 28 km/h (Suzuki and Muromachi, 2011)).

The life time of passenger cars is taken as 16 years (Modaresi, Lovik et al., 2014). This assumption is based on average passenger car life time in US, Norway and Japan with

a standard deviation of 3 years (normal distribution)<sup>3</sup>. However, the life time of a passenger car differs in different countries among others depending on the income level, the taxation system and availability of public transport systems. The average age of the existing fleet is about 8 years in Germany, 9 years in Brazil and 11 years in the US (RolandBerger, 2013).

### ***Battery electric vehicles (BEV)***

As mentioned in chapter 2, the battery is the most critical component in a battery electric vehicle (BEV) due to its costs and durability. There is a discussion about the lifetime of batteries in the literature. Duvall (2003) argues that the battery would last between 130,000 and 150,000 km, which corresponds to about 8 years for an average driver. Neubauer, Brooker et al. (2012) state that the lifetime of the battery is at least 15 years with the maximum battery capacity loss of 50%. Hartmann and Özdemir (2011) assume that a battery would last 4,500 cycles (about 12 years) in 2030. Gerssen-Gondelach and Faaij (2012) are much more pessimistic and are arguing with a lifetime of 1,000 cycles (about 3 years) in 2015 and 3000 cycles (about 8 years) in 2025.

On the other hand, today, most of the OEMs (BMW, 2015; Nissan, 2015; Toyota, 2015b; VW, 2015) are giving battery warranties with 8 years or 100,000 miles (ca. 161,000 km). Renault ZOE has a shorter warranty period of 5 years or 60,000 miles with 70% of battery capacity (Renault, 2015). Therefore, in this study a minimum lifetime of 8 years is assumed for the battery.

BEVs are analyzed in 3 different categories (A, B, and C segment according to Table 6) in this study. Techno-economic characteristics of mini cars (or passenger cars in A-segment), which are available on the market with the market introduction year between 2010 and 2013, are presented in Table 7. Although most of the A-segment BEVs (11 among 21 available cars) are having a capacity of 2 passengers, four-seaters are not negligible (9 among 21) in this segment<sup>4</sup>. The average curb weight for A-segment BEVs is about 950 kg. The electrical driving range varies between 40 and 160 km, with

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<sup>3</sup> Depending on this assumption, 99.7% of passenger cars would have a lifetime between 7 and 25 years

<sup>4</sup> Only one model has a capacity of three seats.

a default value of 130 km<sup>5</sup> for an average A-segment vehicle. The prices of A segment cars start with about 9,300 US \$ for a Renault Twizy and amount to 25,000 US \$ for an average A-segment passenger car.

**Table 7: Techno-economic characteristics of A-segment battery electric passenger cars**

	Unit	Default values and Ranges <sup>a</sup>
Technical factors	Capacity (Passengers) Cap/vehicle	2 (2-4)
	Speed (max) km/h	100 (45-130)
	Range <sup>b</sup> km	130 (40-160)
	Energy consumption <sup>b</sup> kWh <sub>el</sub> /100vkm	15 (12-20)
Economic factors	Vehicle price US \$	25,000 (9,300-65,000)

- a) DLR vehicle concept database for small serial and serial vehicles (available on the market) with the market introduction year between 2010 and 2013. There are 23 considered vehicles, which include among others Citroen C-Zero, Peugeot iOn, Renault Twizy, VW e-up! and Karabag 500 Electro.
- b) The range and the (tank to wheel) energy consumption values are referring to the statements of manufacturers, which are mostly based on standardized driving cycles. The energy consumption for real driving conditions might be significantly higher than the standardized driving cycles (**Mock, Tietge et al., 2014**). As a consequence, the range (for a real driving condition) might be lower.

Sources: DLR vehicle concept database

Small battery electric vehicles (or BEVs in B-segment) are presented in Table 8. The passenger capacity varies between 4 and 5 passengers and the average curb weight is about 1,100 kg, which is slightly higher than the A-segment. Furthermore, the electrical driving range is also higher than in the A-segment with an average of 150 km (variation between 100 and 220 km). The price of an average B-segment car is about 36,000 US \$.

<sup>5</sup> Average and median for electrical driving range (among 23 available BEVs) are 127 km and 135 km respectively.

**Table 8: Techno-economic characteristics of B-segment battery electric passenger cars**

	Unit	Default values and Ranges <sup>a</sup>
Technical factors	Capacity (Passenger) Cap/vehicle	4 (4-5)
	Speed (max) km/h	115 (60-150)
	Range <sup>b</sup> km	150 (100-220)
	Tank to wheel energy consumption <sup>b</sup> kWh <sub>el</sub> /100vkm	16 (10-22)
Economic factors	Vehicle price US \$	36,000 (8,000 <sup>c</sup> -70,000)

- a) DLR vehicle concept database for small serial and serial vehicles (available on the market) with the market introduction year between 2010 and 2013. Considered vehicles include among others BMW i3, Renault ZOE, Mitsubishi i-MEV, Mercedes-Benz A class, Cherry QQ3EV, JAC J3 iev and Tata Indica Vista.
- b) The range and the tank to wheel energy consumption values are referring to the statements of manufacturers, which are mostly based on standardized driving cycles. The energy consumption for real driving conditions might be significantly higher than the standardized driving cycles (**Mock, Tietge et al., 2014**). As a consequence, the range (for a real driving condition) might be lower.
- c) The cheapest B-segment car is Tara Tiny EV with 99,999 INR (**Mitra, 2008**), which was marketed in 2008 as world cheapest car (today it corresponds to about 1,600 US \$). However, this car is excluded from the list as there are no recent information about this brand and model.

