EVS27
Barcelona, Spain, November 17-20, 2013

Range estimator for electric vehicles

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Abstract

One of the most critical topics for electric vehicles due to the restricted possibility of energy storage is the prediction of the remaining range. By an accurate prediction of range, the driver can decide whether and where a stop needs to be planned to recharge the battery and so avoid what is known as “range anxiety”.

For a high performance vehicle this range prediction requires special algorithms as the possible energy consumption can range from almost 0 Wh/km in moderate downhill driving up to 1000 or even 2000 Wh/km in race track use.

Keywords: ZEV (zero emission vehicle), range, energy consumption, efficiency

1 Introduction

Currently, the existing methodology related to the range estimation of vehicles on the market is based on a fixed consumption value per distance unit, which allows a concentric circle to be displayed in the navigation system. However, it is critical to take into account that the energy consumption depends mainly on the road topography and the driver. As a result, the range estimation of existing vehicles always presents an important degree of error.

The objective of this work is to develop a new high precision range prediction algorithm taking into consideration possible driving modes of a wide range of vehicles (off-road, sport, dynamic, etc.), different driving conditions such as hilly roads on a given route and also external factors which can affect energy consumption. Parts of this information have to be interchanged with the GPS data and can be indicated to the driver in an intuitive way on the HMI screen as shown in Figure 1.

The development of such a feature implies improving the calculation of the vehicle range according to the GPS data and the definition of external and driver correction factors. This document specifies the main concepts of the algorithm, the basic formula and how it was implemented within the vehicle ECU.

Figure 1: Vehicle range displayed on the GPS screen

2 Simulation of energy consumption

2.1 Background regarding range estimation

The existing methodology for consumption prediction in commercial vehicles mainly consists of a fixed consumption value per distance unit. First, the maximum vehicle range is determined following the current homologation procedure, which implies driving according to NEDC cycles for instance in Europe, and afterwards this is reduced according to the remaining state of charge. Finally, the result can be displayed in the navigation system as an indication for the driver. There are various possibilities for presenting the vehicle range in the on-board navigation system to driver or passengers, but the concept is always similar to the examples shown in Figure 2 and Figure 3.

Figure 2: Navigation system including vehicle range

In some cases, vehicle range prediction has been optimized in order to take into account driving style of the driver, electric comfort functions and selected driving mode. These parameters allow different vehicle ranges to be calculated: one which includes all the possible corrections mentioned previously and one with a non-aggressive driving style without electric comfort functions as shown in Figure 3.

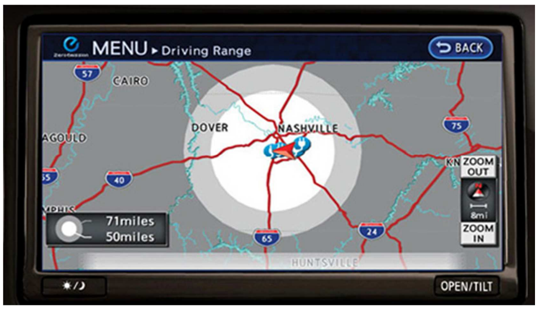

Figure 3: Navigation system of Nissan Leaf

This last solution is currently the most realistic one on the market and is absolutely necessary for vehicle users. However, it does not consider parameters such as road topography or traffic levels, which are critical points regarding vehicle range and which can lead to the driver making wrong decisions. In order to illustrate such a situation, the following case is analysed: the first step of the route is a negative slope for 50 km as shown in Figure 4 and then the driver comes back to the initial point, which implies driving on a road with a positive slope as shown in Figure 5.

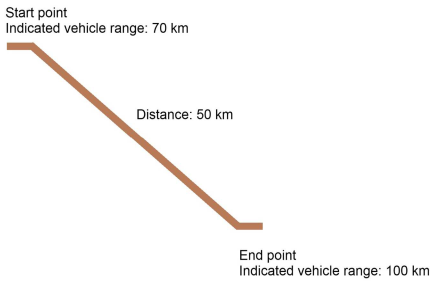

Figure 4: First step of the route with a negative slope

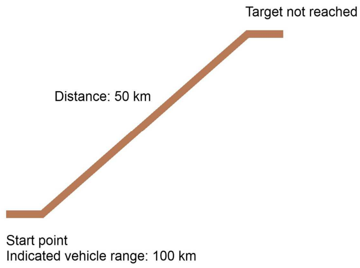

Figure 5: Second step of the route with a positive slope

In that case the estimation increases the available vehicle range during the first step due to the negative slope but it does not consider the necessary energy to come back to the initial start point. Consequently, the driver can suppose from the indicated vehicle range that the vehicle range is 100 km, which is not correct as it could be only 40 km if the reverse route is followed as presented in Figure 5.

Consequently, some improvements have been identified regarding these aspects which are not currently taken into account by vehicles on the market. Some innovative concepts in the same way have been announced regarding the Audi e-tron and the BMW i3, but these vehicles are still concept cars and are not available to the general public. As a result, the purpose of the following algorithm is to present a fully operational prediction which considers inputs of GPS-calculated routes and driver information.

2.2 Concept

The core algorithm of the range estimator strategy consists of calculating the vehicle range for different routes in order to show the available range in all directions in the GPS screen as illustrated in Figure 6.

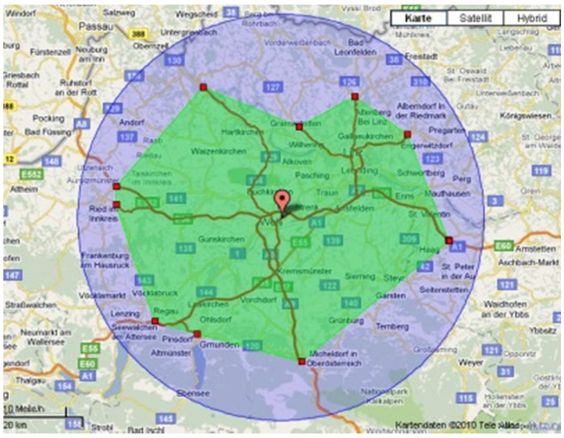

Figure 6: GPS screen with range estimation

Each route displayed in the navigation system screen corresponds to the maximum vehicle range according to the battery capacity. This is defined by a set of data which allows the necessary energy consumption to be calculated for each point of the route.

