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Electrification of transport logistic vehicles: A techno-economic assessment of battery and fuel cell electric transporter

Florian Kleiner[1,2], Enver Doruk Özdemir[2], Stephan A. Schmid[2], Martin Beermann[3], Bülent Çatay[4], Bob Moran[5], Ock Taeck Lim[6], Horst E. Friedrich[2]

[1]*Corresponding author: florian.kleiner@dlr.de*
[2]*German Aerospace Center (DLR), Institute of Vehicle Concepts, Pfaffenwaldring 38-40, 70569 Stuttgart, Germany*
[3]*JOANNEUM RESEARCH, Institute for Water, Energy and Sustainability, Elisabethstraße 18/II 8010 Graz, Austria*
[4]*Sabanci University, Faculty of Engineering and Natural Sciences, 34956, Tuzla, Istanbul, Turkey*
[5]*Office for Low Emission Vehicles (*OLEV*), 33 Horseferry Road, London SW1P 4DR United Kingdom*
[6]*Department of Mechanical and Automotive Engineering, Ulsan University, Mugeo-dong, Nam-gu, Ulsan 680-749, Korea*

Abstract

In order to minimize oil dependency and the negative environmental impacts as described within the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC), emissions of greenhouse gases (GHG) from all sectors of the global economy have to be reduced. Road freight transport is one of the fastest growing modes of transport and has an increasing share in the total GHG emissions of transport. Current concentration is mainly on incremental technology developments to reduce fuel consumption of conventional vehicles. However, there may be potential for (near) zero tailpipe emission vehicles that could result in the large-scale GHG reduction that is needed. In order to identify early (niche) markets for electric vehicle application, this paper gives an overview of current demonstration project activities in terms of powertrain technology implemented and transport task of investigation, with special focus on vehicles with a gross vehicle weight not exceeding 3.5 tonnes. Subsequently, current vehicle architecture and technology configuration is derived from an electric vehicle database created. Based on the insights gathered, and by the use of TACMO, a Transport Application based Cost Model developed at the German Aerospace Center, comprehensive techno-economic assessment was done. Data was collected and results were compared regarding different countries like Germany, Austria, Turkey, the United Kingdom and South Korea. The results show that battery electric vehicles may competitive throughout the countries of investigation and that fuel cell electric vehicles are by far, currently, not an economic solution mainly based on high costs of the fuel cell system and the high hydrogen prices per MJ energy carrier in comparison to electricity and diesel fuel prices. Purchase tax, energy prices and resale value are identified as main influencing factors of the relevant cost of ownership calculation. The analysis done, therefore, enables not only the discussion of current cost effectiveness in comparison to conventional vehicles but enables also the discussion relating to obstacles and further research needs.

Keywords: Light duty commercial vehicle (N1), Total cost of ownership, alternative powertrains, Battery electric vehicle, Fuel cell electric vehicle

1 Introduction

Within all sectors of the global economy, emission reduction measures are required to counteract the negative environmental impacts as described within the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC) [1]. According to the International Energy Agency, the transport sector emitted 23 % of the worldwide CO_2 emissions in 2012, making it to the second largest contributor of CO_2 emissions after the power generation sector [2]. Additionally, road freight traffic activity has almost doubled worldwide over the last two decades [3]. As reported by Eom et al. [4] higher gradients for freight emissions compared to passenger travel emissions for most of the IEA countries are observed. Consequently, worldwide GHG emissions of road freight traffic are expected to increase unless significant improvements of fuel efficiency and/or fuel switch are realized. Current concentration is mainly on incremental technology developments to reduce fuel consumption of conventional vehicles [5], [6]. However, there may be potential for zero tailpipe emission vehicles that could result in the large-scale GHG reduction.

In order to investigate the feasibility and the potential of electrified transport logistic vehicles, this paper gives an overview of possible fields for electric vehicle application in the chapter 2 derived from demonstration projects in Germany, Austria, Turkey, the United Kingdom and South Korea. Additionally, chapter 3 gives an overview of current vehicle architecture and technology configuration.

