Available online at www.sciencedirect.com

ScienceDirect

Transportation Research Procedia 58 (2021) 246–253

Transportation Research Procedia

www.elsevier.com/locate/procedia

14th Conference on Transport Engineering: 6th – 8th July 2021

Optimization of the powertrain of electric vehicles for a given route

Pablo Luque[a,*], Daniel A. Mántaras[a], Jorge Roces[b], Luis Castejón[c], Hugo Malón[c], David Valladares[c]

[a]*Área de Ingeniería e Infraestructuras de los Transportes de la Universidad de Oviedo,*
[b]*Área de Expresión Gráfica en la Ingeniería de la Universidad de Oviedo*
[c]*Área de Ingeniería e Infraestructuras de los Transportes de la Universidad de Zaragoza*

Abstract

The global challenge of reducing pollutant and greenhouse gas emissions has forced the development of alternatives to traditional internal combustion engine vehicles, such as electric or hybrid vehicles. Electric engines are the most efficient for delivery trucks or city buses. Their acceleration and deceleration patterns make them inefficient for the use of internal combustion engines. However, their range and purchase cost are the main factors limiting their use in these applications. The range and acquisition cost of an electric vehicle are mainly related to the energy storage system. Therefore, the optimal size of the battery pack should be considered as a design objective when its application is known. This paper presents a methodology to optimize the battery pack of an electric vehicle based on a given travel distance in a target time. Therefore, it would be applicable to delivery vehicles, buses and any vehicle whose route and travel time are known in advance. The proposed methodology allows minimizing energy consumption by determining the optimal gear ratio for a given route, setting the travel time as a target. A complete vehicle model and a multi-objective genetic algorithm are used for this purpose.

Keywords: Electric vehicle; powertrain; battery pack, energy

1. Introduction

Vehicle manufacturers, R&D centers and universities, among others, have launched electric vehicle projects to reduce carbon emissions and dependence on fossil fuel energy. Many configurations of electric vehicles are designed to attain these objectives (Bayindir, 2001). There are many applications where an electric vehicle can be used in a very efficient way. For example, delivery trucks, in which acceleration and deceleration patterns makes them

* Corresponding author. Tel.: +34-985182059
E-mail address: luque@uniovi.es

10.1016/j.trpro.2021.11.034

inefficient for using internal combustion engines, can be optimized by using electric trucks (Zhao, 2016). Other optimal use can be related to urban buses, in which the zero tail pipe emissions make them the best actual option (Qin, 2016). Something similar would happen in racing electric vehicles, where the track is known and a reference time for the lap is set.

Already knowing the route and an estimated time (Cuesta, 2016), gives us the chance of designing the vehicle especially for it purposes. In what concerns to electric vehicles, one of the most relevant decisions is made during the powertrain design. A regular approach to the design of the powertrain in electric vehicles, starts with selecting the proper motor power and transmission parameters requirements (Yu, 2017). This approach can be a simple solution to this problem, but for many other scenarios, it does not achieve an optimal configuration (Kanchwala, 2017).

Hand in hand with the lack of transmission, clutch or gears, the electric vehicle needs to be extremely efficient, in order to minimize the consumption of energy. For this matter, the influence of including a gearbox with a gear ratio can be determinant on its efficiency (Ren, 2009). This is highly related to the range and performance of the vehicle (Luque,2013 - Abdelrahman, 2017).

In some studies, (Basso, 2019) the authors focus the effort on planning the most efficient route, in order to minimize the energy, consume. Other papers establish the necessity of designing an efficient gearbox for the powertrain, which plays a key role in the design of electric and hybrid vehicles (Dagci, 2018). In Kulik (2018), they pose the option of estimating the requirements for a hybrid electric powertrain base on analysis of the city vehicle GPS track together with accelerometer data.