Consequently, the execution of the vehicle range algorithm implies calculating the following functions:

- Processing of GPS data which define each route as shown in Table 1
- Consumption calculation for each section of the route until the sum of consumed energy exceeds the remaining capacity
- Vehicle range calculation

The most critical part is the consumption estimation which is the keystone of the algorithm. Indeed, during each execution of the algorithm the vehicle is simulated in order to estimate the complete consumption for a given route to obtain an accurate vehicle range. In other words, it could be represented as a loop which is executed until the battery is considered as completely discharged.

Table 1: Example of GPS data table for one route

Distance	Speed	Slope
1852 m	90 km/h	0 %
97 m	50 km/h	1 %
16 m	50 km/h	2 %
4 m	50 km/h	0.5 %
13 m	50 km/h	0.8 %
11 m	50 km/h	0.7 %

Complete route

2.3 Energy consumption

2.3.1 Background regarding energy consumption calculation

As the complete sequence from the energy deposit to the wheel must be taken into account, the energy consumption can be defined by several main sources as illustrated in Figure 7.

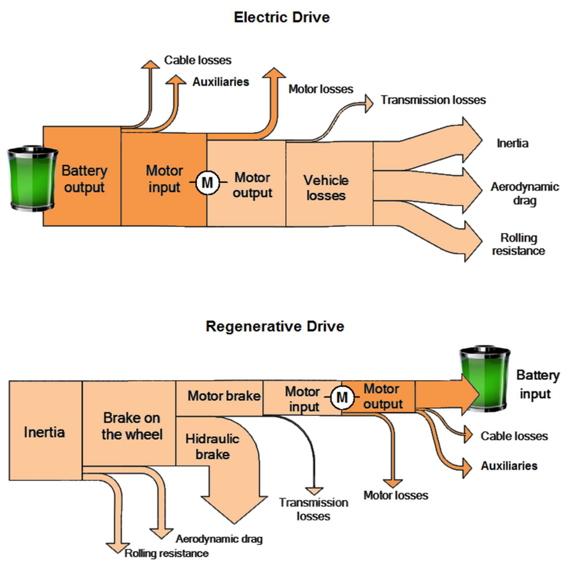

Figure 7: Energy flow sequence for electric and regenerative drive

Regarding the vehicle consumption itself, three main contributions can be identified: energy needed to move the vehicle, auxiliaries' consumption and energy loss in electric and rotating parts.

- The energy needed to drive along a specific route mainly depends on the vehicle's resistance to movement (road friction, inertia and aerodynamic drag), route profile (topology and allowed speed) and driver profile. In addition, energy invested to overcome resistant forces can be partially recovered depending on the driver's profile and regenerative brake calibration.
  The driver profile represents the way each driver transforms the visual inputs he gets from the route (slope, allowed speed, bends, roundabouts, traffic lights, traffic conditions, etc.) to the accelerator and brake pedals. As a starting point, factors that characterize the possible behaviours that a driver can perform along a route have been implemented in an energy consumption algorithm that also considers vehicle resistance to movement and route topography.
  Furthermore, as electric vehicles often offer the possibility to select different driving modes, this point was also considered in addition to the corrections which could be recorded as driver historic data.

- Auxiliaries' consumption depends on the design of the components and their use profile. Vehicle measurements were realized to evaluate their impacts on vehicle and consequently the related consumption has been integrated within the main algorithm via several maps to simulate the most accurate consumption along the different routes.

- The main energy loss happens in rotating parts and electric components due to their efficiency. Tests of the whole powertrain were performed on a dyno to measure the combined efficiency of the powertrain assembly and allow calibration of the single components theoretical efficiency. The algorithm is already designed to consider the powertrain assembly efficiency (inverter + motor + transmission) by means of three-dimensional efficiency maps (efficiency according to speed, torque and voltage) on traction and regeneration.

Taking into account the previously described energy consumption sources, an algorithm has been developed to simulate the vehicle behaviour along a given route in order to estimate the energy consumption for each part of it.

2.3.2 Main energy consumption algorithm

The purpose of this algorithm is to obtain the estimated vehicle range for each selected route. From these data the vehicle route is simulated and the estimation consumption algorithm is executed for each part provided by the navigation system until the estimated remaining energy reaches the minimum reserve. As a result, the last simulated travelled distance is the estimated range for that route.

In other words, the complete algorithm can be illustrated as a while loop depending on the remaining energy and it is separately executed for each route, which can be presented as shown in Figure 8.

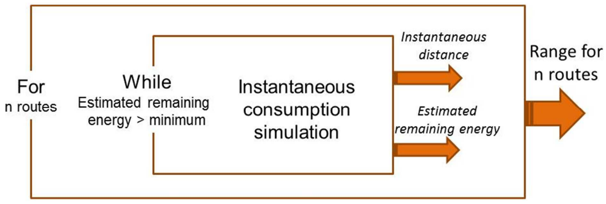

Figure 8: Vehicle range calculation

The estimated energy consumption is initialized to 0 Wh before the first execution of the while loop and is updated during each execution according to the functions described in sections Vehicle and driver behaviour simulation and Consumption calculation.

When the while loop is executed, the following sequence is processed:

- GPS data processing
- Simulated and integrated consumption calculation
- Estimated remaining energy
- Simulated speed
- Simulated distance achieved

When the minimum battery level is reached, the while loop is stopped and the range for the selected route is the latest travelled distance calculated. If more routes must be simulated, the while loop restarts with the next one. Otherwise the range estimation finishes and shows the results until the next execution of the complete algorithm.