By using the Transport Application based Cost Model (TACMO) of the German Aerospace Center, the relevant cost of ownership of battery electric and fuel cell electric vehicle technology configurations for a specific transport task has been investigated and compared to a conventional diesel driven vehicle within chapter 4. Only vehicles designed and constructed for the carriage of goods and having a maximum mass not exceeding 3.5 tonnes are examined (N1 category vehicles regarding European definition).

2 Possible fields of application

In recent years, there are increased activities for the development and operation of electric logistic vehicles. In order to identify early (niche) markets, ongoing and terminated demonstration projects considering the electrification of transport logistic vehicles have been identified and collected in a demonstration project database. In this database, main characteristics of the demonstration project are gathered (the name of the project, duration, status, overall aim, focus areas, fleet size of vehicles in test, vehicles category of vehicles in test, powertrain technology of vehicles in test and transport task of vehicle operation). Table 1 gives a summary for N1 category vehicles with corresponding transport task in different countries. The transport tasks of operation are clustered in urban delivery, regional delivery and air terminal operation. Urban delivery comprises in analogy to [7] the distribution in cities or suburban sites of consumer goods from a central store to selling points (e.g. “last-mile” delivery). Regional delivery covers the delivery of consumer goods from a central warehouse to local stores (e.g. “first-mile” delivery) [7]. Differences relates to the driving profile, payload factor and yearly mileage. On the other hand, air terminal operation is an interesting niche market, which is only observed in Germany. In Austria an electric road train is introduced between the regional air terminal and the city center of Klagenfurt.

Table 1: Activities for N1 category vehicles

Country	Powertrain technology	Transport task	Number of projects
GER	BEV/HEV	Urban delivery	7
GER	BEV/HEV	Regional delivery	3
GER	BEV	Air terminal	1
GER	FCEV	-	0
AUT	BEV/HEV	Urban delivery	4
AUT	BEV/HEV	Regional delivery	1
AUT	FCEV	Urban delivery	1
TUR	BEV	Urban delivery	7
TUR	BEV	Regional delivery	1
TUR	FCEV	-	0
UK	BEV/HEV	Urban delivery	1
UK	FCEV	-	0
SK	BEV/HEV	-	0
SK	FCEV	-	0

In Germany, eleven projects concentrate on N1 category vehicles powered either by hybrid (HEV) or battery electric (BEV) technology. Five out of eleven projects are already finished. None of the demonstration projects are concentrated on fuel cell electric vehicles (FCEV).

In Austria, four projects concentrate on N1 category vehicles powered either by hybrid or battery electric technology. All projects are ongoing. One of the demonstration projects also introduces fuel cell electric vehicles.

Seven projects have been completed in Turkey involving N1 category battery electric vehicles. Five of the projects are concentrated on the postal, express and parcel delivery services whereas one project is concentrated on e-grocery delivery and one is concentrated on catering service.

In the United Kingdom, the Low Carbon Vehicle Procurement Programme placed 200 battery electric or hybrid vans into operation in 21 public sector fleets for a minimum of one year real-world operation.

South Korea does not have any demonstration projects operating for the investigation of N1 category electric vehicles.

Most implementations focus on urban transport, while a few involves regional transport.

Unfortunately, real driving profiles are not available for the logistics vehicles within the mentioned demonstration projects. However, a dedicated research project in Austria has simulated real driving profiles of road transport vehicles, with the objective to derive simulated real-world energy consumption values and CO_2-emissions [8]. The simulations were based on typical logistic transport tasks, on real-world traffic conditions (level of service) and on different typical vehicle categories (N1, N2 and N3) combined with different propulsion system architectures. Vehicle driving profiles with electric propulsion systems were simulated for N1 and N2 vehicle classes, together with various conventional and hybrid electric propulsion systems. Nevertheless, the relevant cost of ownership (RCO) calculation approach, which is presented within chapter 4, requires knowledge about driving profiles. For this reason Common Artemis Driving Cycles (CADC), as shown in Figure 1, are used for generic driving profile generation and vehicle energy consumption calculation. New European Driving Cycle (NEDC) is not used due to the fact that this cycle does not reflect real driving conditions for light duty vehicles [9].

