An electric vehicle with an internal combustion engine as a range extender

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Summary

The current article focuses on a design study of an electric vehicle with a range extender. First, a basic study of a traditional battery electric vehicle and its properties (like reachable travel range) is presented. As a next step the vehicle is modified. An additional power unit is added to ensure an extension of the limited vehicle range. After that the modified vehicle is analysed. The results show the required parameters of the range extender unit for a specified travel range and new expected properties of the electric vehicle. A preliminary design study of the internal combustion engine is worked out. The optimized engine model is used for a final vehicle analysis. For that aim different simulation models based on parametric modelling are used. The result is presented and commented.

Keywords: electric vehicle, vehicle range, range extender, internal combustion engine, simulation, GT-SUITE

1.Introduction

Nowadays, the electric vehicles are becoming more and more popular. Since the first introduction of the electric power train more than a century ago, the available technology, manufacturing processes and human knowledge have changed amazingly. These prerequisites allow us to build much better electric vehicles with significantly improvement of their performance, efficiency, and reachable travel range (distance).

Fig. 1. *A range extender unit Nissan e-POWER (1)*

In any case, the range autonomy of the electric vehicles is one of the main obstacles for great success and growth. So as a next possible step, beside the refinement of the battery technologies and lowering their price, is a discreet modification of the traditional electric vehicle, which is additionally equipped with an auxiliary power unit used for extending the reachable travel range by supplying the battery system with electricity on road. This unit is called a ranger extender (REx) and it consists of an alternative power source (usually a small internal combustion engine) driving an electric generator which charges the battery system of the vehicle. The vehicle power train layout (configuration) looks very similar to the series hybrid drive train layout. The aim of the range extender unit is to increase the vehicle travel range, but in most cases this device serves only as an insurance and it removes the anxiety of staying broken down on road with a flat (discharged) battery.

The present article presents a simple computer simulation study of an electric vehicle. It shows a comparison of the properties of a traditional battery electric vehicle (BEV) and the same battery electric vehicle equipped with a range extender. The vehicles are tested under NEDC and WLTP. All simulations are done with models built in a specialized CAE software – GT-Suite from Gamma Technologies.

2. The electric vehicle – a few facts from the history source

The history of the electric vehicles began sometime in the 19th century. The electric cars have not got a specific inventor. The idea for this type of vehicle power train appears after series of discoveries and inventions – from the electricity and the electric batteries to the electric motors. The first successful electric vehicle attempts were introduced in the second half of the 19th century. At that time the electric source of power was not only the new one. There were already the steam engines and internal combustion engines, of course alongside the horse power which was still the main source.

The steam engine was already proved as reliable for powering factories, trains and ships. Of course there were also steam powered vehicles, but these engines were not very practical for personal vehicles. They required a long time to start up, needed water and coal refilling etc. The internal combustion engines also were

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not without faults. They were also very noisy and the exhaust gases which they produced were disgusting. It was difficult to operate and drive these vehicles – they needed hand starting with a crank, they had hard gear changing, etc.

On the other side, the electric vehicles looked very promising. They did not have of the issues of the steam and internal combustion engines. In comparison they were very quiet, easy to drive and did not produce smelling pollutants.