Sources: DLR vehicle concept database

Medium BEVs (C-segment) are presented in Table 9. Most of the C-segment passenger battery electric vehicles are having a passenger capacity of 5 people. The average C-segment passenger car has a curb weight of about 1,400 kg. The electrical driving range is between 150 and 320 km, where an average C-segment BEV has a range of 180 km. The prices vary between 32,000 and 77,000 US \$, where 45,000 US \$ is taken as a default value for the C-segment.

The energy consumption of BEVs is not significantly different for different segments (see Table 7,

Table 8 and Table 9). For conventional internal combustion engines, energy consumption increases significantly for larger segments. The main reason for this phenomenon is the increased curb weight. For example, 300 kg more weight would increase the energy consumption of a conventional vehicle about 6 kWh/100km. However, as BEVs are much more efficient, the increased weight influences the energy consumption not as much as it would be the case for conventional technologies. An increased weight of 300 kg would result in an increase of energy consumption of about 1 kWh/100km for BEVs (Redelbach, Klötzke et al., 2012). Therefore, energy consumption values for BEVs in different segments are similar to each other (between 10 and 22 kWhel/100km).

**Table 9: Techno-economic characteristics of C-segment battery electric passenger cars**

	Unit	Default values and Ranges <sup>a</sup>
<b>Technical factors</b>	Capacity (Passenger) Cap/vehicle	5 (4-7)
	Speed (max) km/h	140 (120-180)
	Range <sup>b</sup> km	180 (150-320)
	Tank to wheel energy consumption <sup>b</sup> kWh <sub>el</sub> /100vkm	17 (13-21)
<b>Economic factors</b>	Vehicle price US \$	45,000 (32,000-77,000)

a) DLR vehicle concept database for small serial and serial vehicles (available on the market) with the market introduction year between 2010 and 2013. Considered vehicles include among others Nissan Leaf, Volvo C30 and BAIC E150 EV.

b) The range and the (tank to wheel) energy consumption values are referring to the statements of manufacturers, which are mostly based on standardized driving cycles. The energy consumption for real driving conditions might be significantly higher than the standardized driving cycles (Mock, Tietge et al., 2014). As a consequence, the range (for a real driving condition) might be lower.

Sources: DLR vehicle concept database

### ***Fuel cell electric vehicles (FCEV)***

Although many prototypes for FCEVs have been developed in the past by OEMs, there are significantly less FCEV models on the market compared to BEVs. Hyundai started in 2013 with the series production of the compact sport utility vehicle (J-segment) ix35

FC (Hyundai, 2015). Other Asian OEMs are following with the first available D-segment (large car) models (e.g. Toyota Mirai, Honda FCX Clarity) coming into the market shortly (Honda, 2015; Toyota, 2015a). Daimler has postponed the introduction of the B class FC model (a multi-purpose car, M-segment) to 2017 (Krust, 2013).

As the OEMs are not planning to offer FCEVs for the A, B and C segments at least until 2017, these segments are not considered in this study for FCEVs. The data in Table 10 is based on the mentioned FC vehicles above with the corresponding segments (D, J and M segment).

**Table 10 Techno-economic characteristics of fuel cell electric passenger cars:**

		Unit	Default values and Ranges <sup>a</sup>
Technical factors	Capacity (Passenger)	Cap/vehicle	4 (4-5)
	Speed (max)	km/h	166 (160-170)
	Range <sup>b</sup>	km	480 (380-580)
	Life time of fuel cell	km	130,000 <sup>c</sup>
	Tank to wheel energy consumption <sup>b</sup>	kWh <sub>H2</sub> /100vkm	34 (32-35)
Economic factors	Vehicle price	US \$	58,000 (32,000-77,000)

- a) DLR vehicle concept database for fuel cell vehicles (which are/will be available on the market between 2013 and 2017). Considered vehicles are Hyundai ix35, Toyota Mirai, Honda FCX Clarity and Mercedes B Class FC.
- b) The range and the (tank to wheel) energy consumption values are referring to the statements of manufacturers, which are mostly based on standardized driving cycles. The energy consumption for real driving conditions might be significantly higher than the standardized driving cycles (**Mock, Tietge et al., 2014**). As a consequence, the range (for a real driving condition) might be lower.
- c) GM demonstrated a durability of 3500 h of operation for automotive fuel cell stacks, which corresponds to ca. 130,000 km. As average vehicle lifetime is 5,500 h of operation, the durability should be improved. GM argues to achieve 200,000 km lifetime for fuel cell stacks between 2015 and 2020 (**Eberle, Müller et al., 2012**).

