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Sustainability evaluation of electric taxi fleet in the city of Poznan

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Abstract

One of the factors affecting the reduction of the environmental burden from the road transport is the replacement of the conventionally-fuelled vehicles by other types of powertrains, including the electric drives.
The paper relates to the possibility of the implementation of the electric taxicabs in the city of Poznan, an agglomeration of 550 thousand inhabitants, located in the western part of Poland.
Several variants of fleet electrification have been analysed by authors. The scenarios differed in the number of taxis, a number of shifts and the way of charging. In the paper the results of total fleet electrification, i.e. 1800 taxicabs operating in two-shifts mode and using quick charging stations are presented. For this variant benefits associated with reduction of CO2 and economic impact of using electric vehicles have been estimated. The results have been compared with the emission and costs of conventionally fuelled vehicles.

Keywords: electric vehicles, taxi fleet, sustainable city.

1 Introduction

Transport development provides economic opportunities, drives growth and helps to bring a better quality of life. Unfortunately transport generates a number of external costs such as congestion, noise, emission of harmful substances into the environment, depletion of non-renewable resources and energy consumption.
The environmental burden from the road transport may be reduced by replacing the conventionally-fuelled vehicles by other types of powertrains, including the electric drives. Electric vehicles can be a solution to a number of problems that are

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generated by transport in the city – they generate less noise and less pollution (compared to vehicles fitted with combustion engines). Vehicle electrification has significant potential to reduce fuel consumption, minimize the CO2 emission and diversify energy sources. One of the main disadvantages of these vehicles is the need to build a network of charging stations. Moreover, electric vehicles have a limited range that depends on the capacity of the battery and its service life. The cost of production of the batteries influences the already high cost of electric vehicles compared to conventional vehicles.

The introduction of the electric vehicles may become the key element in the sustainable transport strategy development in urban areas, but due to the fact that electric vehicles are still unpopular, the demand for these vehicles should be boosted by the vehicles fleets owners, especially by the companies providing transport services. Electric vehicles are particularly useful in taxi operations, because taxi cabs are used mainly in the city and the time spent at the taxi stand can be used for battery charging.

Taxis are great polluters in the city. A taxi based in Amsterdam produces on average an equal amount of exhaust fumes as 35 private cars [8] and in cities with a large number of taxis such as Tokyo, conventionally powered taxis generate 20% of the air pollution [3]. The introduction of electric cabs is therefore a good solution to reduce the exhaust emissions and it popularizes the idea of electric transport among the citizens.

Electric taxi fleets have been introduced in several cities and some other cities are introducing or planning to introduce the clean fleet concept. A total fleet of 3000 taxis operates in Amsterdam, around 2500 taxis are active during the working week and this number rises at the weekend. The Dutch capital is striving to have about 500 electric taxis active in the city. Amsterdam-based Taxi Electric was the first private taxi company to switch to a fleet of 100 percent electric taxis in 2011. From October 2014, all journeys by taxi departing from Amsterdam Airport Schiphol are made in electric cars. A fleet of 167 Tesla S taxis is the largest fleet of all-electric taxis of any airport in the world.

The largest fleet of electric taxis is used in Beijing. In the capital of China a total of almost 46 000 taxis are registered. In order to reduce the exhaust emissions, the Beijing authorities decided to solve the problem by introducing a fleet of electric taxis. In 2011 there were 50 electric vehicles in the streets and in 2015 this number grew to 3400 [2]. In June 2014, the municipal government enacted "Plan for Demonstration and Adoption of EVs in Beijing (2014-2017)", stating that all the taxis in ten suburban cities will be replaced with electric vehicles gradually, and new deployment of taxis in urban area must be electric cars [9]. The projected demonstration scale should exceed 5000 in 2017.

The authorities plan to electrify 15% of the taxi fleet in Zurich and 30% in New York. However, the most ambitious plans have London authorities, which announced the total electrification of the taxi fleet by 2020 [7].

In Poland, there is only one taxi company, based in Warsaw, providing since 2012 transport services with fully electric cars. Poznan, with its population of over

550 000, is the fifth largest city in Poland, and together with the neighboring suburban area, it makes up an agglomeration inhabited by nearly one million people. There are currently 3000 taxis operating in Poznan, usually working at one shift with annual mileage of the vehicle of 38000 km (average 10,39 km/fare).
Assessment of taxi fleet electrification scenario is based on the analysis of the impact on sustainable transport development in the City of Poznan taking into account the environmental and economic aspects and comparing to conventionally powered vehicles. The detailed results of the simulation contain the following information:

- vehicle charging infrastructure,
- total CO2 emissions for the fleet,
- operating cost of taxicabs.