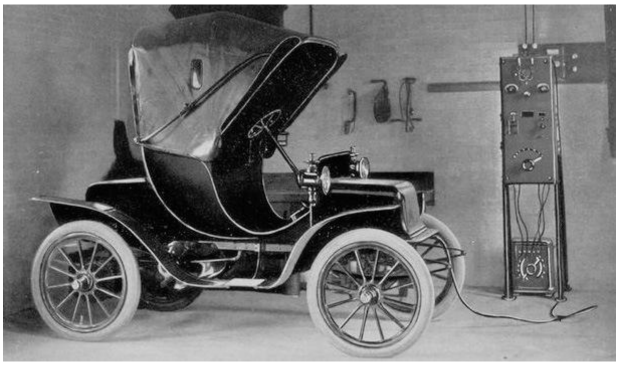


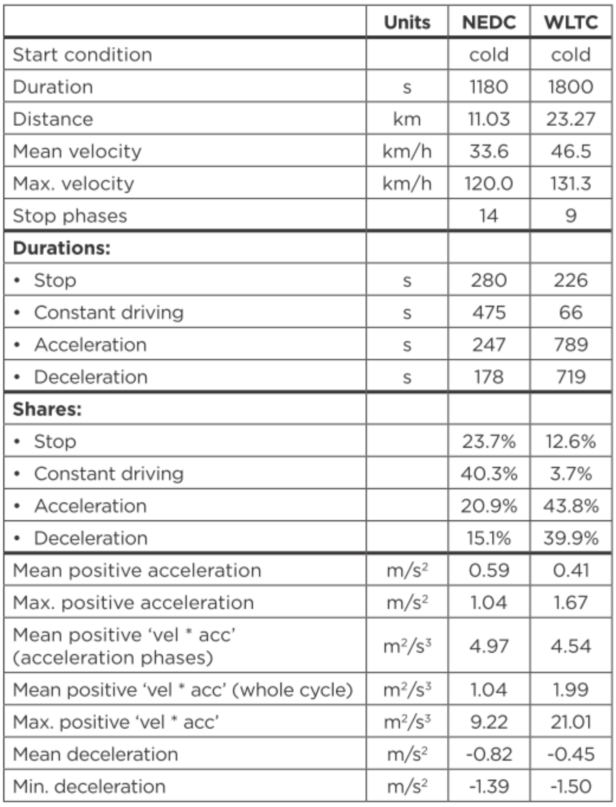
Fig. 2. *A historic electric vehicle (2)*

Unfortunately, the electric vehicle disappeared in 1930s on the grounds of few facts – they were expensive (ICEs were cheaper thanks to the rapid development and improvement), there was no electricity outside the big cities, as well the great discoveries of crude oil reserves around the world led to intense petrol's price reduction and that changed the petrol availability.

Nowadays, the electric vehicles are appearing again and becoming popular for many similar reasons for which these vehicles were popular more than a century ago. That trend started at the beginning of 1990s, when the questions about the ecology and the environmental damage from engines' exhaust emissions started to be an everyday occurrence. That also led to a rapid regulation growth and many new emission restrictions were introduced, which have still been changing. [9]

3. The new legislation

The brand new Worldwide Harmonised Light Vehicle Test Procedure (WLTP) was introduced on 1th September 2017. It initiated a beginning of a new era in automotive engineering. The WLTP is a new procedure for laboratory tests which are used to measure fuel consumption, CO_2 and pollutant emissions from passenger cars. The previous test i.e. the New European Driving Cycle (NEDC) was introduced in the 1980s. But during the following years automotive technology and driving conditions substantially changed and the NEDC became insufficient. That led to the development of a new test procedure which is designed to obtain more accurate test results and better to reflect the real driving conditions and behaviour. The conditions in the old NEDC test are based on a theoretical driving profile, unlike those in the new WLTP cycle, which are based on a real-driving data for better representation of everyday driving profiles. Such a big change in the legislation could not be done overnight, so it will be done gradually in a few steps. The table below compares the both driving cycles [5, 11].



	Units	NEDC	WLTC
Start condition		cold	cold
Duration	s	1180	1800
Distance	km	11.03	23.27
Mean velocity	km/h	33.6	46.5
Max. velocity	km/h	120.0	131.3
Stop phases		14	9
Durations:			
• Stop	s	280	226
• Constant driving	s	475	66
• Acceleration	s	247	789
• Deceleration	s	178	719
Shares:			
• Stop		23.7%	12.6%
• Constant driving		40.3%	3.7%
• Acceleration		20.9%	43.8%
• Deceleration		15.1%	39.9%
Mean positive acceleration	m/s^2	0.59	0.41
Max. positive acceleration	m/s^2	1.04	1.67
Mean positive 'vel * acc' (acceleration phases)	m^2/s^3	4.97	4.54
Mean positive 'vel * acc' (whole cycle)	m^2/s^3	1.04	1.99
Max. positive 'vel * acc'	m^2/s^3	9.22	21.01
Mean deceleration	m/s^2	-0.82	-0.45
Min. deceleration	m/s^2	-1.39	-1.50