2.3.3 GPS data processing

The on-board navigation system provides the main characteristics of each segment of the selected routes: the speed limit, the slope and the distance. From these characteristics, a strategy has been developed to simulate the behaviour of the driver. It consists of two main parts: a first one to load the GPS data and a second one to transform the speed limitation into a speed target for the driver taking into consideration the remaining distance before the next speed limitation and the related acceleration or braking phases as illustrated in Figure 9.

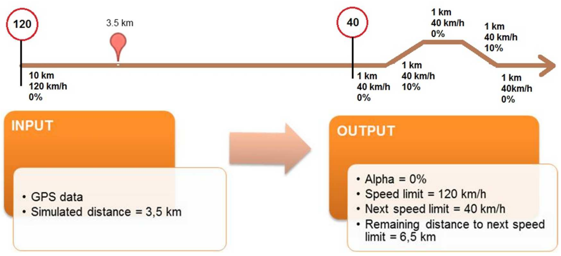

Figure 9: Example of GPS data loading

Furthermore, it is important to take into account that drivers may behave differently compared to the expected one. In other words, they may go faster or slower than the legal speed limitations, which would lead to a wrong estimation of the energy consumption. In the same manner, some traffic factors can have impacts on the consumption and lead to an increase of energy consumption. Consequently, different factors have been identified to modify the speed target of the driver as shown in Figure 10 and have been integrated in the vehicle speed estimation:

- Braking
- Overtaking
- City driving
- Speed average

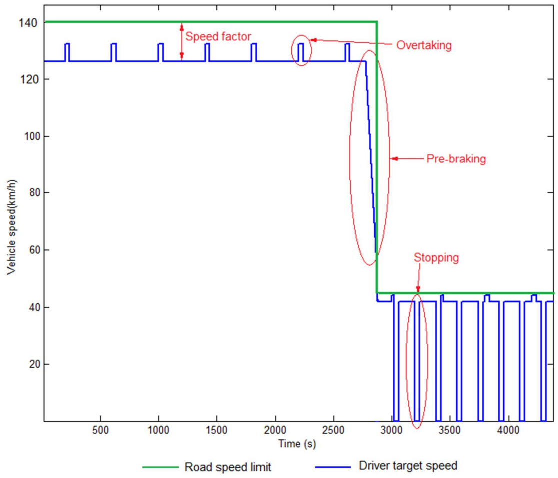

Figure 10: Adaptation of vehicle speed target

Braking

When a traffic signal indicates a reduction of the speed limitation, the vehicle is supposed to arrive at this point with a reduced speed. As a result, the driver should anticipate it and should start braking before this moment. The profile of the vehicle speed evolution depends mainly on the driver and can be one of the following possibilities:

- Braking after the limitation sign
- Braking abruptly
- Braking smoothly
- Braking with a long anticipation using the natural vehicle resistance with no or very low pressure on the brake pedal to save energy

Overtaking

Overtaking is a typical driving situation and can be more or less frequent according to the driver. In terms of speed evolution, it can be characterized by a speed increase and then a decrease to return to the right lane. As a result, each driver is identified by an overtaking frequency, time and magnitude which have different impacts on the vehicle speed.

City driving

In city areas vehicle speed is rarely steady due to traffic limitations and constant stoppings at traffic lights, zebra crossings, stop signs or traffic jams. As each speed modification and vehicle stops imply different energy consumption, the city area can be identified by several factors: speed limitation, stopping period and stopping time.

Speed average

Despite the speed limitation, each driver behaves differently and has a different average speed; some tend to overspeed while other prefer driving slowly. For this reason, a factor can be learnt according to the driver's behaviour and included to determine the driver's target speed depending on the speed limitation.

2.3.4 Vehicle and driver behaviour simulation

This part of the algorithm simulates the driver response to a target speed. It is based on a feedback control loop with pre-feeding of the disturbances as shown in Figure 11 and can be divided in several parts:

- Controller
- Resistance force
- Saturation
- Driver response
- Newton's law

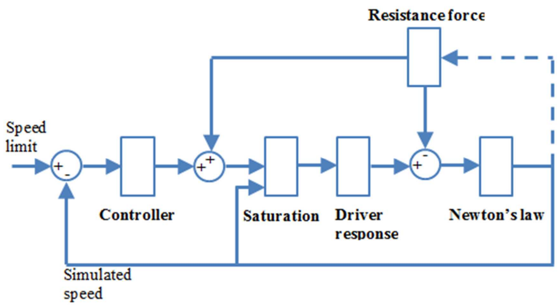

Figure 11: Simulation of the driver behaviour

Controller

The controller is based on a closed loop controller whose purpose is to calculate the necessary acceleration to reach the target speed described in the section GPS data processing. Then, this acceleration is transformed into a force via the vehicle weight and the inertia. Finally, the resistance force is evaluated and is summed to this target acceleration force in order to obtain the force needed to achieve the target speed.

Resistance force

The vehicle resistance to movement is the sum of the forces that act in the opposite direction of any movement and that must be exceeded to go in the expected direction.

The main forces are aerodynamic drag, rolling resistance and gravity force in a slope. Once the vehicle properties are known, these forces can be calculated in each segment as a function of the slope and the simulated speed:

$$F_{aero} = \frac{1}{2} \times C_d \times \rho_{air} \times A_f \times V^2 \qquad (1)$$

$$F_{rolling} = m \times g \times f \times \cos\alpha \qquad (2)$$

$$F_{slope} = m \times g \times \sin\alpha \qquad (3)$$

The following abbreviations have been used for the equations: C_d is the aerodynamic drag coefficient, ρ_{air} is the air density, A_f is the frontal area, m is the vehicle mass and f is the coefficient of rolling resistance. As the study was based on a race car project, the aerodynamic drag coefficient depends on the position of the rear wing, which could be 12º for race driving mode and 7º in other modes.