Key data regarding the CADC are [10]:

- Urban driving cycle:
  Average speed of 17.6 km/h, maximum speed of 57.7 km/h, driving distance of 4,870 m (including “engine start” phase, which are the first 73 seconds)
- Rural driving cycle:
  Average speed of 57.4 km/h, maximum speed of 111.5 km/h, driving distance of 17,272 m
- Motorway driving cycle:
  Average speed of 96.8 km/h, maximum speed of 131.8 km/h, driving distance of 28,736 m

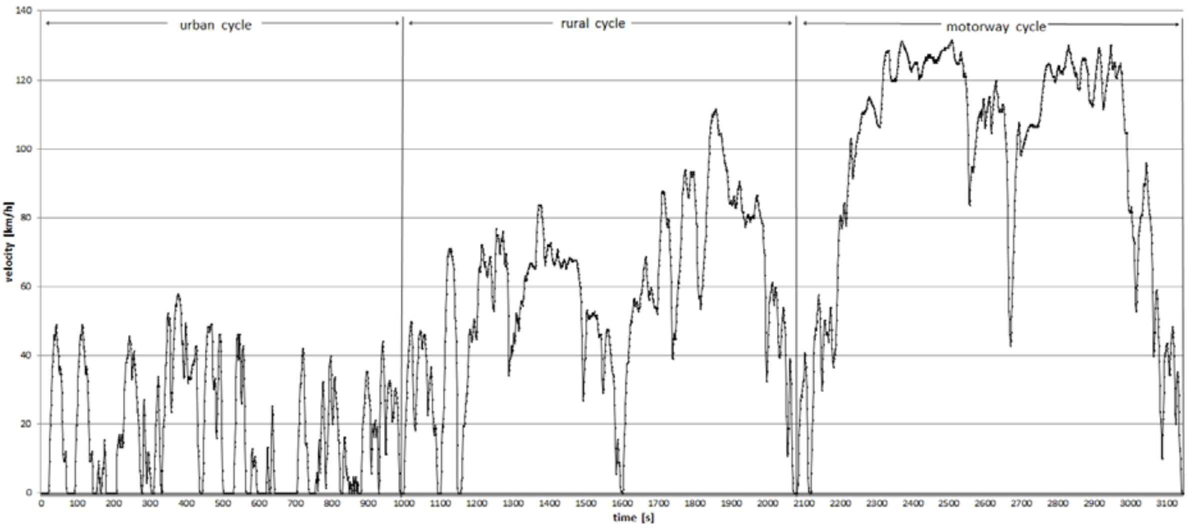

Figure 1: Common Artemis Driving Cycles (CADC) [9]

By specification of urban, rural and motorway driving shares, energy consumption can be calculated. Utilized driving shares in this paper are illustrated in Table 2.

Table 2: Transport task weighted driving shares

Transport task	Urban driving share	Rural driving share	Motorway driving share
Urban delivery	100%	0%	0%

Moreover, the information for payload factor and yearly mileage are required in order to perform RCO calculation. According to [7] payload factor of 50 % (in this case 385 kg) for urban delivery is used. The yearly mileage and vehicle holding period assumed, 20,000 km and four years respectively.

3 Overview of current vehicle architecture and technology configuration

There are increasing activities in terms of research and development of electric vehicle concepts. For the purpose of current state of the art, a vehicle database was created, where main characteristics of the vehicles are gathered (intended market, the producer, name of the vehicle, powertrain technology implemented, production status, vehicle category, etc.) In total, 74 vehicles are listed regarding the different vehicle categories N1, N2 and N3, whereof 49 are N1 category vehicles. Most of the N1 category vehicles (47) are equipped with battery electric powertrain technology. In addition, one plug-in hybrid electric and one fuel cell electric powertrain technology is listed in the database.
Within this paper, battery and fuel cell electric vehicle assessment in comparison to a conventional diesel vehicle is of particular interest. Figure 2, Figure 3 and Figure 4 show the powertrain concepts schematically. For a battery electric powertrain, required power for propulsion is provided by the electric drive system (including electric motor and power electronics) and the battery system. Depending on the vehicle concept and used electric motor, transmission is not obligatory. The battery is to be charged externally.