Fig. 3. *Parameters of the NEDC and WLTC driving cycles (3)*

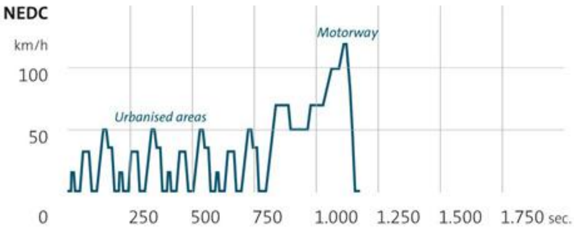


Fig. 4. *The NEDC driving cycle profile (4)*

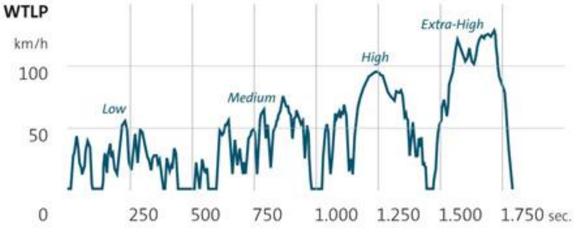


Fig. 5. *The WLTP driving cycle profile (5)*

4. Electric vehicle simulations

There are a lot of varied simulation software which can be used to perform miscellaneous vehicle analyses during the design process on different system levels. In this case it is the GT-SUITE from Gamma Technologies. This package is an advance flexible multi-physics modelling and simulation tool, that offers a lot of capabilities focused on automotive industry (vehicles, engines etc.).

In the current research study the GT-SUITE simulation package is used for an preliminary analysis and comparison between a traditional pure battery electric vehicle (BEV) and a modified electric vehicle equipped with a small especially designed internal combustion engine, used in a combination with an electric generator as a vehicle range extender (REx). Simulation models are set up for the study and the properties of the vehicle are explored. All vehicle tests are performed in the conditions of two driving cycles - the old NEDC and the new WLTP, which allow us to compare how vehicles perform under different circumstances.

4.1. Vehicle model description

In the following part, a description of the considered electric vehicle layout (configuration) and the simulation model are presented. There are a few different possible layouts for an electric vehicle, but the simplest one will be considered and worked up. The vehicle body is equipped with a battery system for supplying with electricity and a single electric motor, which drives the wheels' axles through a drive shaft or gears, and a differential. The battery is usually charged from the power plug, but regenerative braking mode can be also present.