Sources: DLR vehicle concept database

The electrical driving range of FCEVs varies between 380 and 580 km, with a default value of 480 km, which is significantly higher than the range of BEVs presented for A, B

and C segment. The energy consumption by a FCEV is about 34 kWh<sub>H2</sub>/100 km, which is higher than BEVs. Higher energy consumption of FCEVs is reasonable since the electricity is produced on board from hydrogen with the corresponding efficiency (between 40% and 60%) of fuel cell system DoE, 2006. The prices of FCEV are between 32,000 and 77,000 US \$, which are also higher than BEVs in C-segment mainly due to the additional costs of the fuel cell stack.

### 3.2 Public passenger transport

Public mass transport enables the accommodation of large flows of people at comparably low cost and energy demand and little space requirements which qualify them for highly condensed megacity contexts.

Public passenger transport comprises in this study road and rail bound vehicles and aerial ropeway systems. There exist more than these vehicle concepts and also cross-concepts, but the outlined are the most important ones in urban contexts to the authors' view.

#### 3.2.1 Buses

Buses are road-bound public transport vehicles that offer passenger seating and mostly also standing capacities. We distinguish between minibuses, buses and trolley buses. **Minibuses** have a seating capacity of more than 9 and up to 25-30 and are usually not designed to accommodate standing passengers. Minibuses are mostly 6-8 m long. Informal and private transport operators in emerging countries tend to use minibuses instead of larger buses. **Buses** have standardized lengths of 12 or 18 m long (the latter articulated), further categories are buses with lengths between 8-12 m (midibuses) and with 24 m (double-articulated buses). We investigate the standard 12 m bus (also called solobus) with typical combined seating and standing capacities for 60 – 80 passengers. **Trolleybuses**, operating electrically under an overhead catenary, are usually articulated and 18 m long with a capacity of between 120 and 150 passengers both for sitting and standing. In order to compare the passenger capacities over time of the examined vehicles, a further metric is introduced: the number of passengers that can be transported in one direction in one hour (pass/h/dir.) in a corridor for a given headway (i.e. the time span between two vehicles).

Investigated drivetrain options for buses in this report include battery electric, fuel cell electric and overhead catenary electric (trolley) configurations.

### ***Battery Electric Buses***

Battery electric buses (BE buses) are still expensive primarily because of cost-intensive batteries. However, battery electric bus prices have been reported to sink massively recently, since especially Chinese cities place substantial orders generating economies of scale (Hales, 2014).

Batteries are heavy due to their low energy density and a full charge lasts several hours restricting operational flexibility. As a consequence, the range of battery electric buses is limited. Partly due to these range constraints most battery electric buses on offer are only up to 12 m long, reducing energy demand and battery size, although BYD has an articulated 18 m battery bus on offer. Most bus operators demand full flexibility during an operational day (8 to 16 hours). In response, several battery charging strategies, as outlined in Chapter 2.1, have emerged (conductive and inductive quick charging and battery swap stations). In this report, however, mainly battery electric buses are investigated, that are recharged conductively over a few minutes each at terminus stations while turn-around and longer overnight at the depot.

Battery lifetime in bus operations depends very much on environmental conditions (mainly outside temperatures) and on the charging and discharging profile. Chinese battery bus producer BYD claims up to 12 years of battery lifetime. The battery capacity should be minimum 80 % of its original capacity after 12 years (Halvorson, 2014). A lifetime of 7.5 years is estimated for Barcelona's bus operator (EVObsession, 2013). We assume an average battery lifetime of 8 years for buses.

The following tables specify typical BE minibuses (Table 11) and buses (Table 12). Range of battery buses is in general limited and depends on battery size and the driving profile. Battery truck producer Smith suggests ranges of ca. 130 km for its Smith Edison minibus and BYD states a range of about 250 km for its K9 bus with 324 kWh of installed battery capacity (BYD, 2015). Prices of battery buses vary among producer, configuration and production output. We take 80,000 US\$ for BE minibuses and 400,000 US\$ for BE buses.

**Table 11: Techno-economic characteristics of battery electric minibuses (6-8 m)**

	Unit	Default values and Ranges
<b>Technical factors</b>	Capacity (Passenger) Cap/vehicle	15 (10-30)
	Passengers per hour per direction @ 3 min. headway Pass/h/dir.	300 (200-600)
	Speed (max) km/h	70 (60-80)
	Range km	130 (80-200)
	Energy consumption (battery level) kWh/100 pass-capacity-km	1.9 (1.1-2.8)
<b>Economic factors</b>	Vehicle price mUS\$	0.08 (0.03-0.2)
	Life time of vehicle a (years)	12 (10-20)
	Life time of battery a (years)	8 3-15