Saturation

Once the target force has been calculated by the controller, it is critical to limit it according to the maximum force that the vehicle can produce, which depends on its speed, battery voltage, vehicle driving mode, state of charge, power and vehicle dynamics parameters. Depending on these parameters, the maximum force for each situation is considered as the force limit. However, it is important to take into consideration that the maximum tractive force that the vehicle can develop on the wheels depends on the overall transmission ratio and the transmission efficiency as well. This final force is considered as the tractive force limit. Consequently, if the force commanded by the controller and vehicle resistance exceeds this value, the target force is limited to this force limit as illustrated.

In the same way, the brake force must be monitored and the maximum brake force is calculated as the sum of the maximum regenerative and hydraulic brake forces. If the brake force commanded by the controller exceeds the brake force limit under a specific situation, the target brake force is limited to this force limit.

Finally, these force limits can be defined as maximum and minimum boundaries as illustrated in Figure 12.

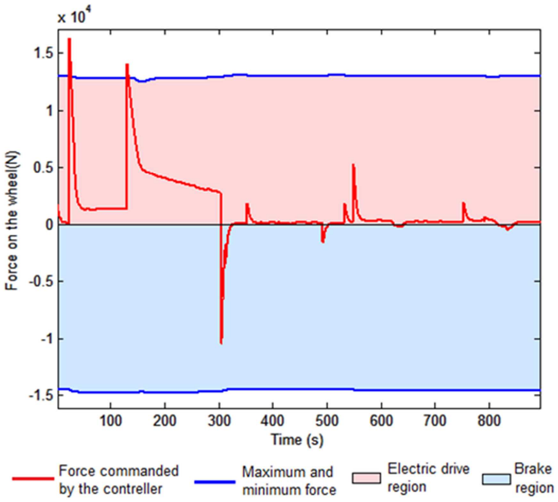

Figure 12: Maximum and minimum force limits vs. force commanded by the controller

<u>Driver response</u>

Once the target force has been limited according to the vehicle characteristics, it will be the basis for evaluating the force requested by the driver. For this purpose the following sequence is executed:

- Calculation of the expected accelerator and brake pedal position to produce the target force
- Calculation of driver's response to the target pedal position taking into account the driver's response time and his foot tremble
- Calculation of the force percentage that the driver applies considering the pedal calibration for each vehicle driving mode

The main factors that characterize the driver's response to a target pedal position are the response time and the response gradient. Both factors depend mainly on the experience and aggressiveness of the driver, which are evaluated permanently in order to learn and record the most adequate correction. Sporty driving implies a small response time to reach the target pedal as fast as possible whereas a relaxed driving means a longer response time to avoid abrupt accelerations and increase the comfort as shown in Figure 13.

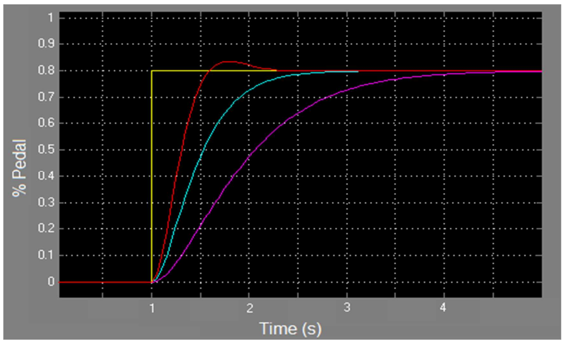

Figure 13: Simulated driver's throttle responses to a target throttle step

Furthermore, it is important to consider that every driver has a natural tendency to tremble while applying a force on the accelerator pedal. This effect depends on the driver's accuracy in maintaining a stabilized position and can affect the vehicle consumption by leading to small accelerations and decelerations around a target speed. Several analyses have been realized to characterize this impact in order evaluate the extreme cases as presented in Figure 14.

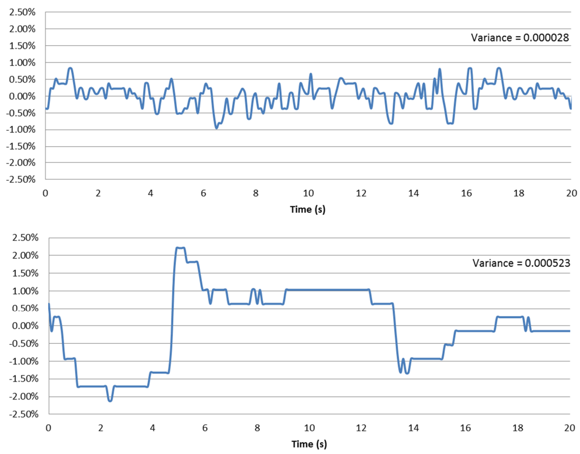

Figure 14: Recorded driver's tremble for an expert driver at the top and a conventional driver at the bottom

Consequently, this effect is integrated in the driver response as an impact depending on the tremble variance and period. Both factors are learnt and recorded during each route, which allow having a specific correction for each driver.

Finally, the saturation of the target force and the driver's response time imply having a force filtering and mean that the vehicle cannot reach the target speed instantaneously, which is typical for any real driving situation and is illustrated in Figure 15.

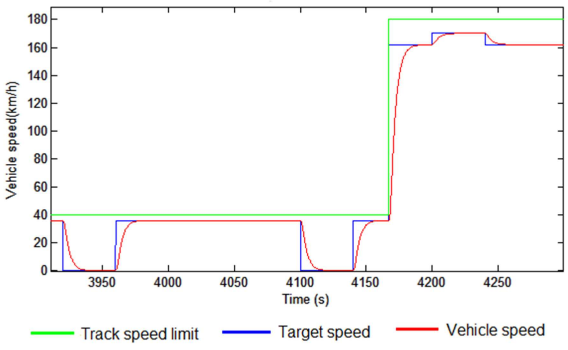

Figure 15: Example of route speed limit, target speed and vehicle speed

Newton's law

As last step of the vehicle behaviour simulation, the estimated vehicle speed is calculated thanks to Newton's law: $F = m \times a$ where m is the vehicle mass and a is the acceleration.