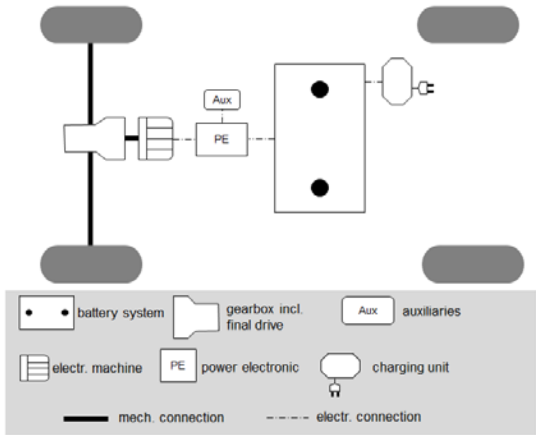

Figure 2: Schematic battery electric powertrain concept

According to registered vehicles technical data, mainly Li-Ion high energy battery technology and permanent magnet synchronous machines are implemented for battery electric logistics vehicles.
In contrary to the battery system, where the electricity is stored within the battery system, fuel cell systems produce their electricity on board via the reaction of hydrogen and oxygen. A battery (primarily high power system) is still required to operate the fuel cell system at ideal efficiency rates. Only the electrical multifunctional vehicle (EMF Citylog) has been identified as a N1 category fuel cell electric vehicle so far. Unfortunately, technical data is not available. However, looking at first mobile applications implemented in passenger cars and which are similar to the vehicles under investigation, current state of the art technology is the polymer electrolyte membrane fuel cell (PEMFC) in combination with hydrogen storage at 70 MPa pressure.

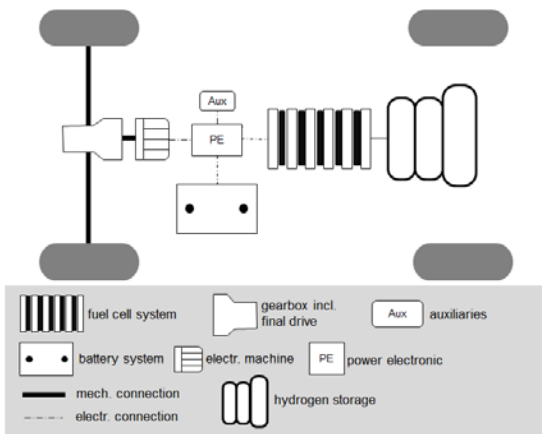

Figure 3: Schematic fuel cell electric powertrain concept

Conventional vehicles are powered by highly developed internal combustion engines utilizing diesel or gasoline as fuel (ICE-D/G). Within the vehicle N1 category vehicles, mainly four-cylinder inline diesel engines are implemented in combination with manual 6-Gear transmissions.

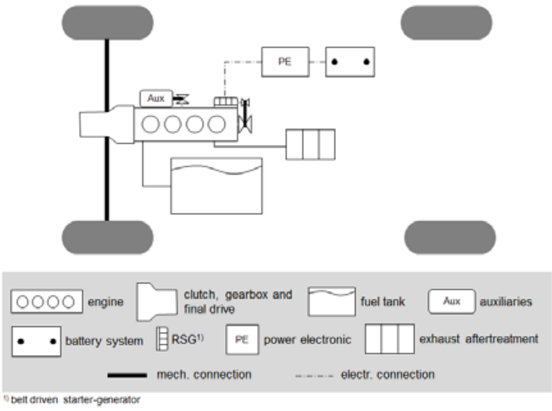

Figure 4: Schematic conventional powertrain concept

For the vehicle energy consumption simulation implemented within the RCO calculation approach, not only key powertrain configuration data is necessary but also key vehicle parameters are required. Table 3 illustrates key vehicle parameters used for this study. Gross vehicle weight (GVW) specification is taken as the median of collected gross vehicle weight data regarding battery N1 category battery electric vehicles. Other key vehicle parameters are based on own assumptions.