In relation to the techniques used for the optimization of the powertrain, some studies have explored the option of using genetic algorithm as a strategy for optimization the parameters of the powertrain of a hybrid vehicle. Among that, the use of multi-objective design for different systems of vehicles, it is widely used (Callejo, 2015) for optimization.

This multi-objective genetic algorithm can also be used to define operational strategies of, for example, fleets of trucks, reducing its operational cost, for an early amortization of the expensive hybrid electric vehicles (Fries, 2017).

It can be seen the appropriateness of developing an optimization method, that defines the optimal powertrain for an electric vehicle and a determined route (Luque, 2020). An already defined path and time, allows the designer to find a solution adapted to the specific need of the vehicle (Valle, 2018). The use of multi-objective genetic algorithms for this matter, would serve as a reliable generic method of finding the optimal configuration for the powertrain (Luque, 2021), for a case given the particularities of the route.

This paper presents a methodology to calculate the optimal transmission for a given route, setting the travel time as a target. This would allow adapting the transmission ratio to the route, being applicable to transport vehicles on one or several given routes. It would allow designing optimal transmissions or gearboxes for each route or defining an automatic shifting strategy depending on the selected route.

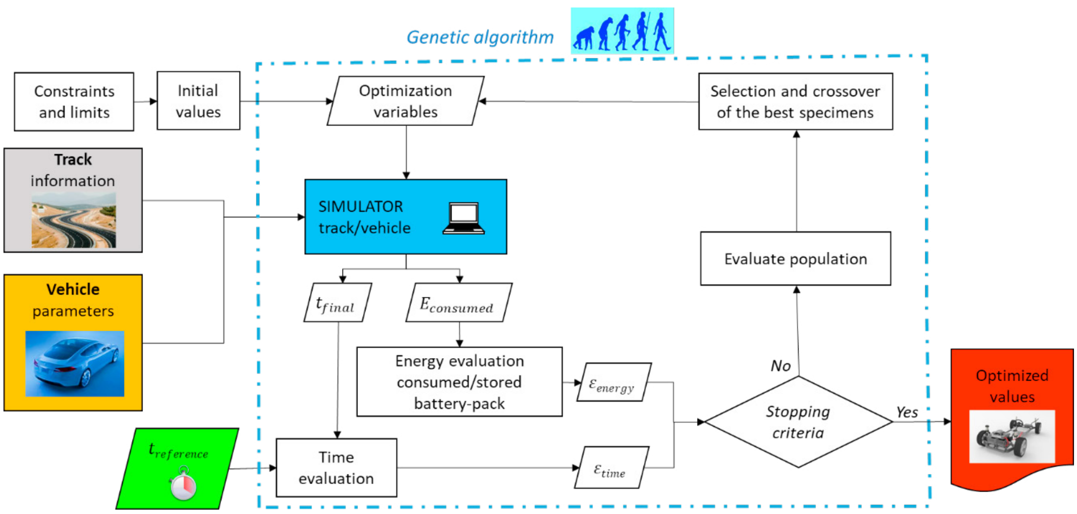

Fig. 1. Flowchart of proposed methodology

2. Methodology

This work proposes an optimization methodology for powertrain design. The minimization of the weight of the battery pack is established as design objective. Problem constraints are a given route and the travel time. The proposed flowchart is the one shown in figure 1.

The characterization of the route, the vehicle to be optimized and the reference time are established as a starting point. With all this in mind the possible design constraints and limitations, a first set of initial values of the parameters to be optimized is proposed. These values include aspects of the powertrain design, such as transmission ratio or engine characteristics. In addition, the mass of the battery is another parameter to optimize.

These parameters allow to obtain, after calculation with the module "simulator", the results of time (t_{final}) and consumed energy ($E_{consumed}$). These obtained values are evaluated with the time set as a reference ($t_{reference}$) and the stored energy, obtaining the values error of time (ε_{time}) and energy (ε_{energy}). By using a multi-target genetic algorithm, the modification of the design parameters is proposed in order to minimize the errors obtained. When the stopping criteria have been reached, the optimization process stops.