Sources: DLR vehicle database; Smith Electric Vehicles, 2011; VansA2Z, 2015

**Table 12: Techno-economic characteristics of battery electric buses (12 m)**

	Unit	Default values and Ranges
<b>Technical factors</b>	Capacity (Passenger) Cap/vehicle	75 (60-80)
	Passengers per hour per direction @ 3 min. headway Pass/h/dir.	1500 (1200-1600)
	Speed (max) km/h	90 (80-100)
	Range km	250 (150-300)
	Energy consumption (battery level) kWh/100 pass-capacity-km	1.8 (1.3-2.5)
<b>Economic factors</b>	Vehicle price mUS\$	0.4 (0.2-1)
	Life time of vehicle a (years)	12 (10-20)
	Life time of battery a (years)	8 3-15

Sources: DLR vehicle database

### ***Fuel Cell Electric Buses***

Fuel cell electric buses (FCE buses) are less subject to range limitations than battery electric buses are. Extensive operator experiences with fuel cell buses have been build-up in recent years in a number of European and North American cities as part of public financed research projects (FTA, 2014a; CHIC, 2015). Ranges of 250 km for FCE minibuses and 350 km for FCE buses are taken as default values in this report.

Prices of fuel cell electric buses are still high and not competitive to diesel buses because so far they are not manufactured in series production and fuel cell systems are complex and, thus, costly. Costs of about 2 million US \$ per fuel cell electric bus are reported at present, but are decreasing currently mainly because of sinking fuel cell costs and improvements in fuel cell bus assembly and installation processes (CTtransit, no year) Ahluwalia, Wang et al., 2012 suggest a cost target of 650,000 USD per bus by 2015, which would still be a cost premium of 50-80 % over conventional diesel buses.

Technical and operational specifications of FCE buses are assumed to be similar to those of BE buses differing only in range, energy demand, price and life time. We assume the energy demand of fuel cell buses to be 2.5 times that of battery electric buses (calculated at battery or tank level respectively), mainly due to the fuel cell efficiency, which is about 40-45 % (combined efficiency of fuel cell stacks and periphery). Costs of FC buses are still very high as outlined above. A drawback of fuel cells is their still limited life time. Producers grant 12,000 – 15,000 hours lifetime warranty in current generation fuel cells for transit bus applications (Ballard, 2014). We assume a lifetime of 20,000 hours in our calculations. At 16 hours of operations per day and 330 days of operation per year, this yields a lifetime of 3.8 (rounded up to 4) years.

The following tables specify the characteristics of typical FCE minibuses (Table 13) and buses (Table 14).

**Table 13: Techno-economic characteristics of fuel cell electric minibuses (6-8 m)**

	Unit	Default values and Ranges
<b>Technical factors</b>	Capacity (Passenger) Cap/vehicle	15 (10-30)
	Passengers per hour per direction @ 3 min. headway Pass/h/dir.	300 (200-600)
	Speed (max) km/h	70 (60-80)
	Range km	250 (150-500)
	Tank to wheel energy consumption kWh/100 pass-capacity-km	4.8 (2.8-7)
<b>Economic factors</b>	Vehicle price mUS\$	0.25 (0.15-0.8)
	Life time of vehicle a (years)	12 (10-20)
	Life time of fuel cell a (years)	4 3-5

Sources: DLR vehicle database

**Table 14: Techno-economic characteristics of fuel cell electric buses (12 m)**

	Unit	Default values and Ranges
<b>Technical factors</b>	Capacity (Passenger) Cap/vehicle	75 (60-80)
	Passengers per hour per direction @ 3 min. headway Pass/h/dir.	1500 (1200-1600)
	Speed (max) km/h	90 (80-100)
	Range Km	350 (250-400)
	Tank to wheel energy consumption kWh/100 pass-capacity-km	4.5 (3.3-6.3)
<b>Economic factors</b>	Vehicle price mUS\$	1.0 (0.6-1.5)
	Life time of vehicle a (years)	12 (10-20)
	Life time of fuel cell a (years)	4 3-5

Sources: DLR vehicle database



## ***Trolleybuses***

Trolleybuses draw the traction electricity via a current collector from a two-pole catenary. Thus, there are no range restrictions as with battery electric and fuel cell buses. But trolleybus systems require the funding, erection and maintenance of an overhead catenary system. Furthermore, an advantage of trolley bus systems over light rail systems is that they require less capital expenditure.

There are efforts to integrate additional energy storage systems on-board, e.g. batteries and super-capacitors, in order to bridge non-electrified sections and to reduce energy consumption by regenerative braking. In field tests, energy reductions of 10-20 % by re-using regenerative braking energy have been reported (TROLLEY Project, 2013).

In general, energy demand for auxiliaries (mainly heating, ventilation and air conditioning) is substantial in electrified urban traffic. A German trolley bus operator reports up to 45 % share of auxiliaries (mainly heating) on total combined auxiliaries and traction energy consumption in German winter conditions (TROLLEY Project, 2013). This high share of auxiliaries can also be seen on BE and FCE buses.

The techno-economic characteristics of trolleybuses (capable of braking energy recuperation) are presented in Table 15.