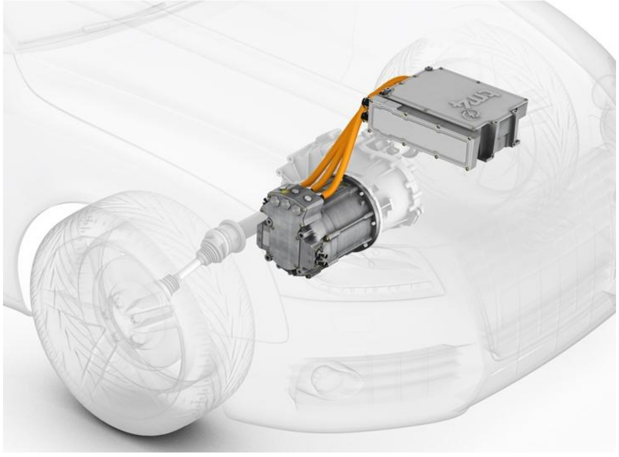


Fig. 6. *Electric power train systems TM4 MOTIVE (6)*

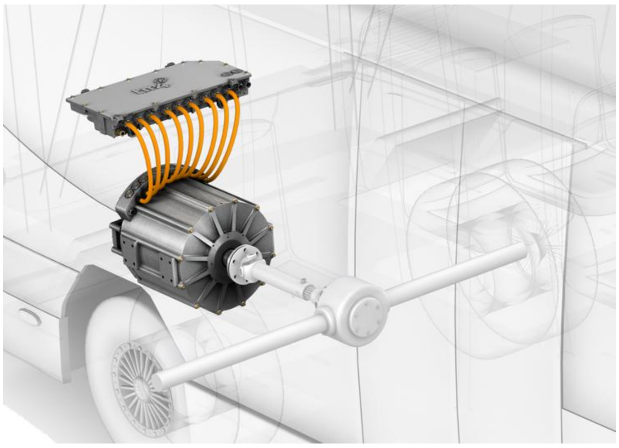


Fig. 7. *Electric power train systems TM4 MOTIVE (7)*

Next, the same power train layout will be extended with a range extender unit that consists of an internal combustion engine and an electric generator, supplement also with controlling electric devices.

This electric vehicle architecture is very similar to the layout of the series hybrid power train. So the simulation models of out vehicle are based on predefined series hybrid layout with some modifications.

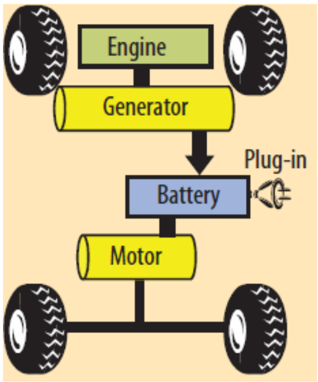


Fig. 8. *Series hybrid vehicle layout (8)*

It is suitable to test some configurations: 1/ an electric vehicle with 60 Ah battery, 2/ the same vehicle with a range extender and 3/ a vehicle with a battery with a higher capacity of 94 Ah. Their analysis shows the differences in reachable electric range only by changing the size of battery and also the contribution of using a range extender instead of increasing the battery size. This study also shows preliminary parameters (output performance) for a suitable range extender unit. The next part studies the internal combustion engine separately.

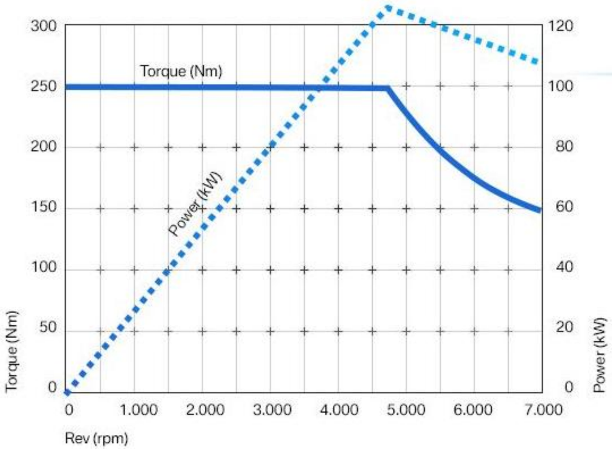


Fig. 9. *BMW i3 electric motor power and torque curves (9)*

The main specification (parameters) of the considered electric vehicles, used in the simulation model is presented below. Some of them are specified according to the market available configurations of BMW i3 electric car. The power and torque characteristic of the i3 electric motor is presented in fig. 9. The electric model is tuned to approximately correspond to the course of the both BMW motor parameters. However, the simulation models are not calibrated in any way to a specific real vehicle and the provided example data are only for an illustration.

Table 1. *The specification of the considered electric vehicle.*

	BEV 60 Ah	**BEV 94 Ah**	**Rex 60 Ah**
Vehicle weight [kg]	1270	1320	1390
Battery weight [kg]	230	280	230
REx weight [kg]	-	-	120
Electric motor power [kW/rpm]	125/4800	125/4800	125/4800

Figure 10 shows the considered simulation model in GT-SUITE. It consists of different parts, which define the electric vehicles, like the IC engine, the electric generator, the battery, the electric traction motor and last but not least the vehicle itself. Of course there are also a few different controlling objects.