3. Analysis of electric vehicle dynamics

The electric vehicle under study has a powertrain that can be characterized by the following parameters: Maximum torque (T_{max}), Maximum power (p_{max}), Maximum engine speed and Total transmission ratio (i_t). These values are supposed to be optimized according to the needs of the study. It may be that some of these values are set at the beginning of the study, having, for example, restrictions on the type of motor to be used. Another characteristic parameter of the motor is the cut-off speed ($v_{cut-off}$). This speed sets the limit between maximum torque and constant power traction. Various yields and efficiencies will also be taken into account in the powertrain design. The powertrain design allows to obtain, in every location of the route, the traction force (F_T), including the effect of all drive axles.

$$F_T = F_f + F_r \tag{1}$$

In addition, the mass in running order of the vehicle is known and the load status. Regarding the battery pack, the type and therefore the voltage of each cell, cell unit weight and energy density are taken as initial information. The full weight of the battery pack (m_b) is considered a design variable that is intended to minimize for the given route.

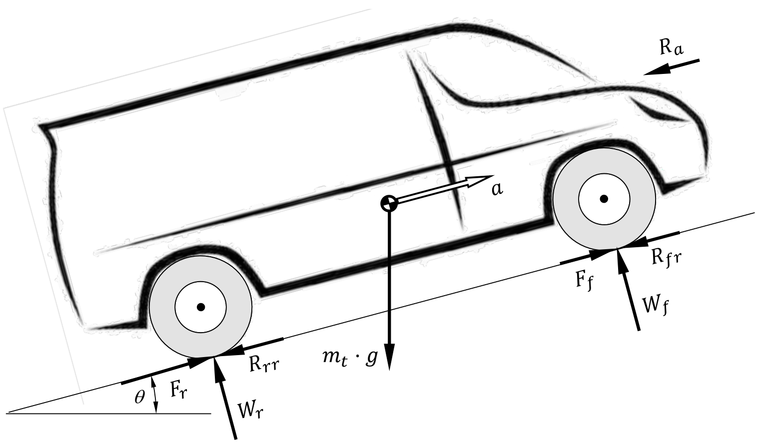

Fig. 2. Vehicle dynamics

According to Figure 2, the dynamics of the vehicle is characterized by resistances or drag forces that include both the rolling resistances on the axles (R_{fr}, R_{rr}), as well as the aerodynamic resistances (R_a), other mechanical losses, and the grade resistance (Allonca, 2019). The over-all drag forces are characterized by the following expression:

$$R = A + B \cdot v(t) + C \cdot v^2(t) + m_t g \cdot sin\theta \tag{2}$$

The total mass of the vehicle (m_t) can be expressed as the sum of the mass of energy storage systems (m_b), such as batteries and auxiliary systems and the rest of the vehicle's masses (m_v). Depending on the powertrain design, drive shaft position, wheelbase, weights in every shaft (W_f, W_r) and center of gravity position, the vehicle's traction capacity may be limited by the adhesion of the drive wheels to the rolling surface. It should therefore be checked, both the performance of the powertrain and the limitations of the environment.

4. Route analysis

As already mentioned, the method proposed on this paper has the objective of defining an optimization method for designing the powertrain of an electric vehicle, knowing its final purpose. This includes knowing a reference time for the route and the route itself. A route can be a complex consecution of different sections like strait lines, open curves, closed curves, uphill or downhill. This makes the study of the route quite complex, taking in mind the necessity of applying the equations to the entire track. To simplify this problem, a solution is proposed. If we can find a method to typify every section of a route, and then apply the calculation process to it summing up all the sections at the end, will be easier, more precise and more efficient. The general methodology implies that the complete route for which you want to optimize the vehicle must be divided into sections that are characterized by having the constant values of the section parameters. The parameters that characterize each section are: Start point, End point, Ramp/slope, Radius of curvature (in the case of a straight section, the radius is considered to be infinite, ∞) and adhesion. If a change of ramp/slope or adhesion occurs on the same constant radius curve, it must be divided into as many sections as there are different values.