2 Fleet Electrification Assumptions

Currently in Poznan there are no electric taxicabs. This is due to the fact that in the city there are almost no charging stations (there is one charging station in the city centre and two charging stations installed near large shopping malls - one in the south and the other in the north of the city). What is more, there are no incentives to purchase electric vehicle at all. The charging stations are not subsidized either. No infrastructure and lack of incentive programs virtually blocks the sales of electric vehicles in Poland. But recently, the Poznan city authorities have taken steps to develop a strategy for sustainable transport, which is why the implementation of environment friendly solutions, including electric taxis, stands a chance.
Several variants of taxi fleet electrification have been analysed. The scenarios differed in the number of taxis, a number of shifts (one, two or three) and the way of charging. Two scenarios of fleet electrification have been considered: 50% and 100% of the fleet.
Because of to the lack of charging stations in Poznan all the charging options have been taken into account. There are three ways to charge a vehicle: traditional (3-7kW, works fine only in a one-shift system), accelerated (22kW) and quick (50kW, the best solution for intense vehicle use) [3]. Quick charging stations are too expensive for the one-shift system because the cost of infrastructure is very high and the taxi still remains idle for most of the day (operates an average of 4 hours per shift), but they are the only available option in a three-shift system. In a two-shift system one can use both accelerated-charging and quick-charging terminals.
Another problem was the choice of the vehicle model. Not every electric vehicle available in the market can be used as a taxi. Only four- or five-door vehicles should be used for commercial carriage of passengers. The vehicles must also have sufficient luggage space. Out the vehicles available in the Polish market, Renault Fluence, Renault Kangoo, Nissan Leaf and a passenger version of Nissan

eNV200 can be used as taxis. From the compared models of electric vehicles the Nissan Leaf has the lowest costs of operation. Its advantage, similarly to the other model of the Japanese manufacturer (eNV200) is the possibility of quick battery charging with direct current based on the Chademo standard. The battery of Renault Fluence and Renault Kangoo cannot be charged in this way.

The design, technical characteristics and results of the actual performance of Nissan Leaf were analyzed in detail. This allowed obtaining data necessary to build a simulation model and to validate the model of electric vehicle energy consumption. For the purpose of estimation of the battery charging time, an analysis has been performed of available methods of battery charging and charging stations in terms of their technical characteristics.

For the averaged values of the number of taxicabs, the lengths and numbers of trips as well as the energy consumption level, a simplified model was created of energy consumption by a fleet of taxicabs and their averaged ranges including the demand for SOC level and charging time depending on the type of charging station.

In the remaining part of the paper the results of total electrification of taxicab fleet i.e. 1800 taxicabs are presented. The number of 1800 taxis was chosen due to the fact that the authors assumed the two-shifts working day and calculated the number of taxis based on average daily vehicle-hours.

3 Modeling Tool

The emissions value were estimated using the software MATSim, in which traffic in the Poznan urban area (both private vehicles, taxicabs and public transport) was modeled and simulated. MATSim is an open-source framework to implement large-scale agent-based transport simulations. In recent years, there have been substantial developments of activity-based models in travel modeling, including also agent-based simulation. In these models, the need of performing an activity is the basic element of analysis, while travelling is its derivative. Due to that, all trips of a given person are logically connected, both in space and time, which results in a chain of interleaving trips and activities. Such models have been created for many cities, including Zurich, Berlin or Tel Aviv [1,4]. Research studies have proven that the results obtained with the multi-agent activity-based simulation are more consistent with the reality (for instance, in terms of traffic flows, travel times etc.) than the classical 4-step approach [6].

The development of the MATSim scenario for the Poznan agglomeration began in 2012, and since then, the model has been continuously extended and improved. It is a 24-hour multi-agent activity-based simulation of the Poznan agglomeration, combining both private and public transport.