**Table 15: Techno-economic characteristics of trolleybuses (18 m)**

		Unit	Default values and Ranges
<b>Technical factors</b>	Capacity (Passenger)	Cap/vehicle	135 (120-150)
	Passengers per hour per direction @ 3 min. headway	Pass/h/dir.	2700 (2400-3000)
	Speed (max)	km/h	80 (60-100)
	Range	Km	Not limited
	Energy consumption at pantograph	kWh/100 pass-capacity-km	1.95 (1.3-2.6)
<b>Economic factors</b>	Vehicle price	mUS\$	0.9 (0.6-1.3)
	Life time of vehicle	a (years)	20 (15-25)

Sources: DLR vehicle database

### 3.2.2 Rail

Rail-borne public transport systems can be distinguished into light rail transit (trams and light rail trains), rapid rail (metro) and heavy rail systems (in this study commuter rail).

#### *Light Rail Transit*

In urban areas, light rail transit trains operate on dedicated tracks alongside streets whereas tram systems operate on rails laid directly into the streets. Light rail transit (LRT) systems are usually faster than tram systems, the distance between stations is larger and they allow the accommodation of more passengers (Walker, 2010). Light rail trains draw the traction energy from overhead catenary lines, though some systems have been equipped recently with on-board energy storage systems that are charged inductively or via moveable pantographs at stations, to enable catenary-independent operation in sections or on the whole line (Railway Gazette, 2012, Railway Gazette, 2014). Table 16 gives an overview of techno-economic characteristics of light rail transit systems.

**Table 16: Techno-economic characteristics of light rail transit systems**

		<b>Unit</b>	<b>Default values and Ranges</b>
<b>Technical factors</b>	Capacity (Passenger)	Cap/vehicle	300 (140-500)
	Passengers per hour per direction @ 3 min. headway	Pass/h/dir.	6000 (2800-10000)
	Speed (max)	km/h	70 (60-80)
	Energy consumption at pantograph	kWh/100 pass-capacity-km	1.5 (0.8-2.0)
<b>Economic factors</b>	Vehicle price	mUS\$	4 (3.5-4.2)
	Life time of vehicle	a (years)	30 (20-40)
	Infrastructure cost	mUSD/km	(25) 20-32

Sources: Verband Deutscher Verkehrsunternehmen (VDV), 2008; Bombardier, 2012; Gradwohl and Ensbacher, 2013; Bozzo, Canepa et al., 2014; Gueguen and Ringwald, 2014

### ***Metros (rapid transit)***

Metros are a form of rapid transit systems usually operating underground or elevated on separated tracks. They are designed to handle large passenger flows over greater distances at higher speeds and larger station spacing than tram systems. Compared to tram and light rail transit, metro networks are substantially more expensive, mostly because they are usually constructed under the surface which requires costly tunneling works (Gueguen and Ringwald, 2014). Table 17 gives an overview of techno-economic characteristics of metro systems.

**Table 17: Techno-economic characteristics of metro systems**

		<b>Unit</b>	<b>Default values and Ranges</b>
<b>Technical factors</b>	Capacity (Passenger)	Cap/vehicle	800 <sup>a)</sup> (200-1500)
	Passengers per hour per direction @ 3 min. headway	Pass/h/dir.	16000 (4000-24000)
	Speed (max)	km/h	80 (60-90)
	Energy consumption at pantograph	kWh/100 pass-capacity-km	1.6 (0.7-2.3)
<b>Economic factors</b>	Vehicle price	mUS\$	9 (6-15)
	Life time of vehicle	a (years)	30 (20-40)
	Infrastructure cost	mUSD/km	120 (70-200) <sup>b)</sup>

a) 110 m train

b) Lower bound value for higher percentages at grade and upper bound value for complex underground metros.

Sources: Flyvbjerg, Bruzelius et al., 2008; Verband Deutscher Verkehrsunternehmen (VDV), 2008; AnsaldoBreda, 2010; MVG, 2010; AnsaldoBreda, 2011; Alstom and Bombardier, 2013

### Commuter Trains

Commuter rail systems (as part of heavy rail) operate on standard gauge rails, usually on rails laid at grade. They link urban and suburban areas to city centers and are designed to carry great passenger flows. Whereas some systems are operated with DC current (e. g. Berlin and Hamburg in Germany), other commuter rail systems share the AC railway energy system with conventional regional and long-distance trains and also use the same railway stations. Table 18 gives an overview of techno-economic characteristics of commuter rail systems.

**Table 18: Techno-economic characteristics of commuter rail systems**

		Unit	Default values and Ranges
Technical factors	Capacity (Passenger)	Cap/vehicle	1000 (300-1500)
	Passengers per hour per direction @ 3 min. headway	Pass/h/dir.	20000 (6000-30000)
	Speed (max)	km/h	100 (80-140)
	Energy consumption at pantograph	kWh/100 pass-capacity-km	1.9 (1.4-2.5)
Economic factors	Vehicle price	mUS\$	12 (8-15)
	Life time of vehicle	a (years)	30 (20-40)
	Infrastructure cost	mUSD/km	70 (20-150)

Sources: DLR vehicle database, Bombardier, 2010; Stephan, 2013

### 3.2.3 Aerial Ropeway

Aerial ropeways (or aerial tramways) are a special form of urban public passenger transport. The system, mostly operated with detachable gondolas or cabins being suspended by pylon-held ropes, is well-known from ski-areas. But aerial ropeway systems have also seen a massive uptake in recent years in cities with topographically difficult urban terrain with steep slopes (especially in Latin America), where buses or rail-bound systems cannot operate satisfactorily. The non-propelled gondolas are hauled on a circulating rope which is driven by central electric drives in the mountain or

in the valley station (Alshalalfah, Shalaby et al., 2014). Table 19 gives an overview of techno-economic characteristics of typical aerial ropeway systems.