After the analysis of the route, there is a division of sections characterized by its starting and ending point. If distances to the origin are taken, it is clear that the endpoint of a section (n) coincides with the start of the next one (n+1). Each section must be characterized by a maximum speed (v_{max}), which is function of the vehicle and the road. The vehicle has a circulation limit according to the powertrain. The road imposes a limit that is a function of the maximum lateral acceleration radius of curvature and the posted speed. Once the route partition has been defined, the behaviour of the vehicle within each section must be analyzed.

The simulator considers that the initial speed of the section (n) is the final speed of the stretch $(n-1)$, so when it reaches that section, the speed is assumed to be known. In general, it is established as a condition that when it under traction force, the powertrain will be considered the maximum tractive effect (considering both the limit of the powertrain and the adhesion). The maximum speed in every section cannot be exceed. At the end of the section (n) cannot be exceed the starting limit speed of the next section $(n+1)$, which will be taken by default the maximum speed. If the vehicle is driving at a speed higher than the final speed, a braking procedure must be established. The point from which braking must start must be determined to reach the end of the run at the defined speed.

As a conclusion, a complex and long track can be automatically segmented into an undefined number sub-tracks or sections, each one also defined by its parameters that can be its length l, its slope θ, its initial speed $v_{initial}$, its maximal speed v_{max} and its final speed v_{final}. In general, each section can be defined by its maximal speed v_{max}, that restrict the circulation throw that section. For example, if the maximal speed of the section is greater than the cutoff speed of the motor of the vehicle, it can be defined four different dynamic behaviors:

A. The vehicle accelerates from $v_{initial}$ to v_{cut_off} at constant torque. The acceleration in this subsection is:

$$a_{Tmax}(t) = \frac{\frac{T_{max} i_t}{R} - \left(A + B \cdot v(t) + C \cdot v^2(t) + m_t g \cdot sin\theta\right)}{m_t \gamma} \tag{3}$$

B. The vehicle accelerates from v_{cut_off} to v_{max} at constant power. The acceleration in this subsection is:

$$a_{pmax}(t) = \frac{\frac{p_{max}}{v} - \left(A + B \cdot v(t) + C \cdot v^2(t) + m_t g \cdot sin\theta\right)}{m_t \gamma} \tag{4}$$

C. The vehicle circulates at constant speed v_{max}. The acceleration in this subsection is 0. In this case the tractive force must be such that it equals the drag resistances, resulting in zero acceleration

D. The vehicle breaks from v_{max} to v_{final}. The acceleration of this subsection is:

$$a_b(t) = \frac{-F_b - \left(A + B \cdot v(t) + C \cdot v^2(t) + m_t g \cdot sin\theta\right)}{m_t \gamma} \tag{5}$$

A general sequence of speed variation is shown in figure 3.

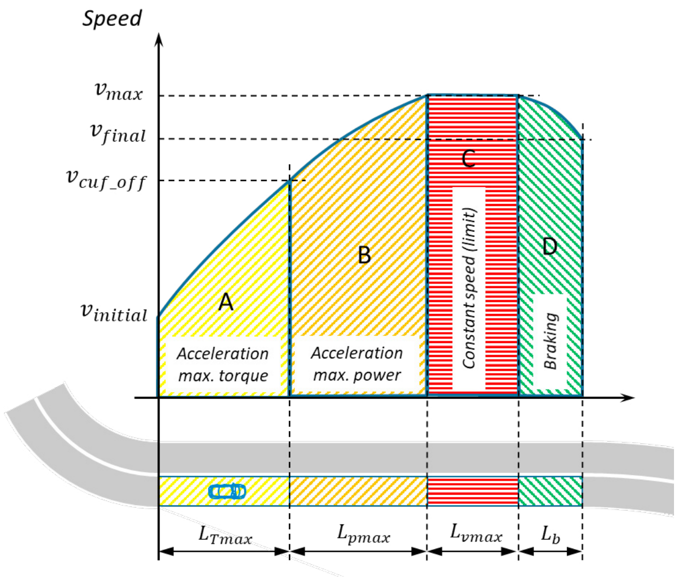

Fig. 3. Speed variation in a general section.