The road network model was extracted from Open Street Map (OSM) and includes all roads and link roads (such as entrances or exits from motorways). The authors decided to create an algorithm for automatic generation of a network model for the Poznan agglomeration, and used OSM for this purpose. The final result is a high-detail road network model that consists of 17026 nodes and 40129 links. This model was calibrated in order to determine traffic flow parameters for links (e.g., flow capacity, storage capacity, freeflow speed) for each of the 13 modeled road classes [5]. The travel demand model was derived from the official trip-based 4-stage model used by the planning department of the city of Poznan. This model dates back to 2000, but since then has been frequently updated. Since the official model was originally designed for the morning and afternoon peak hours, it had to be extended to describe travel demand throughout the day, hour after hour. As a result, the demand for private transport is represented by 24 sets of hourly origin-destination (O-D) matrices, each set consisting of nine different matrices, one for each of nine travel motivations, namely home → work/education/shopping/other, work/education/ shopping/other → home, and not related to home. This totals up to 216 origin-destinations matrices [6]. Having calculated the O-D matrices and subdivided the area into homogenous subzones, the next step was to generate the population of agents. In the first attempt, an assumption was made that each agent performs only one trip, so the number of agents equals the demand represented by the O-D matrices, which is almost 840 000. Departure times were randomly distributed (uniform distribution) over each hour, and therefore, the only decision made by each agent during the replanning phase concerned the route choice for the preselected pair of locations.

Figure 1: Microscopic road traffic simulation in the Poznan agglomeration (at 7:00)

The described Poznan model has been used for simulation of realtime electric taxi dispatching, which is done by means of the Dynamic Vehicle Routing Problem

(DVRP) extension. The DVRP software allows detailed simulation of rapidly changing demand and supply of services, but also the traffic flow and other related transport services. It is used to simulate a variety of problems of fleet management such as vehicle routing problems, allocation of vehicles and drivers to tasks or scheduling charging of electric vehicles, allowing research on effective strategies for online fleet management. Additionally, the ability to conduct simulations of the system in many variants allows the use of DVRP software to support decision-making process on strategic (charging stations location) or tactical (fleet size, toll system) problems.

In order to assess the environmental impact of the fleet electrification, the MATSim simulation model had to be updated with CO2 emissions module. Based on the analysis of existing emission models, the HBEFA (HandBook Emission FActors for road transport) model has been chosen as a database for MATSim emission module. HBEFA provides fuel consumption and emission factors, i.e. the specific emission in g/km for all current vehicle categories, for a wide variety of roads and traffic situations. The types of vehicles and roads are clearly classified. Vehicles are divided into passenger cars, light duty vehicles, heavy duty vehicles, buses and motorcycles, and the roads are determined by location (urban or rural), destination (main or local), sinuosity, the slope and the current traffic conditions (e.g. freeflow, discrete). Traffic data (local travel patterns) determine the cycles of test-drives for measurements on chassis dynamometers and determining appropriate (for a given type of traffic) emission factors.

4 Vehicle charging infrastructure

Due to oversupply of taxicabs (in Poznan taxicabs drive on average only 100 km) the main limitation in taxicab fleet electrification is the extent of the charging infrastructure. If we want to avoid over-investing in the charging infrastructure we need to assume that at certain times of year (winter in particular) the use of infrastructure will be close to 100%, while the taxicabs will need relatively short time for charging (usually 10-20% of the idle time; total idle time is approx 50% of the entire taxicab operating time). As a result, the critical resource is the charging station, not the taxicab. Such a specificity of the problem has great impact on the method of fleet management. There are two strategies of charging:

a) The closest charging station – This strategy emulates typical behaviors of the drivers of electric taxicabs, when the scheduling system is not centrally controlled. To the best knowledge of the authors, this is the only method of organization of the taxicab charging process in all electric taxicab implementations worldwide. The advantage of the system is its simplicity, yet, due to a lack of coordination it is necessary to group the chargers into large charging stations (one or several). It is assumed that taxicabs set off to the charging point when the battery level drops below a given threshold (e.g.

30 or 50%).

b) The problem of assigning chargers to the taxicabs – This strategy solves the problem of assigning chargers to taxicabs in a coordinated fashion aiming at best possible use of the chargers and the taxicabs globally. As the vehicles are planned to be charged in the quick-charging mode, they are charged until the SOC (state of charge) level of 80% of the usable battery capacity is reached and then they are disconnected for the next vehicle to start charging. The charging process may end early only if the taxicab has been given a fare to service.

The analysis of supply and demand of the taxi services performed based on the recorded taxicab routes in Poznan and the estimation of traffic energy consumption in the recorded routes have shown that:

- Approx. 50% of the time the vehicles remain idle, hence, from the point of view of a single vehicle, quick charging while the taxicab is on duty is not a problem, even in the winter season. The preliminary energy consumption analyses for the recorded routes have shown that even at low temperatures when the heating system is permanently on, the time needed for quick charging (low temperature mode – 25 kW) is approx. 24% of the taxicab operating time (42% idle). For slow charging, it would be necessary to use an additional heating source.
- More than 95% of the trips are carried out within the city limits and more than 99% of the trips are shorter than 20 km (longer trips are agreed on separately). As a result, as long as the taxicabs are charged continually, their limited range is not an actual limitation from the point of view of a single taxicab, irrespective of the weather conditions.