**Table 19: Techno-economic characteristics of aerial ropeway systems (detachable gondolas)**

		Unit	Default values and Ranges
Technical factors	Passengers per hour per direction	Pass/h/dir.	4000 (3000-6000)
	Speed (average)	km/h	27 (21-31)
	Energy consumption	kWh/100 pass-capacity-km	8 (6-10)
Economic factors	Infrastructure cost incl. gondolas	mUSD/km	12 (5-20)

Sources: Leitner, 2012; Alshalalfah, Shalaby et al., 2014; Doppelmayr, 2014

### 3.3 Comparison of energy demand for passenger transport modes

In this Chapter, typical characteristics of various passenger transport modes have been described and quantified. Each transport system and vehicle class has its own advantages and drawbacks in terms of the suitability for specific transport tasks. One central evaluation criteria for comparing transport systems among each other is the energy demand. Comparing energy demand of different transport systems is, however, a non-trivial problem and to do so, requires a set of assumptions on vehicle occupancy rates and production paths of hydrogen in order to create a common basis for comparison. As basis, we take the electrical energy demand for operations per 100 passenger-km.

In order to compare the transport means in terms of their energy demand per passenger realistically, average occupancy rates for every type of vehicle are used. Data on occupancy levels is scarce and differs by city, type of transport and between peak and off-peak times.



The occupancy rate for pedelecs, e-bikes scooters and motorbikes are assumed to be 1.0, although the average occupancy rate can be as high as 1.5 depending on the city (Singh, 2000).

For rickshaws, occupancy rates between 1.76 and 2.55 are reported (without driver) in the literature (Singh, 2000; CISTUP, 2012; RITES, 2011). In this study, an average value of 2.0 is taken for the occupancy rate of auto rickshaws.

Schäfer, Heywood et al. (2009) and Schäfer (2011) report passenger car occupancy rates of 2.0 to 2.5 with a tendency to decline with rising income levels and decreasing household sizes. Singh mentions an occupancy rate of 3.18 for India (Singh, 2000). For Bengaluru (India), a passenger car occupancy rate of 2.59 is given (RITES, 2011). On the other hand, a passenger car occupancy rate of 1.75 in 1990 (with a range of 1.00 – 4.75) and 1.74 in 2005 (with a range of 1.43 - 6.00) is reported in Singapore (Fwa and Chua, 2007). In this study, an average occupancy rate of 2.5 is assumed for the passenger cars with at least 4-seats. For 2-seaters, as there is no specific occupancy rate data is available, a value of 1.8 is assumed for this study.

Average occupancy rates of public transport systems in megacities in developing countries can be assumed to be higher than in developed cities. Average passenger occupancy rates of all public transport systems (buses, LRT, metros, commuter trains and aerial ropeways) are taken as 40 % (based on total seating and standing capacity) following published data on occupancy rates of Chinese bus lines with 44 % and 39 % (IFEU, 2008) and metro lines with 39 % (He, Meng et al., 2011).

Table 22 gives average occupancy rates for individual passenger transport and public transport means used to calculate and compare energy demand per passenger.