The simulation module analyzes the dynamic response of the vehicle in every section of the given track. The calculation procedure include la classification of the different subsections, according to the vehicle response. The total length of a section is described by 4 subsections, having each one its own length:

- ✓ L_{Tmax}: Subsection length associated to the maximal torque.
- ✓ L_{pmax}: Subsection length associated to the maximal power.
- ✓ L_{vmax}: Subsection length associated to the maximal speed.
- ✓ L_b: Subsection length associated to the braking phase.

At the end, the total length of a i-section $L(i)$ is the sum of the length of this 4 subsections:

$$L(i) = L_{Tmax}(i) + L_{pmax}(i) + L_{vmax}(i) + L_b(i) \tag{6}$$

These lengths can be calculated based on the dynamic behaviour of the vehicle.

$$L(i) = \int_{v_{initial}}^{v_{cut\_off}} \frac{v \cdot dv}{a_{Tmax}(v)} + \int_{v_{cut\_off}}^{v_{max}} \frac{v \cdot dv}{a_{pmax}(v)} + v_{max} \cdot t_{vmax} + \int_{v_{max}}^{v_{final}} \frac{v \cdot dv}{a_b(v)} \tag{7}$$

The total time spend in go across a section is describe by 4 subsections, having each one its own time:

- ✓ t_{Tmax}: Time spend going throw the section of maximum torque.
- ✓ t_{pmax}: Time spend going throw the section of maximum power.
- ✓ t_{vmax}: Time spend going throw the section of maximum speed.
- ✓ t_b: Time spend going throw the breaking section.

At the end, the total time spend going throw a section is the sum of the time needed for the 4 subsections:

$$t_{total} = t_{Tmax} + t_{pmax} + t_{vmax} + t_b \tag{8}$$

The total time (t_{total}) to travel the section will be:

$$t_{total} = \int_{v_i}^{v_c} \frac{dv}{a_{Tmax}(v)} + \int_{v_c}^{v_{max}} \frac{dv}{a_{pmax}(v)} + t_{vmax} + \int_{v_{max}}^{v_f} \frac{dv}{a_b(v)} \tag{9}$$

As it can be seen, a general section of the route or track can be composed by the combination of these four types of subsections. In case of vehicle and route limitations, in each study section in which the route has been divided, one or more subsections may disappear. Some special cases could appear, as follows:

- The maximum speed is not reached: This implies that the maximum speed phase (C) disappears. In that case $t_{vmax} = 0$. It can be expressed mathematically as:

$$v < v_{max}, \forall t \tag{10}$$

- The maximum speed acceleration of the run is not reached (B): This implies that the maximum speed phase disappears. Speed (v) never exceeds the change rate (v_{cut_off}). It can be expressed as:

$$v < v_c, \forall t \tag{11}$$

This can occur with or without maximum speed phase. If you the maximum speed phase is not reached, an additional constraint should be considered:

$$v_{max} < v_c \tag{12}$$

- No braking phase: This implies that the braking phase (B) disappears. In that case the speed does not reach the final speed.

$$v < v_{final}, \forall t \tag{13}$$

This can be achieved in three different ways:

I. Finishing the section in maximum speed
II. Finishing the section at maximum power
III. Finishing the section at maximum torque

- It starts from acceleration at constant power: This implies that the acceleration phase at maximum torque (A) disappears. In that case the initial speed exceeds the cut-off speed.