In light of the above the fundamental factor having impact on the functioning of the electric fleet is the charging infrastructure, particularly, the type, number and location of the chargers as well as method of scheduling of the charging process.

The economic analysis (see point 6) has shown that it is more economical to use electric vehicles in a two-sift mode (the vehicles belong to a taxi company). Besides, quick chargers are a preferred option, particularly when the fleet operates in the winter. Assuming operation in shifts, it is impossible to charge the vehicle after working hours, hence, the infrastructure must be composed in such a way to enable the vehicles' regular charging even at times when the system is heavily loaded (many fares and many vehicles). Friday is a critical day, when high taxi traffic (typical of working days) lasts until 16:00 and after 17:00 weekend evening peak occurs. For Fridays,on average, 1.3 fares fall for 1 vehicle/hour, which translates into 14.1 kilometers covered in just below 30 minutes. On this basis the minimum number of chargers and charging times have been estimated depending on the weather conditions for the time window Friday 7:00 – Saturday 4:59 (table 1). It is noteworthy that in the spring, summer and fall it is possible to use the normal power capacity of the quick chargers (50kW), while in the winter in the low temperature mode it is only 25kW.

Table 1: Required number of charging stations depending on season

	Summer (with A/C)	Spring/ Autumn	Winter (with heating)	Winter (independent heating)
Vehicle-hours	2948	2948	2948	2948
Energy [kWh]	10271,9	7692,4	16536,4	7692,4
Energy/hour [kW]	466,9	349,7	751,7	349,7
Number of charging stations	9,3	7,0	30,1	14,0
Time of charging (per shift) [h]	0,6	0,8	3,6	1,7
Charging as % of idle time	7%	10%	42%	20%

Under subzero temperatures, when taxicab interior heating is required (including when stationary), an extended charging infrastructure is necessary. For the analyzed fleet of vehicles the number of chargers is 31 assuming 100% of use and assuming that during a single charging we can charge not more than 60% of the battery usable capacity (quick charging up to 80% SOC) and the vehicle must get to the charging station not less than every 2.1 hours.

A solution worth considering in the e-mobility adaptation period is the application of heating powered with liquid fuel (e.g. Webasto) which would reduce the demand for electrical energy to the spring/fall level but the vehicles will still need to stay at the charging station twice the regular time due to reduced charging speed.

At high temperatures vehicles must get to the charging station approx. every 3.4 hours and in the outstanding time of year every 4.6 hours, which enables a better distribution of the load of a charging station in time.

Due to the unpredictability of taxicab arrival at the charging station (depending on the taxicab coordination level), the charging infrastructure must be adequately larger to ensure accessibility as the vehicles arrive.

In order to optimize the charging stations, it was initially assumed that the number of chargers for the variant with the heating powered by liquid fuel should be 18 (i.e. 4 chargers above the minimum). Without charging coordination it is necessary to group the chargers in large charging stations, which is the case for all electric fleet implementations to date. It does have a downside however – an extended charging station arrival time. It was assumed that the variant of 18 chargers located at the central station is the output variant and then tests were performed whether upon the introduction of coordination it would be possible to locate the chargers more evenly maintaining their constant number. The objective was the reduction of the traveled distance (no fare) at the same size of the charging infrastructure. The following variants of location were prepared for the configuration: 1x18 (1 station 18 chargers), 2x9, 3x6, 6x3, 9x2 and 18x1 (18 stations one charger each). The above variants were evaluated in a simulation using the Poznań agglomeration model in the MATSim software. The strategy of 'closest charging station' was tested only for the 1x18 variant (lack of coordination forces the use of a central charging station). For comparison, a simulation of a fleet of conventionally fueled taxicabs was performed.