Table 3: Key vehicle parameters for N1 category vehicles

	unit	
GVW	kg	2,200
Cross-sectional area	m²	3.25
Air drag coefficient	-	0.38
Rolling resistance coefficient	‰	7.75

Same applies to key powertrain configuration data, shown in Table 4. The presented configuration data is based on the median of registered battery electric vehicles with the exemption of the average powertrain efficiencies. For the ICE-D vehicle, standard vehicle configuration for a comparable vehicle available on the market is used. Simulation mass is calculated by TACMO based on the vehicle configuration. Due to the high average powertrain efficiency, the battery electric vehicle shows the lowest final energy consumption but also has a limited driving range.

Table 4: Key powertrain configuration data used [a]

		ICE-D	BEV	FCEV
ICE max. performance	kW	55	-	-
Gearbox max. input torque	Nm	231	231	231
Diesel storage	l_{diesel}	60	-	-
EM & PE nominal power	kW	-	49	49
Actual usable battery capacity	kWh	-	22.5	2
FC-System nominal power	kW	-	-	49
H_2 storage (700 bar)	$kg_{Hydrogen}$	-	-	3.7
Vehicle tare weight	kg	1,430	1,478	1,517
Payload	kg	385	385	385
Simulation mass	kg	1,815	1,863	1,902
Average powertrain efficiency	-	0.31	0.68	0.41
Final energy consumption (urban delivery)	MJ/km	2.52	1.18	1.99
Range (urban delivery)	km	852	69	223
a) correspond to vehicles like VW Caddy or Citroën Berlingo				

4 Relevant Cost of Ownership comparison

Within this section, the economics of electric vehicles in comparison to conventional vehicles are analysed for urban delivery as transport task. By using a four-step evaluation approach, which is illustrated in Figure 5, relevant costs of ownership can be calculated for various vehicle concepts.

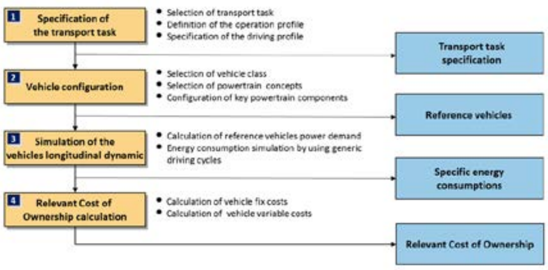

Figure 5: Four step evaluation approach used by TACMO

The evaluation approach is implemented in TACMO, a transport application based cost model, developed at the Institute of Vehicle Concepts of the German Aerospace Center.

Figure 6 schematically illustrates the relevant cost of ownership approach used within this study. Following cost data refers to the year 2013. Costs for the glider (of N1 vehicles) kept constant for each powertrain concept. The glider comprises all components except for the powertrain of a vehicle. These are the chassis (frame, suspension, braking system, etc.) and the body (platform, cab, etc.). Main cost components for different powertrain configurations are shown in Table 5.

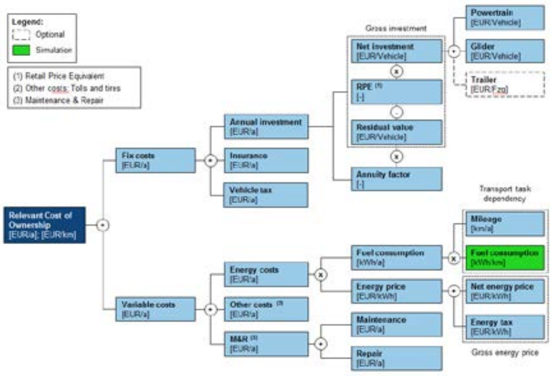

Figure 6: Relevant Cost of Ownership approach

Table 5: Main cost components for N1 vehicles in EUR_{2013} based on [11]