**Table 20: Occupancy rates of individual and public passenger transport means used in this report**

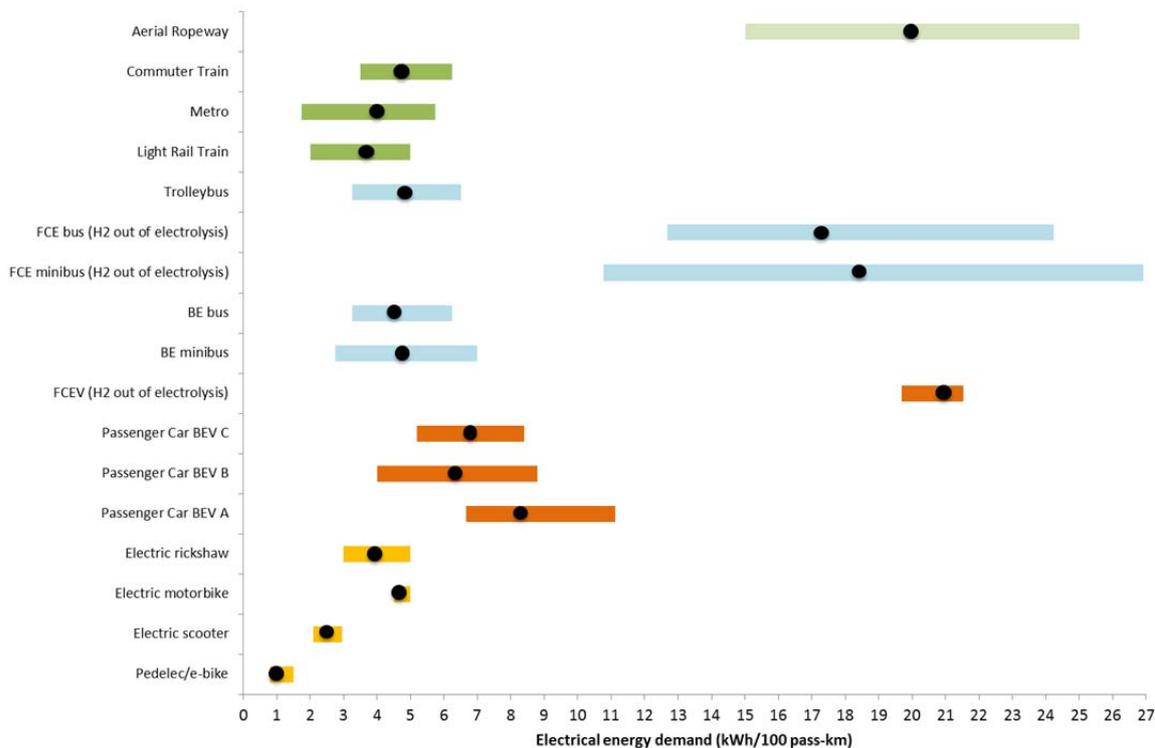
<b>Individual passenger transport</b>	<b>Passengers per vehicle</b>
Pedelec, e-bike, electric scooter and motorbike	1.0 (1.0 – 2.0)
Electric rickshaw (without driver)	2.0 (1.76 – 2.55)
Passenger car (BEV/FCEV) with at least 4-seaters	2.5 (1.74 – 3.18)
Passenger car with 2-seaters	1.8 (1.0 - 2.0)

<b>Public transport</b>	<b>Average occupancy rate (seating and standing capacity)</b>
Bus	40 %
LRT	40 %
Metro	40 %
Commuter Train	40 %
Aerial Ropeway	40 %

In this study, it is assumed that hydrogen is produced via electrolysis (with electricity from renewable energy sources). In order to compare battery electric and fuel cell electric vehicles in terms of their energy demand, the losses due to the production of hydrogen via electrolysis are included. An efficiency of 65% for hydrogen production through electrolysis is included to calculate electric energy demand (based on Özdemir, 2012).

Figure 5 shows the resulting electrical energy demand in kWh per 100 passenger-km of all investigated passenger transport systems. The figure shows the range of typical energy demands and the default values (black dots) as presented in the tables in this Chapter.



**Figure 5: Electrical energy demand of passenger transport systems**

Energy demand: Reference level for electric energy demand is for battery electric vehicles the battery, for overhead catenary vehicles the energy drawn from the pantograph and for fuel cell electric vehicles the electricity to operate the electrolyzer ( $\mu = 0.65$ ) with which hydrogen can be produced out of electricity. The dots represent the default values among the ranges as described in this study.

Assumptions on occupancy rates: pedelec, e-bike, electric scooter and motorbike: 1.0 pass./vehicle; electric rickshaw: 2.0 pass./vehicle; passenger car (4-seater): 2.5 pass./vehicle; passenger car (2-seater): 1.8; all public transport means: 40 % (of combined standing and seating capacities).

**Main findings:**

Two- and three-wheeler and public transport systems (bus, LRT, metro, commuter train) are characterized by having a lower energy demand than cars have (apart from aerial ropeway systems which have a relatively high energy demand).

The electrical energy demand of fuel cell electric vehicles is considerably higher than that of battery electric vehicles due to the conversion losses during the hydrogen

production and fuel cell operation. However, this should not discourage the usage of fuel cells in transport applications since hydrogen can play an important role as storage medium for fluctuating supply of renewable energy itself. Furthermore, hydrogen vehicles have considerably higher ranges and shorter refuel times compared to battery electric vehicles.

The consumption ranges shown in Figure 5 are only due to the uncertainties as to the energy consumption per vehicle km. However, the results show that for the energy consumption per passenger-km, the average occupancy level is at least as important as the technical factors. As these values may differ significantly for different cities, a city-specific analysis is required in order to assess the energy consumption locally.

### **3.4 Freight transport**

In this section, only locally emission-free vehicle profiles of vehicle category N1, with a maximum of 3.5 tones gross vehicle weight (GVW), are presented. N1 category vehicles are, as described within European Commission, 2007, vehicles with at least four wheels designed and constructed for the carriage of goods. Most important for freight transport is the available payload which varies in the range of 300 kg until 1.400 kg. In this study, 600 kg is assumed as a default value, which is representative for a vehicle with around 2.2 tons GVW. Additional default values, gathered from currently existing or presented battery and fuel cell electric vehicles, are presented within Table 21 and Table 22. Battery electric N1 category vehicles do not significantly differ in comparison to passenger cars regarding possible driving range and maximum speed. Driving ranges given are varying in a range of 65 km and 170 km as specified by the manufacturers and, therefore, based on standardized driving cycles. Median of vehicles considered is 130 km and 110 km/h in terms of maximum speed. Due to the greater vehicle weight and vehicle dimensions in comparison to passenger cars, energy consumption is higher. Life time of battery is in analogy to passenger cars assumed to be 8 years. The prices of N1 category vehicle car start at about 29,600 US \$ for a Peugeot iOn Cargo and amount to 35,000 US \$ as average N1 vehicle price.