9x2 (9 locations) | 6x3 (6 locations) | 1x18 (1 central station)

Figure 2: Examples of charging stations locations

Table 2: Effectiveness of taxi services with and without coordination and for different combination of charging stations

	Without coordination	*Scheduling of charging*				*Diesel taxi*
		1x18	*3x6*	*9x2*	*18x1*	
Distance without client [km]	40,2	39,7	39,3	38,6	38,3	37,6
Distance with client [km]	75,2	75,2	75,2	75,2	75,2	75,2
Total distance [km]	115,4	114,9	114,5	113,8	113,5	112,8
Distance without client as total distance [%]	35%	35%	34%	34%	34%	33%
Time of travel to client [min]	7,5	7,4	7,4	7,3	7,3	7,2

Table 2 presents the efficiency of the taxi services from the point of view of an individual taxi driver (8 hour shift) and the fare (client). Because electric taxicabs must be recharged, they must cover longer distances without a fare. Besides, the average time needed to get to the client is extended as part of the trip begins at the charging station. The changes in the indexes, however, are on the level of several percent, hence they do not result in a drop in the service quality or increase of costs. The best solution is to distribute the charges in accordance with the energy demand spatial distribution (the 18x1 variant). This, however, forces coordination of the charging process.

5 Assessment of Environmental Impact

Based on the results of the simulation of electric vehicles (MATSim and the battery charging discharging module) it was possible to determine the global consumption of electrical energy. Then, based on the emission coefficients for electrical energy, depending on its source, the level of global emissions was obtained (use of energy sources to power vehicle fleets).
Taking into account the total emissions (well-to-pump and pump to wheels) electric taxis are always a better choice if they are charged using the so-called green energy. If the taxis are charged with a "typical" electricity produced in Poland (energy mix: 85% coal, lignite and gas, 15% renewable sources) the advantages are not obvious.

Table 3: Comparison between the daily CO2 emissions for taxi operations in the city of Poznan for electric and conventionally fuelled taxis (1800 vehicles operating in two shifts)

Season	Electric taxis CO_2 emissions (kg)					Diesel taxis CO_2 emissions (kg)
	Without coordination	Scheduling of charging				
		1x18	3x6	9x2	18x1	
Spring and Autumn	3980	3850	3710	3490	3420	4170
Summer (with A/C)	5570	5390	5210	4910	4810	9 960
Winter (with standard heating)	9420	9140	8840	8350	8200	7 830
Winter (with independent heating)	5750	5620	5480	5250	5180	7 840

Table 3 shows the results of simulations for daily CO2 emissions (measured in kg) assuming the emission of 820 g of CO2 per kWh and using the diesel variant for conventionally fuelled taxis. In the case of winter two heating options were considered: standard heating (battery/fuel) and independent (webasto heating system with fuel). The independent heater does not draw power away from the battery and therefore maintains the range of electric vehicles. Basically, the transition to electric taxis results in a reduction of CO2 emissions throughout the year except for winter.
The benefits ranges from 44% to 52% for the summer to 5% to 18% for spring and autumn. In winter period with standard heating electric taxicabs emit 5% to 20% more of CO2. Only a change to alternative independent heating gives a reduction in CO2 emissions (27% to 34%).