	ICE-D	BEV	FCEV
Glider	12,446	12,446	12,446
ICE-D	2,035	-	-
Gearbox	931	-	-
Diesel storage	120	-	-
Exhaust after-treatment (Euro 6)	858	-	-
EM	-	1,764	1,764
PE	-	735	735
Battery system	-	8,550	1,520
FC-System	-	-	47,775
H_2 storage	-	-	3,083
Net-Investment	16,390	23,495	67,323
Gross-Investment	22,127	31,718	90,886

The retail price equivalent (RPE) factor is a common used mark-up to compare the Net-investment costs with all other factors that influence the final price of a vehicle like dealer profit, dealer cost, manufacturer profit and manufacturer overhead. The retail price equivalent factor is set to 1.35 according to [12], and kept constant for all powertrain concepts considered. It is assumed that vehicle insurance for new technology implementation will be higher taking the higher risk of a new technology into account. Therefore, in analogy to [13], vehicle insurance cost correlate with vehicles gross investment cost. A default value of 1.5 % is taken for this study [13]. Country related differences in cost data necessary for RCO calculation are illustrated in the following Tables. Contrary to Germany and the United Kingdom, Austria, Turkey and South Korea collect a one-time tax at vehicle purchase (based on net purchase price), which has to be considered. Net purchase price (without taxes) is equivalent to the Gross-Investment cost shown within Table 5. Purchase taxes considered are illustrated within Table 6. Additionally, motor vehicle tax calculation method varies across the countries of consideration and, therefore, different expenditures have to be considered as shown within Table 7.

Table 6: N1 vehicle purchase tax in EUR_{2013}

Country	ICE-D	BEV	FCEV
GER	0	0	0
AUT [a]	1,390	0	0
TUR [b]	2,213	3,172	-
UK	0	0	0
SK	885	0	0
a) Based on [14] b) Based on [15]			

Table 7: N1 motor vehicle taxation in EUR_{2013}/a

Country	ICE-D	BEV	FCEV
GER [a]	125	0	0
AUT [b]	231	0	0
TUR [c]	479	479	-
UK [d]	772	0	0
SK	830	0	0
a) [16] b) [17] c) [18] d) [19]			

Same applies to the gross energy prices. Values given within Table 8 correspond to the yearly average prices of 2013. As to electricity, prices including all taxes and levies for industrial demand of 20 MWh < consumption < 500 MWh, reported by [20] and VAT adjusted are used for the calculation. Korean energy prices refer to [21]. Diesel fuel and hydrogen prices given, correspond to prices at refueling station, whereas prices for electricity do not include recharging point investment. For that reason additional investment of 950 EUR_{2013} [22] for a recharging point (Wallbox) is added to the Gross-investment costs of the BEV.

Table 8: Gross energy prices in EUR_{2013} excluding VAT (GER: 19%, AUT: 20%, TUR: 18%, UK: 20%, SK: 10%)

Fuel	Diesel	Electricity (Industrial)	Hydrogen
Unit	$€_{2013}$/l	$€cent_{2013}$/kWh	$€_{2013}$/kg
GER	1.13	18.20	12.00
AUT	1.12	13.13	9.10
TUR	1.42	9.19	-
UK	1.56	13.36	-
SK	1.19	6.79	10.83

According to [23] maintenance and repair expenditures are 0.072 EUR_{2013}/vkm for ICE-D, 0.058 EUR_{2013}/vkm for BEV and 0.063 EUR_{2013}/vkm for FCEV. These expenditures do not include battery replacement. Current warranty periods of original equipment manufacturers (OEM) are between 5 and 8 years which correspond to approx. 97,000 km and approx. 161,000 km respectively [24], [25], [26], [27]. Vehicle holding period for this study is set to four years and, therefore, consideration of battery replacement is not required. Besides taking maintenance and repair expenditures into account, a comprehensive assessment requires the consideration of a vehicle's resale value. As data regarding alternative powertrain is still very rare, the model presented within [23] is used for resale value calculation. Hence, resale values after four years with an annual mileage of 20,000 km are result in 13,952 EUR_{2013} for ICE-D, 22,484 EUR_{2013} for BEV and 58,339 EUR_{2013} for FCEV.