**Table 21: Techno-economic characteristics of battery electric vehicles in N1 vehicle category**

		Unit	Default values and Ranges <sup>a</sup>
Technical factors	Capacity (payload)	ton/vehicle	0.600 (0.306-1.400)
	Speed (max)	km/h	110 (45-130)
	Range <sup>b</sup>	km	150 (65-170)
	Tank to wheel energy consumption <sub>b</sub>	kWh <sub>e</sub> /100vkm	18 (12-26)
	Life time of battery	a (years) cycles	8 (1,000-4,500)
Economic factors	Vehicle price	US \$	35,000 (29,600-60,000)
	Life time of vehicle	a (years) <sup>c</sup>	12

a) median of in total 17 battery electric vehicles regarding N1 vehicle category

b) The range and the (tank to wheel) energy consumption values are referring to the statements of manufacturers, which are mostly based on standardized driving cycles. The energy consumption for real driving conditions might be significantly higher than the standardized driving cycles (**Mock, Tietge et al., 2014**). As a consequence, the range (for a real driving condition) might be lower.

c) Commercial vehicles ≤ 7,5t GVW for Germany

Sources: DLR vehicle database; IINAS, 2012; Hartmann and Özdemir (2011); Gerssen-Gondelach and Faaij (2012)

Currently, there are no available fuel cell electric vehicles within N1 vehicle category on the market. For that reason default values regarding capacity, maximum speed and life time of vehicle are taken from battery electric vehicles. Energy consumption and price of the vehicle are estimated based on DLR calculations (see Table 22). The electrical driving range of FCEVs varies between 281 and 425 km depending on size of hydrogen storage used, with a default value of 425 km, which is significantly higher than the range of N1 category battery electric vehicle. The energy consumption of a FCEV is about 44 kWh<sub>H2</sub>/100 km. Higher energy consumption of FCEVs is reasonable since the electricity is produced on board from hydrogen with the corresponding efficiency (between 40% and 60%) of fuel cell system (DoE, 2006). The price assumption made regarding the FCEV is 86,200 US \$, which is higher than the vehicle

price for battery electric N1 category vehicles mainly due to the additional costs of the fuel cell stack.

**Table 22: Techno-economic characteristics of fuel cell electric vehicles in N1 vehicle category**

	Unit	Default values and Ranges
Technical factors	Capacity (payload)	ton/vehicle 0.600 (0.306-1.400)
	Speed (max)	km/h 110 (45-130)
	Range	km 425 (281-425) <sup>a</sup>
	Tank to wheel energy consumption	kWh <sub>H2</sub> /100vkm 44 <sup>b</sup>
	Life time of fuel cell	km 130,000 <sup>c</sup>
Economic factors	Vehicle price	US \$ 86,200 <sup>d</sup>
	Life time of vehicle	a (years) 12

- a) Based on own calculations and depending on size of hydrogen storage: 3.7 kg or 5.6 kg
- b) based on VW Caddy specific vehicle data and TTW average powertrain efficiency of 0.41; regarding NEDC
- c) GM demonstrated a durability of 3500 h of operation for automotive fuel cell stacks, which corresponds to ca. 130,000 km. As average vehicle lifetime is 5,500 h of operation, the durability should be improved. GM argues to achieve 200,000 km lifetime for fuel cell stacks between 2015 and 2020 (**Eberle, Müller et al., 2012**).
- d) The price might differ depending on the vehicle configuration

Sources: DLR vehicle database; IINAS, 2012

## 4 Conclusions

The aim of this project is to collect, describe and structure data on locally emission-free individual passenger transport, public transport and urban freight transport systems that are suitable for megacity contexts. Vehicle concepts are investigated in terms of technical, operational and commercial aspects. Considered are electric and fuel cell electric systems which are either available on the market today, or will likely be within the next 5 years. Data are compiled for two- and three-wheelers, passenger cars, buses, light rail trains, metros, commuter trains, aerial ropeway and freight transport systems.

The results of this report can be used as input to combined energy and transport scenarios for individual cities and also as a foundation for in-depth analysis on transport options for specific megacities, where decreasing the adverse environmental effects of the transport sector is a main challenge and opportunity likewise.

Comparison of transport modes on a city-specific level is an important further research area, since each urban setting has its own characteristic transportation problems and challenges. As a consequence, rather than “one-solution-fits-all”, megacity-specific tailor-made solutions are needed. Another further research topic could be the assessment of infrastructure and in particular energy infrastructure requirements for different oil-free transport alternatives (e.g. overhead catenary lines, charging points, hydrogen fueling stations etc.).

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