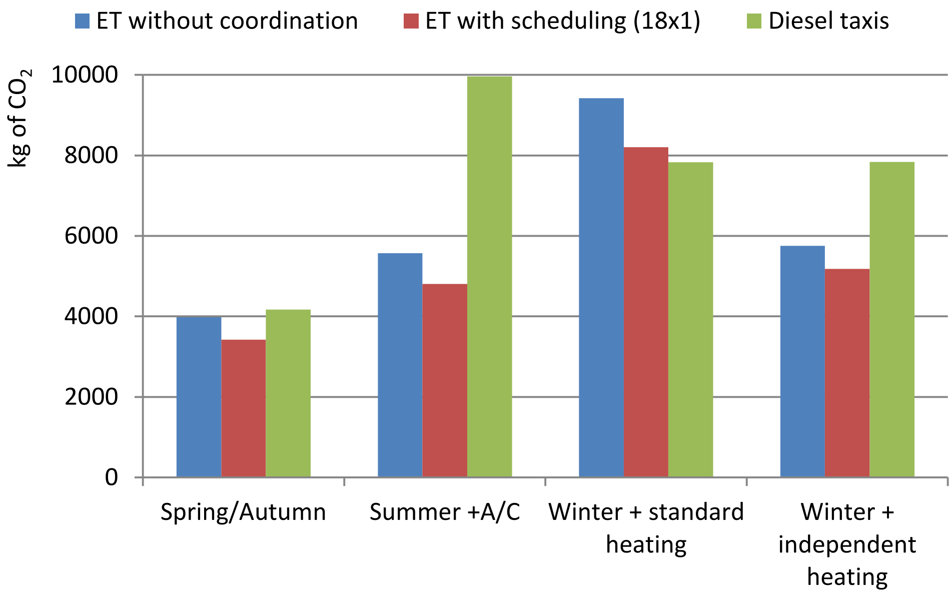

Figure 3: Emissions of CO2 for electric taxis (ET) and diesel taxis

The simulations have also been performed for a mixed fleet (50%/50%) with 10 charging stations instead of 9. The obtained results indicate that it is a good solution only if good coordination of vehicle charging is secured. If the charging processes are not coordinated, a significant increase in the number of charging stations per one electric vehicle will have to take place. The outstanding results (emissions, arrival time, idle kilometers, fare waiting time) change proportionally to the share of electric vehicles in the entire fleet.

6 Assessment of Economic Impact

From the perspective of a taxi operator, the analysis of the operating costs, including the initial expenditure is of paramount importance. The greatest impact on the operating costs of electric vehicles have: the purchase of the vehicle (depreciation), battery renewal or battery lease and the costs of consumed energy.
Table 4 presents estimated annual costs of operation of chosen electric vehicle i.e. Nissan Leaf that were compared to the models fitted with diesel engines of similar technical parameters.
The adopted assumptions for the cost analysis are as follows:

- The purchase price is reduced by 15% of the catalogue price for fleet purchase.
- The cost of purchase is included as the cost of depreciation. A 4-year period of depreciation is assumed (at 0.25).
- Annual mileage of the vehicle is 80500 for electric vehicles and 79100 for

diesel vehicles (two shifts, 115 km per shift for electric taxis and 113 km for diesel vehicles, 350 working days in a year).

- For electric vehicles, an additional cost is the renewal of battery. The purchase of a new one after 160000 km has been assumed for Nissan Leaf.
- Inspection intervals have been assumed at 20000 km; maintenance service of electric vehicles is 15% cheaper compared to conventional vehicles.
- Net cost of energy is 0.11344 euro/kWh.
- Net cost of diesel fuel 1.0326 euro/l.
- Daily consumption of energy for electric vehicles is 33.18 kWh (15.97 kWh/100 km).
- Daily consumption of fuel for vehicles fitted with combustion engines - 8l/100 km in the urban cycle + 4l/day of stoppage.
- Annual cost of insurance was assumed at 3% of the vehicle value.
- Cost of battery amount to 10618 euros. With 2-year depreciation (resulting from the battery use) the annual cost will amount to 5336 euros.
- The operating cost does not include driver wages.
- All costs included in the calculation are costs net of VAT.
- All euro amounts were converted at 1 euro = 4.3 Polish zloty.

Table 4: Comparative analysis of the operating costs of electric and conventional vehicles

	Nissan Leaf	*Nissan Juke dci110HP*	*Nissan Qashqai dci110HP*
Net price [euro]	20 250	10 993	11 152
Depreciation [euro/year]	5 062	2 748	2 788
Insurance [euro/year]	607	330	335
Battery exchange [euro/year]	5 336	0	0
Service [euro/year]	632	732	732
Cost of fuel or energy per day [euro]	4.21	23.1	23.1
Total cost per year [euro]	13 112	11 880	11 925

Annual cost of operation of Nissan Leaf taxicab, based on the mileage of 80500 km per year, amount to 13112 euros. Comparing this cost with the costs of operation of taxis fitted with combustion engines (diesel), the annual cost of operation of Nissan Leaf is 10% higher than other comparable Nissan models fitted with combustion engines. For one-shift variant the difference is of 20% [3].

5 Conclusion

Taking into account the total emissions (well-to-pump and pump to wheels) electric taxicabs are a better choice comparing to vehicles fitted with diesel engines not only when charged using the green energy but also when charged with a mixed electricity (energy mix: 85% nonrenewable, 15% renewable sources). The only exception is winter period if taxicabs are heated with standard heating. Alternatively, during the winter independent heating with liquid fuels can be used to reduce environmental impact of electric vehicles.

However, from an economic point of view, electric taxis are more expensive, so less favorable option than conventionally powered vehicles in countries that do not provide any financial incentives for electric vehicle owners.

The change from conventional to electric taxicabs might be an economically viable solution for companies offering taxi services, but it is a solution (for the current market conditions in Poland) less favorable than the use of diesel taxis and implies either the necessity of price increase or operating with a lower profitability ratio of a taxi company. Moreover, the cost of infrastructure is an additional expense, therefore to enable a progressive introduction of electric taxis, the investment in charging infrastructure should be subsidized.

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