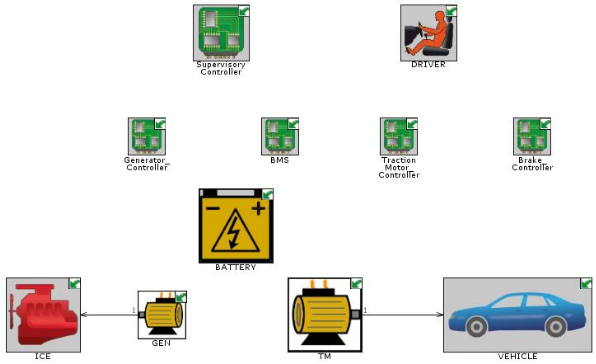


Fig. 10. *A vehicle simulation model in GT-SUITE*

4.2. Electric vehicle simulation results

This part presents some results from electric vehicle simulation. Only the single model described above is used to provide all analyses. In the pure electric version of the vehicle the internal combustion engine simply turns off.

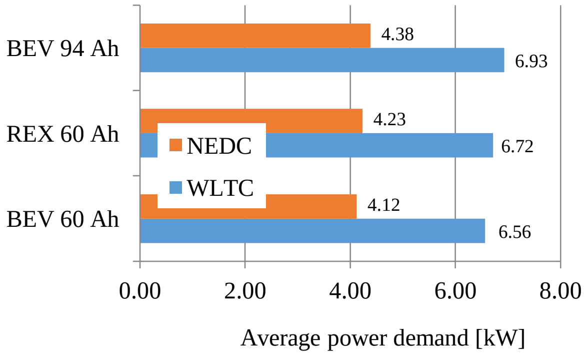


Fig. 11. *The average traction power demand*

The Driver part in the simulation model is just what the name says - the vehicle controller. It is used to calculate the traction power demand to run a specified driving cycle (so called speed targeting). According to the computed results the average power the electric vehicle with 60 Ah battery needs to travel the NEDC cycle is 4,1 kW and 6,6 kW for the WLTP cycle. For vehicle with 94 Ah battery, which is 50 kg heavier, it is 4,2 kW and 6,7 kW respectively. The BEV with 60 Ah battery equipped with a range extender (i.e. with additional 120 kg) needs average 4,4 kW in NEDC and 6,9 kW in WLTP. The power demand is graphically presented in the figures 11. and 12.

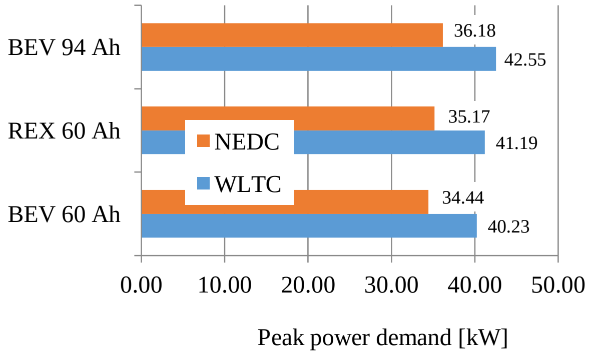


Fig. 12. *The peak traction power demand*

The total electric vehicle range is obtained by running the driving cycle a few times in sequence until the whole electric battery capacity is used. We can see that by increasing the battery capacity to 94 Ah, i.e. adding additional 50 kg, we can obtain 65/53 km longer journey according the NEDC/WLTP cycle (i.e. +53 % for both).

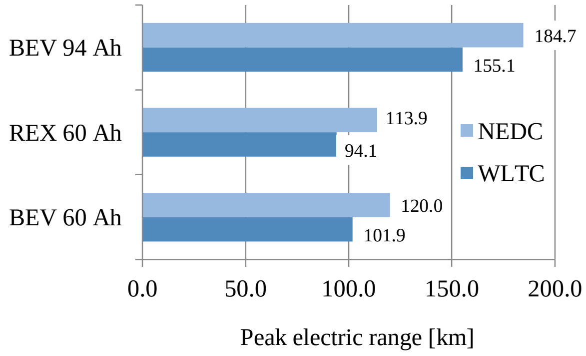


Fig. 13. *The vehicle electric range*

4.3. Range extender vehicle simulation results

Another question arises here: what output power the IC engine in the range extender should produce and how to control its operation, i.e. when to turn it on and off, to provide optimal and reasonable vehicle range. Some preliminary results can be seen next. An engine with output power of 20 kW to 30 kW should be enough to ensure an acceptable extension for this vehicle size. For first steps only one operation point with power of 20 kW is used. Of course, it is meaningful to develop more advanced control strategy and also to ensure more than one operation point of the range extender.