First the acceleration is determined from the previously calculated force and the vehicle mass. Then, this value is integrated to obtain the final estimated vehicle speed. Afterwards, the difference between vehicle speed and route speed limit is calculated, which is the input for the controller and allows the feedback control loop to be closed.

2.3.5 Consumption calculation

This is the last step of the algorithm to determine the vehicle range. According to the remaining energy stored in the battery and the different energy sinks, the energy consumption is determined according to the following sequence:

- Torque distribution
- Energy consumption
- Auxiliaries consumption
- Voltage prediction
- Comparison

Torque distribution

This study was realized within the framework of the development of a 4WD electric race car with one motor per wheel. As a result, an efficient torque distribution was developed to optimize the energy consumption.

First of all, the total motor torque is calculated through the wheel radius, the transmission ratio and the motor efficiency. Then, depending on the estimated vehicle speed and the target force, this torque is divided between the front and rear axles as shown in Figure 16.

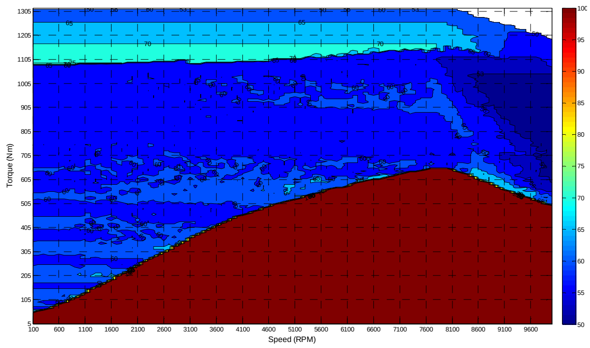

Figure 16: Percentage of power applied on the rear axle

In the same way, under braking conditions the distribution between hydraulic and regenerative braking depends on the brake force, vehicle speed and vehicle driving mode.

Energy consumption

The instantaneous energy represents the necessary energy either consumed (electric drive) or generated (regenerative braking) by each motor to produce a requested torque. As a result, the mechanical power is determined for each motor depending on the speed and the torque which are calculated in the previous steps of the algorithm. With the value of the motor efficiency as presented in Figure 17, the related electric power for each motor is obtained.

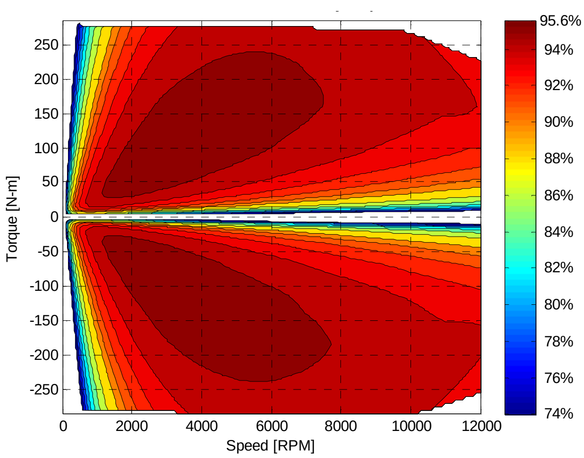

Figure 17: Example of motor efficiency map

Auxiliaries' consumption

In addition to the power for braking or driving with the motors, the consumption related to all the electronic devices of the vehicle such as lights, wipers or ECUs must be taken into account. Furthermore, comfort devices are powered by the traction battery and the related consumption can be significant.

Consequently, analyses have been realized on the target vehicle and a consumption average of all the auxiliaries has been measured. In order to simplify the algorithm and to have a reliable consumption value, this average is considered as constant all along the simulated route and is added to the simulated motor consumption.

Voltage prediction

The battery voltage depends mainly on the state of charge and influences motor efficiency and maximum available torque. The voltage measured on the battery terminals is used to set the voltage at the beginning of the route simulation. Then, the cell voltage is reduced along each route as a function of the state of charge decrease as illustrated in Figure 18.

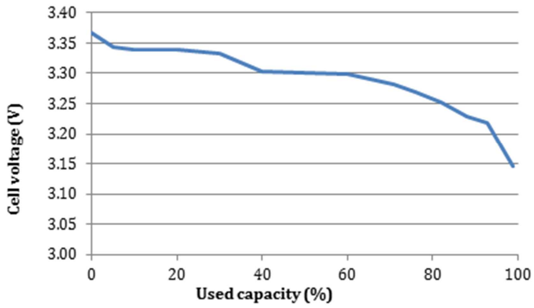

Figure 18: Cell voltage evolution

Finally, the estimated voltage is used to calculate the motor efficiency map, the maximum torque curve and the torque distribution.

Comparison

This is the last step whose purpose is to update the remaining battery capacity according to the estimated energy consumption calculated previously.

When the state of charge starts decreasing, the available power can be reduced depending on the conditions of the vehicle. Once this does not allow the route to be followed with a reduced speed, the vehicle is considered as stopped and the vehicle range is the distance travelled up to this point. Afterwards, the algorithm starts calculating the vehicle range for another route.

3 Results

The objective was to validate the presented algorithm in two steps: first comparing the range estimator results against in-vehicle measurements and then evaluating the influence of different driving factors such as slope, overtaking, speed average, etc.

3.1 Algorithm validation

In order to validate the algorithm and obtain different driver profiles, several in-vehicle measurements were performed over different routes including highway, suburban and urban areas.

As presented in Figure 19, two sets of results from different routes are discussed in order to have a clear example to illustrate the need to have an algorithm such as the range estimator. These two routes combine urban and suburban driving in a hilly route. The main interest of both routes is having the same length, the same starting point, the same destination and, therefore, same difference of altitude. On the contrary, the topography of each route is different, and as a consequence, the balance between positive and negative gradients. This can lead to different consumption depending on the route chosen and also depending on the direction (uphill or downhill).