$$v_{cut\_off} < v_{initial} \tag{14}$$

- The run starts at constant speed and equal to the maximum: This implies that the acceleration phase disappears. In that case, the initial speed is equal to the maximum speed.

$$v_{max} = v_{initial} \tag{15}$$

All this logic is implemented in the simulator. Initially the simulator has the information that characterizes each section. This information is relative to the length of each section, slope, maximum speed and braking deceleration. The simulation module starts from an initial speed of the first section. Every simulation step the vehicle is located in a section (i). This allows you to know the maximum section speed, the maximum permissible final speed and the braking acceleration. If the speed is less than the maximum speed, it accelerates. If the speed is lower than the cut-off speed, acceleration with constant maximum torque is assumed. Otherwise, the engine is considered to drive at constant power. In this case the torque is a function of the power and engine speed.

At each point of the section, it is necessary to check that the speed does not exceed the maximum, so in that case, the torque will be necessary to counteract the losses due to the resistance forces when driving at constant speed.

In parallel, it should be noted, depending on the final speed, that the braking distance required is no less than the distance to the end of the run.

With these conditions, a simulation of the route of each vehicle configuration is obtained based on the design variables. Differences between the times obtained and the reference time are evaluated. It is also checked that the energy consumed is at least equal to that stored in the battery pack. With all this, a set of new vehicle configurations is proposed, using a genetic algorithm. The ultimate goal is to get a weight-optimized solution.

5. Results and conclusions

As an example of application of the proposed methodology, the analysis of a given route is shown in Figure 4.

Fig. 4. Given track used to methodology implementation.

By entering all the characteristic parameters of the vehicle and the route sections, the genetic algorithm is run. Different powertrain configurations of the vehicle are iteratively simulated. Finally, a configuration with a minimized weight of the battery pack is obtained. Figure 4 shows the different points at which a change of status occurs in the vehicle dynamics.

In conclusion, it can be stated that a new methodology is proposed to optimize the chassis of electric vehicles. This methodology focuses on minimizing energy consumption for a given track and travel time. A simulated model of the behavior of an electric vehicle on a given track has been successfully achieved to be used in a multi-objective genetic algorithm in order to optimize the chassis of an electric vehicle. This method is reliable and can be used in many applications, where the time and route are already known. The design variables are composed by the battery pack mass and the gear ratio, both optimized to ensure the best performance on the route. The multi-objective model is validated using a real case that confirms its functionality.

Acknowledgments

The authors of the work want to express their appreciation to the University Institute of Industrial Technology of Asturias for the financing of the project: "Electric racing vehicle type CM. Detail engineering and design level TRL3 (Proof of concept)", whose reference is SV-19-GIJON-1-08

References

Abdelrahman, A.S.; Algarny, K. S. and Youssef, M. Z. (2017). Optimal gear ratios selection for a nissan leaf: A case study of ingear transmission system. IEEE Energy Convers. Congr. Expo. ECCE 2017, vol. 2017-Janua, pp. 2079–2085, 2017.

Allonca, D.; Mantaras, D.A.; Luque, P. and Alonso, M. (2019). A new methodology to optimize a race car for inertial sports. Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology, SAGE Publications Ltd, 01-Jun-2019.

Basso, R, et al. (2019). Energy consumption estimation integrated into the Electric Vehicle Routing Problem. Transp. Res. Part D Transp. Environ., vol. 69, pp. 141–167, 2019.

Bayindir, K.Ç.; Gözüküçük, M.A., and Teke, A. (2011). A comprehensive overview of hybrid electric vehicle: Powertrain configurations, powertrain control techniques and electronic control units. Energy Conversion and Management. Volume 52, Issue 2, February 2011, Pages 1305-1313 https://doi.org/10.1016/j.enconman.2010.09.028

Callejo, A.; García De Jalón, J.; Luque, P. and Mántaras, D.A. (2015). Sensitivity-Based, Multi-Objective Design of Vehicle Suspension Systems. J. Comput. Nonlinear Dyn., vol. 10, no. 3, p. 031008, 2015.