The results, illustrated in Figure 7, show that based on the data used and explained within this section, battery electric vehicles may competitive throughout the countries of investigation. Furthermore, fuel cell electric vehicles are by far, currently, not an economic solution which is mainly driven by the high cost of the fuel cell system and the high hydrogen prices per MJ energy carrier in comparison to the German electricity (approx. factor 2) and diesel fuel (approx. factor 3) prices. Purchase tax, energy prices and residual value are main influencing factors of the relevant cost of ownership calculation. Nevertheless, the driving range limitation of electric vehicles is still an issue. Therefore, the implementation of battery electric vehicle usage has to be decided by the fleet operator individually based on whether the transport task requirements can be fulfilled.

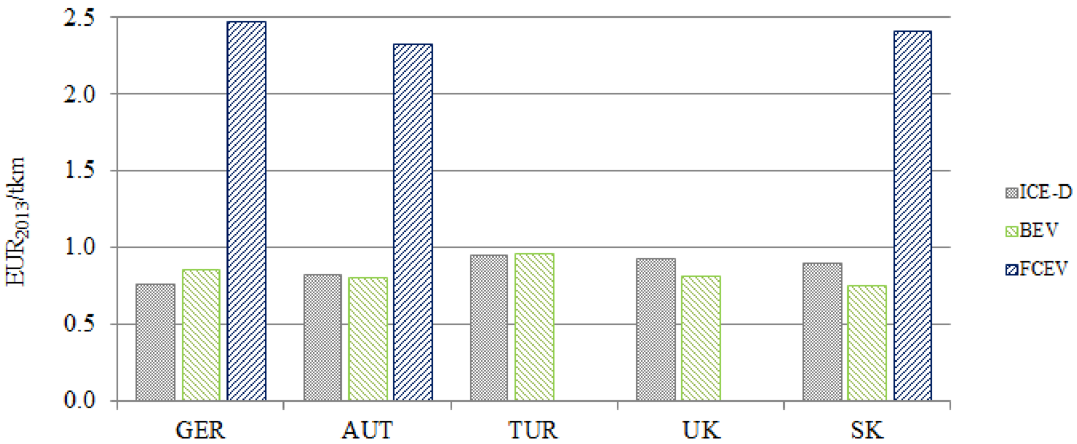

Figure 7: Comparison of country individual Relevant Cost of Ownership per ton-kilometers

5 Conclusion

In this paper, BEV and FCEV powertrains for N1 category vehicles are investigated for possible fields of application, current vehicle architecture and their relevant cost of ownership in different countries with different taxation schemes and energy prices.

The results show that demonstration projects are focused mainly on battery electric vehicles for the N1 category with the urban delivery transport application. Other applications are regional delivery and air (or harbour) terminals.

The results for the current vehicle architecture in different countries indicate that the OEMs are concentrated for BEVs in the N1 vehicle category instead of HEV, PHEVs or FCEVs.

The relevant cost of ownership results for urban delivery application show that battery electric vehicles are (almost) competitive throughout the countries of investigation and that fuel cell electric vehicles are by far currently not an economic solution mainly based on high costs of the fuel cell system and the high hydrogen prices per MJ energy carrier in comparison to the electricity and diesel fuel prices. These results explain also why manufacturers and current demonstration projects activities do not concentrate on fuel cell electric vehicles. Purchase tax, energy prices and residual value are identified as main influencing factors of the relevant cost of ownership calculation.