Since the internal combustion engine is completely unknown at this moment, the simulation model is modified. The combustion engine is replaced with simple mechanical parts (objects) which simulates the engine just by applying torque and speed to a rotating shaft. In electric mode the battery state of charge is set to 100 % (fully charged) and analogically the vehicle is running the specific driving cycle a few times until the battery is completely depleted (discharged). In the second mode the range extender unit is turned on when a specific battery state of charge is reached. The total electric vehicle range is presented below.

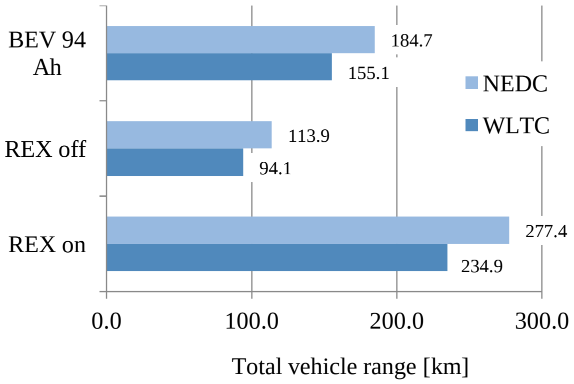


Fig. 14. *A comparison of the total vehicle range*

At this moment we already know approximately output parameters of the engine influent the vehicle range extension. In the example, a 20 kW IC engine can ensure prolongation of the travel range with 50% in both NEDC (+93 km) and WLTP (+80 km) compared to BEV 94.

Different controlling approaches of the range extender can be considered and defined. Two possible of them are described below as an illustration. By the first one (fig. 15) the vehicle runs in electric (charge depleting) mode until a specified value of battery charge state is reached (e.g. 30 %). At this moment the range extender is started. The battery is now being charged. The vehicle is running in charge sustaining mode. Then the range extender is turned off, when a new specified state is reached (e.g. in this case 50 %). The cycle repeats until the whole all fuel in the tank is consumed (e.g. 10 litres). Then the vehicle continues in electric mode until the battery becomes flat.

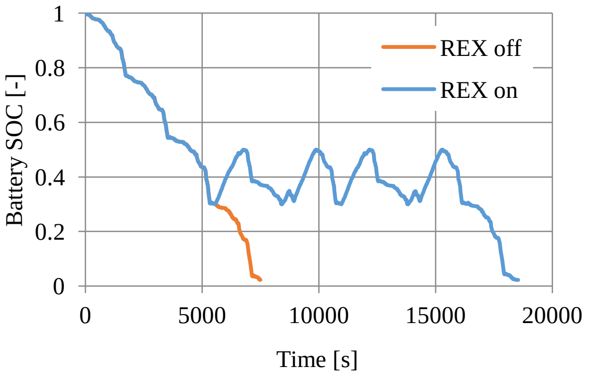


Fig. 15. *The course of the battery SOC*

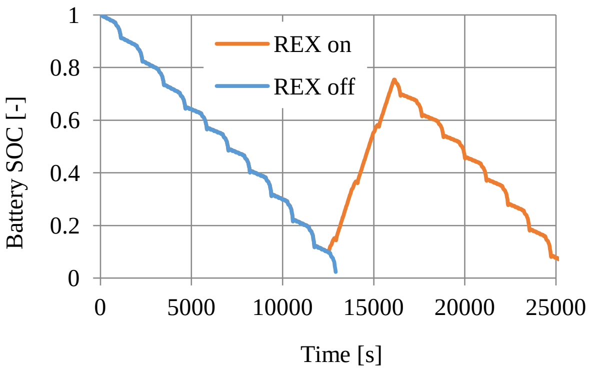


Fig. 16. *The course of the battery SOC*

The second approach considers also running in electric mode until a specific state of charge is reached. Then the range extender is started and it runs at ones until there is a fuel.