Both chosen routes are shown in Figure 19 and the profile of each can be observed in Figure 20.

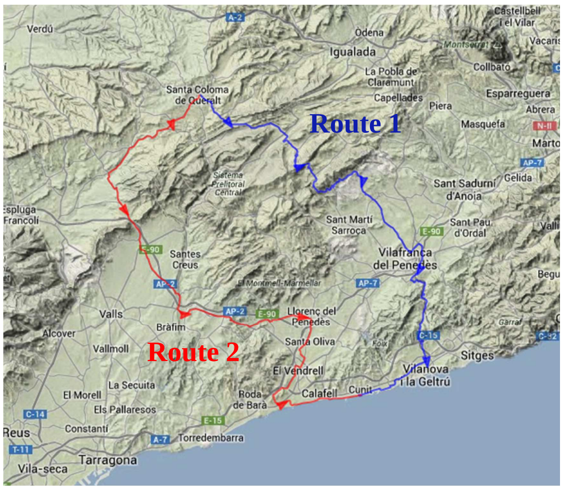

Figure 19: Routes 1 and 2 used for validating the algorithm

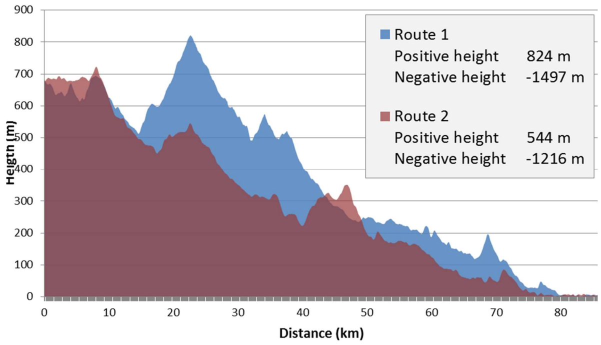

Figure 20: Altitude profile of routes 1 and 2

For a given battery level the range depends mainly on the consumption over a specific route. Thus, in order to validate the results from the algorithm, the simulated consumption obtained in the first execution of the estimator was compared to the measured consumption in the same route as shown in Figure 21 for route 1.

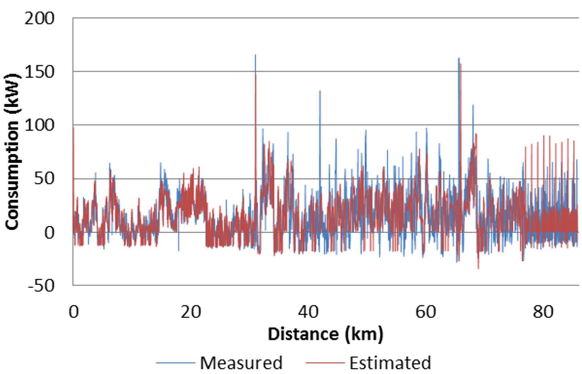

Figure 21: Estimated and measured instantaneous consumption for route 1 downhill

Since the estimated consumption is strongly dependent on the estimated speed profile and most driver factors are determined according to speed and acceleration, the measured and estimated speed profiles are also compared in Figure 22 for route 1.

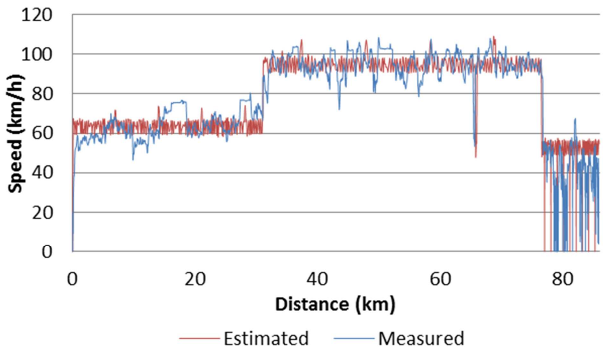

Figure 22: Simulated and measured instantaneous speed for route 1 downhill

The comparison shows good correlation between estimation and measurements and the trend is very similar. Furthermore, it is important to notice that the estimation can take into account events that are likely to happen with a fixed frequency, which cannot be 100% accurate as such events can be unexpected and have a significant impact on the consumption.

From the previous analysis, Figure 22 and Figure 23 show the measured and estimated consumptions for both routes uphill and downhill together with a consumption estimation based on NEDC cycle. It can be observed that the algorithm provided an estimated consumption with an error lower than 2% in all the cases whereas the NEDC estimation can have an error up to 30% in some cases.

Table 2: Measured, estimated and NEDC consumption for routes 1 and 2

	Measured cons. (kWh)	**Estimated cons. (kWh)**	**NEDC cons. (kWh)**	**Estimation error**	**NEDC error**
Route 1 downhill	16.29	16.07	16.92	-1.4%	3.9%
Route 1 uphill	23.87	23.67	16.92	-0.8%	-29.1%
Route 2 downhill	15.23	15.41	16.92	1.2%	11.1%
Route 2 uphill	22.98	22.81	16.92	-0.7%	-26.4%

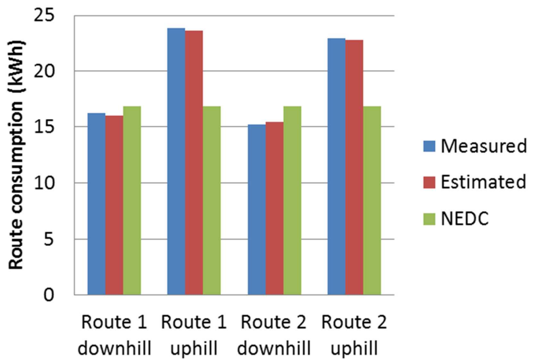

Figure 23: Measured and estimated consumption for routes 1 and 2

It should be noticed that on the same route consumption can increase up to 50% in uphill direction. Consequently, it confirms the fact that it is necessary to take into consideration the altitude difference between the starting point and the destination.