Cuesta, C.; Luque, P.; Mántaras, D.A. (2016). State estimation applied to non-explicit multibody models. Nonlinear Dynamics, 2016, vol. 86 no 3, pp. 1673–1686.

Dagci, O.H.; Peng, H. and Grizzle, J.W. (2018). Hybrid electric powertrain design methodology with planetary gear sets for performance and fuel economy. IEEE Access, vol. 6, pp. 9585–9602, 2018.

Fries, M.; Kruttschnitt, M. and Lienkamp, M. (2017). Multi-objective optimization of a long-haul truck hybrid operational strategy and a predictive powertrain control system. 12th Int. Conf. Ecol. Veh. Renew. Energies, EVER 2017.

Kanchwala, H.; Luque, P.; Mántaras, D.A.; Wideberg, J.; Bendre, S. (2017). Obtaining Desired Vehicle Dynamics Characteristics with Independently Controlled In-Wheel Motors: State of Art Review. SAE International Journal of Passenger Cars - Mechanical Systems, vol. 10, no. 2, pp. 413-425, doi: 10.4271/2017-01-9680

Kulik, E.; Tran, X. T. and Anuchin, A. (2018). Estimation of the requirements for hybrid electric powertrain based on analysis of vehicle trajectory using GPS and accelerometer data. 25th Int. Work. Electr. Drives Optim. Control Electr. Drives, IWED 2018 - Proc., vol. 2018-Janua, pp. 1–5, 2018.

Luque, P., Mántaras, D.A., Orueta, A.M. (2013). Passive safety assessment in rally vehicle using virtual crash test. DYNA, 2013, 88(4), pp. 453–461.

Luque, P.; Mántaras, D.A.; Pello, A. (2013). Racing car chassis optimization using the finite element method, multi-body dynamic simulation and data acquisition. Proc. of the Institution of Mechanical Eng., Part P: J. of Sports Engineering and Technology, 2013, vol. 227, no 1, pp. 3–11

Luque, P.; Mántaras, D.A.; Maradona, A.; Roces, J.; Sánchez, L.; Castejón, L. and Malón, H. (2020). Multi-Objective Evolutionary Design of an Electric Vehicle Chassis. Sensors, vol. 20, 3633; doi:10.3390/s20133633.

Luque. P.; Mántaras, D.A.; Roces, J.; Maradona, A; Sánchez, L. (2021). Electrification of the Low Cost Competition Vehicle. A Paradigma Change. DYNA. vol. 96, no. 3. DOI: https://doi.org/10.6036/9889.

Qin, N. et al. (2016). Numerical analysis of electric bus fast charging strategies for demand charge reduction. Transp. Res. Part A Policy Pract., vol. 94, pp. 386–396, 2016.

Ren, Q.; Crolla, D.A. and Morris, A. (2009). Effect of transmission design on Electric Vehicle (EV) performance. 5th IEEE Veh. Power Propuls. Conf. VPPC '09, pp. 1260–1265, 2009.

Valle, J.A.; Viera, J.C.; Anseán, D.; Brañas, J.; Luque, P.; Mántaras, D.Á., Pulido, Y.F. (2018). Design and Validation of a Tool for Prognosis of the Energy Consumption and Performance in Electric Vehicles. Transportation Research Procedia, 2018, 33, pp. 35–42

Yu, H.; Castelli-Dezza, F. and Cheli, F. (2017). Optimal powertrain design and control of a 2-IWD electric race car. 2017 Int. Conf. Electr. Electron. Technol. Automot., no. 1, pp. 1–7.

Zhao, Y. et al. (2016). Carbon and energy footprints of electric delivery trucks: A hybrid multi-regional input-output life cycle assessment. Transp. Res. Part D Transp. Environ., vol. 47, pp. 195–207, 2016.