5. A twin cylinder ICE as a range extender for an electric vehicle

This point presents a basic simulation study of an internal combustion engine for a range extender for our electric vehicle. Different small engine configurations are suitable for that application. Some of them are more or less explored and they are shown in different research articles. The present study considers a twin cylinder flat (boxer) engine.

5.1. The twin flat engine

As it has been stated above, in this article a flat twin cylinder internal combustion engine as a range extender for the considered electric vehicle is used and analysed. This type of engine has two cylinders, which lie horizontally on opposite sides of a single crankshaft. That common flat engine configurations is called "boxer" with 180° angle between cranks. The both pistons move in phase with each other.

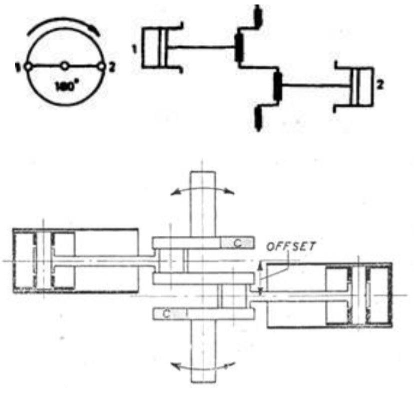


Fig. 16. *The layout of the flat twin engine (10, 11)*

The four stroke flat boxer engine configuration is the only one that does not have any unbalanced forces. This engine has an excellent balance of primary forces, because they counteract all the time. It does not require any additional balancing like adding balancing shafts or crankshaft counterweights to balance the weight of the reciprocating parts. However, in the boxer engines with smaller number of cylinder there are unbalanced moments (rocking couples) coming from the fact that cylinder does not lie in a line with each other. The ignition of each cylinder is equally spaced, the firing intervals are 360°, so the engine will run with higher smoothness.

The flat boxer internal combustion engine with horizontally opposed pistons was introduced (and patented) for the first time by Karl Benz in 1896. The engine was named as contra engine, because the forces of one side opposed the forces of the other one. The boxer engine piston pairs reach the top dead centre at the same time, simultaneously. [6, 12]

5.2. IC Engine simulation model

The initial values for the main parameters of the considered engine are shown in table 2. Some of them are chosen according to findings from previous researches [4]. The engine is a flat two cylinder engine with displacement of 1 litre. The values of the cylinder bore is 91 mm and the piston stroke is 76 mm.

Table 2. *The initial specification of the IC engine.*

Parameter	Unit	Value
Bore, B	[mm]	91
Stroke, S	[mm]	76
Bore/Stroke ratio	[-]	1,2
Cylinder displacement	[cm^3]	494,3
Engine displacement	[cm^3]	988,6
Crank radius, R	[mm]	38
Compression ratio	[-]	12
Connecting rod length	[mm]	150
Connecting rod ratio	[-]	0,25

A basic parametric IC engine simulation model in GT-SUITE is used and modified to meet the twin cylinder engine layout requirements. The model consists of two cylinders each of them with two valves and an inlet port fuel injection. Basic inlet and exhaust manifolds models are presented. The model is set up and the default engine configuration is tested. A simple preliminary optimization of the basic engine parameters is done to enhance the output performance. The course of the engine power and torque, as well the specific fuel consumption are presented next.