Furthermore, the obtained results also indicate that reaching the energy consumption is always higher on route 2 due to its intermediate gradients despite having the same destination as route 1. If this effect was neglected, the vehicle could run out of battery on an intermediate hill although the destination was apparently achievable initially.

Figure 24 and Figure 25 show the range prediction that would be plotted on the HMI screen on downhill and uphill direction respectively if the available battery energy were 15.5 kWh.

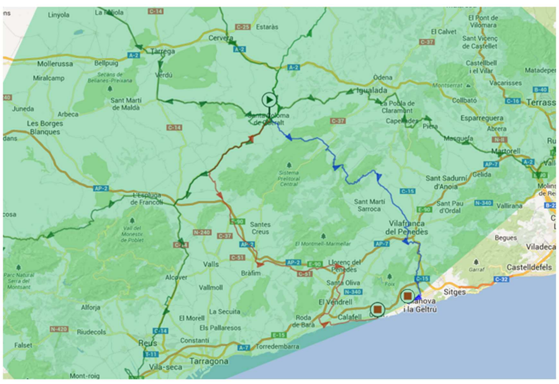

Figure 24: Downhill range estimation

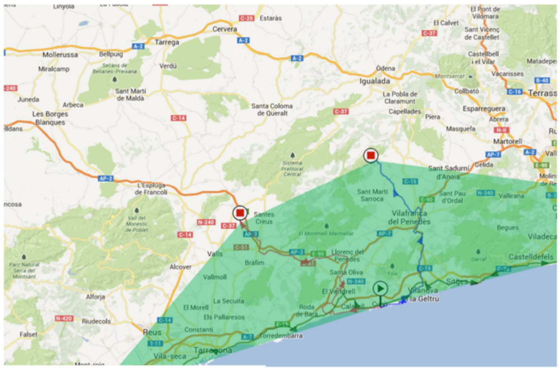

Figure 25: Uphill range estimation

3.2 Parametric studies

Finally, some parametric studies were carried out with the validated algorithm to evaluate the influence of the different driver factors separately. As it is not possible to perform these parametric measurements in vehicle by changing only isolated factors due the speed profile and surrounding drivers, it was decided to use the previously validated algorithm via simulation. In order to realize such calculations, some points have been taken into account:

- Each factor has been modified in order to evaluate its impact compared to a driving situation with a steady speed.
- All the simulations are based on a 4WD race car. It implies obtaining results which can be interpreted in order to obtain conclusions. However, the values are specific to this study and cannot be applied to any vehicle, only the tendency is valid.

Furthermore, it is important to underline that GPS data quality directly impacts on the quality of the final results. As a consequence, it is necessary to have an accurate discretization of the GPS data samples in order to have reliable results for the range estimator algorithm.

3.2.1 Slope

Slope has a high influence on consumption as illustrated in Figure 26 for different speeds. In the case of a slope of 0%, the energy consumption is different according to the vehicle speed; nevertheless the consumption increase has always the same trend when the slope percentage rises: 63 Wh/km per 1% of slope increase.

It can be observed for vehicle speed between 40km/h and 120km/h that consumption can increase up to nine times in case of changing the slope from 0% to 20% and decrease three times in case of changing the slope from 0% to -20% leading to a big vehicle range difference for an electric vehicle.

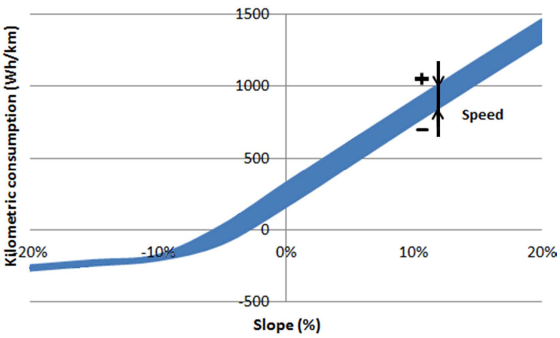

Figure 26: Slope influence over consumption

3.2.2 Steady speed

Speed also has a high influence on consumption. In case of steady speed, the resistance to movement increases with the speed, but consumption does not follow exactly this trend. As the auxiliaries' consumption is constant and the motors efficiency is poor at low speed and torque levels, some vehicles consumption can increase at low speed even though resistance to movement decreases.

Figure 27 shows how this effect occurs in the considered vehicle. In the studied case, efficiency presents two maximums due to the torque distribution.

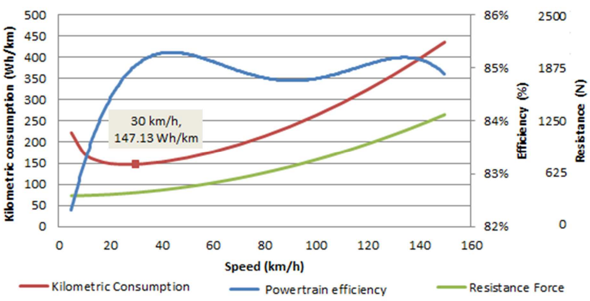

Figure 27: Resistance, efficiency and consumption at steady speed

3.2.3 City stopping frequency and auxiliaries consumption

In urban areas driving with repeated stops generates an increase in the kilometric consumption. According to the frequency and the duration of the stops, the kilometric consumption increases in a non-linear way as shown in Figure 28.

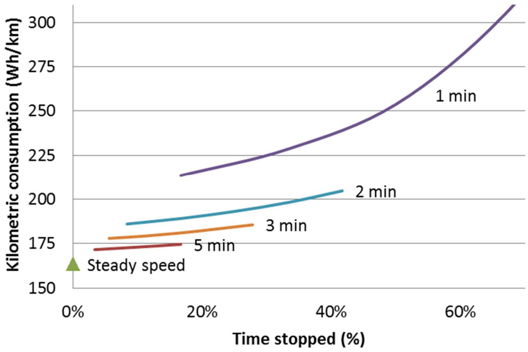

Figure 28: Dependence between consumption and stopping

In city driving with frequent stops auxiliaries' consumption is critical. If auxiliaries' consumption doubles the consumption can be increased up to 5 %.