Future work regarding alternative powertrains for transport logistic vehicles might be a sensitivity analysis for the main influencing factors identified in this paper, investigation and comparison of different transport tasks (urban delivery, regional delivery etc), and investigation of N2 and N3 category vehicles. Overall research, therefore, may focus on summarizing the status of vehicle technology and hurdles of implementation, identifying early niche markets and providing policy recommendations for further research and deployment activities.

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Authors

Florian Kleiner, Research Associate at the German Aerospace Center (DLR). He studied Business Administration and Engineering at Pforzheim University and the University of Technology Sydney (UTS). After graduating his Master degree regarding energy management with specialization in renewable energy at Trier University of Applied Sciences, he is working at the DLR Institute of Vehicle Concepts in the department of Vehicle Systems and Technology Assessment.

Dr. Enver Doruk Özdemir is team leader for road vehicles at the Department of Vehicle Systems and Technology Assessment (Institute of Vehicle Concepts) at German Aerospace Center (DLR) since January 2013. He completed his Ph.D. degree on “alternative powertrains and fuels” in 2011 at the Stuttgart University (Institute for Energy Economics and the Rational Use of Energy). Dr. Özdemir received his

Master Degrees in Mechanical Engineering in 2005 at Middle East Technical University (Ankara, Turkey), where he also studied Mechanical Engineering (B.Sc.) and Sociology (B.Sc. - double major program).

Martin Beermann, Research Associate at JOANNEUM RESEARCH in Austria. He received his master degree in Environmental Process Engineering at Leoben University in Austria. Working at JOANNEUM RESEARCH since 2008, he is focussing on alternative energy and transport systems with a methodological focus on ecological life cycle assessment and life cycle cost assessment.

Bülent Çatay is an Associate Professor of Industrial Engineering in the Faculty of Engineering and Natural Sciences at Sabanci University, Istanbul. He received his B.Sc. in Industrial Engineering from Istanbul Technical University and his Ph.D. in Production and Operations Management from University of Florida. His research interests include transportation and logistics systems, green transport, applied optimization, metaheuristic approaches to solve large-scale problem.

Dr Bob Moran is Head of Regulation and R&D in the UK's Office for Low Emission Vehicles, a cross Government policy unit working to position the UK as a leader in the design, development, manufacture and deployment of ultra low emission vehicles and associated technologies. OLEV comprises people from the Department's for Transport, Business, Innovation and Skills and Energy and Climate Change and aims to simplify policy development and speed up delivery of this important shared agenda. Bob joined OLEV in 2011 having previously worked with the Department for Transport and Ford Motor Company. He was awarded a Ph.D. in Biomechanical Engineering from Edinburgh University in 2002 having graduated from there with an Honours degree in Mechanical Engineering in 1997.

Dr. Stephan A. Schmid is Head of Department at the Institute of Vehicle Concepts at the German Aerospace Center (DLR). He is the National Scientific (Alternate) Delegate of Germany for the Implementing Agreement 'Hybrid and Electric Vehicles' of the International Energy Agency. Dr. Schmid served from 2011 to 2013 in addition as DLRs Transport Representative in Brussels. Dr. Schmid holds a diploma degree in Mechanical Engineering from the Technical University of Karlsruhe, and received his doctoral degree (Dr.-Ing.) in Engineering from the University of Stuttgart.

Prof. Dr. Ock-Taeck Lim received his B.S. and M.S. degrees in Mechanical Engineering from Chonnam National University, Korea, in 1998 and 2002, respectively. He then received his Ph.D from Keio University in 2006. Dr. Lim is currently a Professor at the School of Automotive and Mechanical Engineering at Ulsan University in Ulsan, Korea. Dr. Lim's research interests include internal combustion engines, alternative fuel, and thermodynamics.

Prof. Dr. H. E. Friedrich is Director of the Institute of Vehicle Concepts at the German Aerospace Center in Stuttgart. The institute develops concepts of road and rail vehicles of next generations. The research fields are Alternative Power Trains and Energy Conversion as well as Light Weight Design and Hybrid Construction methods. At the same time he became professor at the University of Stuttgart and he is lecturer at the Technical University of Berlin.