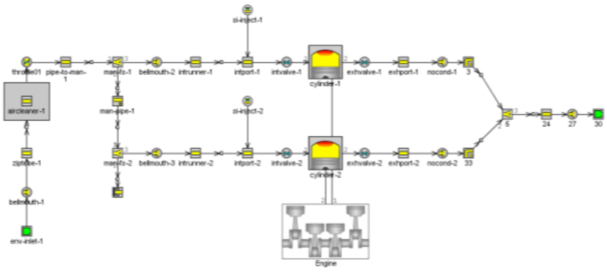


Fig. 17. *The flat engine simulation model*

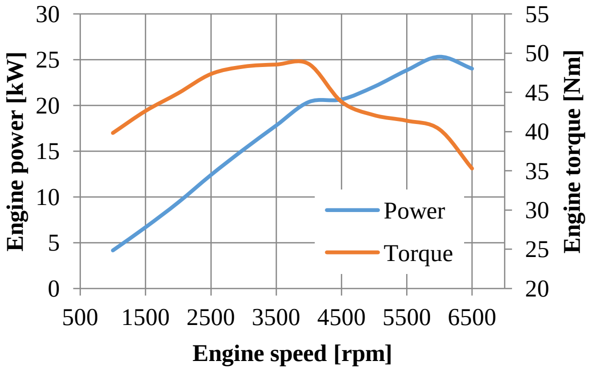


Fig. 18. *The flat engine output parameters.*

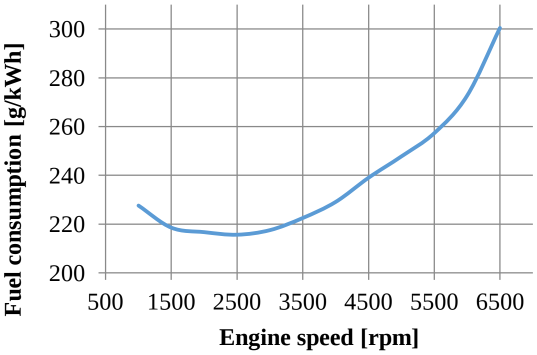


Fig. 19. *The flat engine fuel consumption*

5.1. The flat twin ICE engine in the vehicle

Two suitable IC engine operation points are picked out according to the previous simulation results. They are presented in table 3. These points are set as working points of the range extender engine of the consider electric vehicle. The vehicle model is modified and both points are tested separately. The table below shows the resulting travel ranges of the vehicle in the NEDC/WLTP cycle respectively. It is clear that the higher powered working point ensures a faster battery recharge, but this is compensated by a higher specific fuel consumption and a decreased reachable travel range. In this case the lower speed operation mode ensures better vehicle NVH properties and a higher travel comfort. [6,]

Table 3. *Engine operation points for testing.*

Power [kW]	Speed [rpm]	Fuel cons. [g/kWh]	Range [km]
20	4000	229	277/248
25	6000	274	268/221

So the right selection of engine range extender operation points is a trade off of different parameters. A further and deeper IC engine study and optimization are necessary to meet all requirements. The example above is only an illustration, because the parameters engine power and specific fuel consumptions are very basic. There are a lot of other viewpoints that should be taken into account like the engine exhaust emissions, the engine weight, placing and mounting etc.

6. Conclusion

The current article presents a short overview of the topic of electric vehicles with a range extender. It presents a basic study of a traditional (pure) battery electric vehicle. The reachable travel range (distance) is found out in two different driving cycles - the old NEDC and the new WLTP. After that the vehicle is modified with an additional power unit ensuring an extension of the limited vehicle range. A relation between the required engine power and extended range is estimated. According to this requirement a simple flat twin engine is modelled and analysed. The optimized engine model is used for a final vehicle analysis and verification. The results only confirm the known fact that the electric vehicle with range extender has a great potential and prepares a ground for further research. In fig. 20. one another challenge is shown - the reduction of the range extender unit weight.

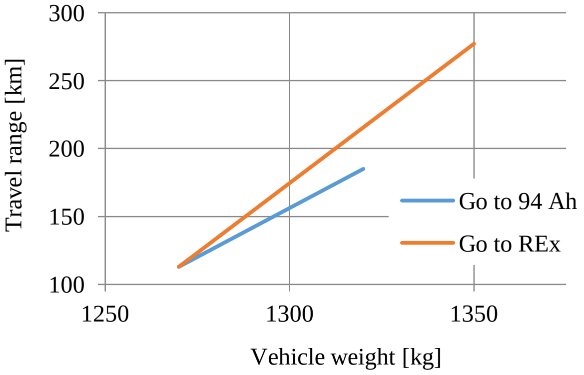


Fig. 20. *The vehicle range*

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(11) http://www.modelenginenews.org/etw/etw_bal/images/bal_f8.jpg