3.2.4 Aggressiveness in roundabouts

Some main roads with high speed limits present frequent roundabouts where the speed is lowered to around 40 km/h when the allowed speed limit is 50km/h in urban configurations. In this situation very different driver profiles can appear. Aggressive braking immediately before a roundabout increases the kilometric consumption substantially, whereas soft braking behaviour decelerating just with coast torque is optimum to lowering the consumption.

A study was carried out on a route with frequent roundabouts with an average distance of 580 m between roundabouts. Results showed that driver aggressiveness while braking increases significantly the consumption as shown in Figure 29, where braking aggressiveness 0 and 10 correspond to 1 m/s^2 and 6 m/s^2 respectively. This phenomenon can be observed with two parameters:

- Considering the speed limit as the vehicle speed can lead to errors up to 23%.

- Considering the average speed of the route as the vehicle speed can lead to errors up to 52%.

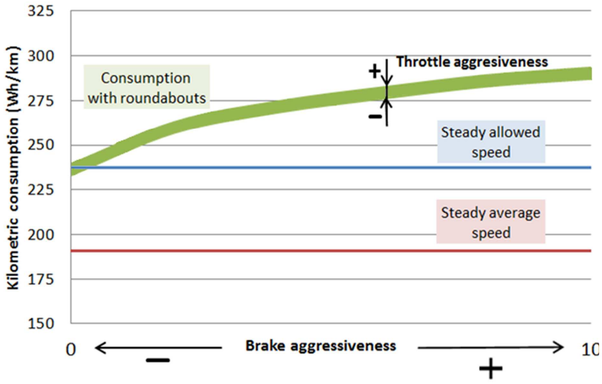

Figure 29: Consumption versus driver's aggressiveness in roundabouts

3.2.5 Pedal tremble

Pedal tremble was initially taken into account but a deep analysis demonstrated that it does not have a significant influence in consumption. The study showed that small involuntary variations in the pedal position can lead to a kilometric consumption increase of 0.03%.

3.2.6 Speed oscillations

Some drivers do not maintain constant speed but they produce continuous speed variations around the target speed. This effect can lead to a consumption increase or decrease in the same vehicle depending on driver's oscillations, target speed and many non-linear vehicle characteristics such as resistance to movement, inertia or motor efficiency map.

In any case, results showed a consumption increase of less than 0.1% under soft speed oscillations; as a consequence this factor was not taken into account.

3.2.7 Overtaking

In highway and suburban driving, the driver's overtaking profile can have a significant impact on consumption. The frequency, the overspeed and the fact of using the brake pedal after overtaking have an important influence on consumption as shown in Figure 30. Aggressive frequent acceleration can increase consumption by up to 6 %.

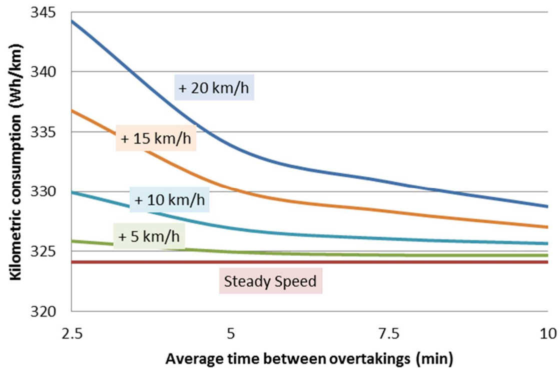

Figure 30: Overtaking profile influence on consumption

3.2.8 Result summary

In order to compare clearly the impact of each factor on energy consumption compared to the steady speed consumption at 0% slope, all the previously calculated results were compiled in the same format as presented in Table 3.

The purpose was to show the most favourable and unfavourable effects that each factor can have by comparison with steady speed average in each situation. As the simulations previously described stated that pedal tremble and speed oscillations have a very low influence on kilometric consumption, they are not represented here. On the contrary, other factors can have a significant influence.

Table 3: Summary of factor influences on energy consumption referred to steady speed

	Maximum	**Minimum**
Slope	+ 838%	- 270%
City driving	+ 86%	+ 5%
Roundabouts	+ 54%	+ 23%
Overtaking	+ 6%	0%
Auxiliaries	+ 5%	<1%

The influence of the factors presented in Table 3 refers to a steady speed situation. In order to compare to the official value obtained from an NEDC cycle which is typically used for range estimation, Table 4 shows the kilometric consumption increase that can be obtained at steady speed referred to NEDC consumption.

Table 4: Influence of steady speed on consumption according to NEDC cycle consumption

	Maximum (120 km/h)	Minimum (40 km/h)
Steady speed	+ 43%	- 38%

4 Conclusions

This study confirmed that the current methodology to determine the vehicle range is not valid as it is critical to take into consideration the road topology. For the same route, the energy consumption can be increased by 700 % when the slope parameter is different. Nevertheless, not only the extreme cases are relevant and a typical traffic jam situation can lead to a consumption increase of up to 86 %.

The current methodology is based on the homologation results which are determined with the NEDC cycle in Europe. Although it is supposed to follow the profile of a vehicle with urban and suburban conditions, it is not representative enough of a real driving cycle as it does not include all the possible conditions regarding accelerations and vehicle speed.

Consequently, many factors have a substantial influence on the energy consumption and they should be properly integrated and adapted for each driver as their impacts are unique for each one.

If this concept is extended to the navigation system, it would be possible to develop a GPS that could not only provide the fastest and the shortest route when choosing a destination, but also the one that requires less energy.

Acknowledgments

This study was developed within the framework of a project in Applus IDIADA. The authors would like to express their gratitude to the powertrain team for their contributions and valuable discussions about the concepts described.

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