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Electric Vehicle Packaging Tool (EVPT), Validation and Application

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Abstract

The eMobility-Lab development Electric Vehicle Packaging Tool (EVPT) supports design and approval of Electric Vehicles. By replacing the existing drive line with an electric drive line the vehicle mass, the moment of inertia and the position of the centre of gravity may change. This may affect the steady-state and dynamic vehicle handling. The EVPT calculates the battery mass from vehicle performance parameters and subsequently the effect on vehicle handling. Furthermore, it also calculates the necessary changes in vehicle set up to recover the original vehicle handling. The EVPT can be applied in the development process; especially in the concept stage where decisions have to be made with respect to quality, costs and development time. The EVPT is developed as a calculation and simulation package and is also available as a set of look up tables, in which case no simulation environment is necessary.

The development as presented on the EEVC 2012 continues in this paper with the validation and application of the EVPT. It is concluded that the EVPT shows a good qualitative and quantitative representation of vehicle handling in practise. The EVPT has been used in an ICE to EV conversion project and has shown its usability in making design choices. Furthermore the paper describes the added value of the EVPT to other software packages: a robust easy to use tool with a specific focus on (electric) vehicle packaging evaluation.

The EVPT is developed in the eMobility-lab research program of the Rotterdam University of Applied Science. The eMobility-lab investigates electric mobility concepts operating in the Rotterdam area, contributing to a sustainable, safe and economic solution for clean transportation.

Keywords: (BEV) battery electric vehicle, regulation, safety, simulation, vehicle performance

1 Introduction

By placing batteries and thus replacing the existing drive line by an electric drive line, the mass and the moment of inertia of a vehicle and the position of the centre of gravity may change. This may affect the steady-state and dynamic vehicle handling. Early in vehicle development, it is important to have an understanding on these relationships in order to be able to make the right design choices from the point of view of vehicle handling, cost and development time. In addition, these choices should meet the requirements regarding passive safety and vehicle packaging.
Since vehicle dynamics [2,3] is a specialized area of research, a user friendly tool can be very helpful in the decision process.
As a result of the exploration stage of the eMobility-Lab [1,4], the following objective is formulated:
The development of a tool to predict the effect of battery placement on the vehicle handling and to assess the measures in the vehicle setup in order to be able to compensate towards the initial/desired vehicle handling.

This tool is referred to as the Electric Vehicle Packaging Tool (EVPT). The paper presented on the EEVC 2012 [7] introduces and explains the product up to examples of the applications of the EVPT. The contents of this paper is summarized in Chapter 2.

Following to this publication the research has been continued with the theoretical and experimental validation. Furthermore the EVPT has been applied in the development of an electric sports car. Finally a comparison will be made between the EVPT and other software packages.

2 The product: Electric Vehicle Packaging Tool, EVPT

The packaging of an electrically propelled vehicle differs greatly from that of conventionally powered vehicles. The heavy internal combustion engine is replaced by a lighter electric motor and heavy batteries replace the lightweight fuel tank. To design such new vehicles, or to adjust existing vehicles with electric driveline components, the vehicle packaging should be reviewed with respect to handling performance. The development tool EVPT should support this process, involving 4 steps: (Figure 1)

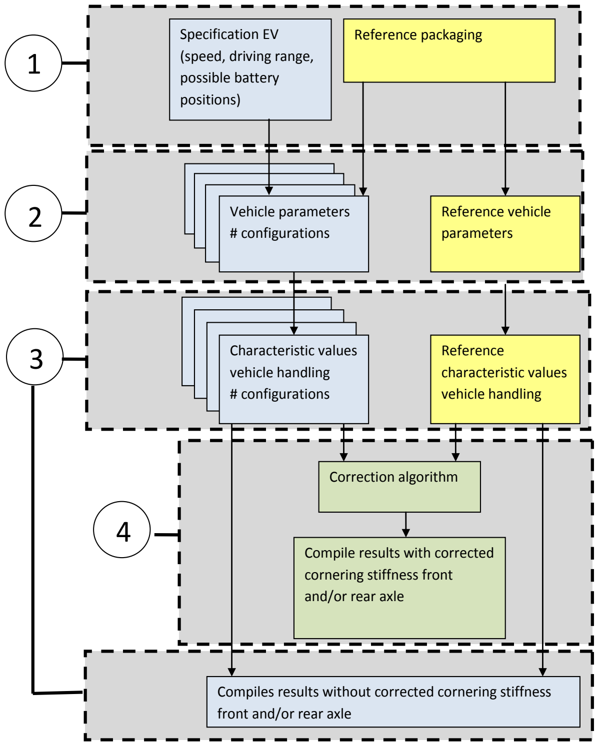

Figure 1: Process steps in the EVPT

1. To determine the EV (Electric Vehicle) parameters and requirements in terms of speed and driving range, and possible driveline component inertias and positions.

2. To compose the configurations with the relevant vehicle handling parameters such as the vehicle mass (m_{tot}) and the mass of the battery (m_{bat}), the location of the center of gravity in longitudinal and vertical direction (z_{pos}) and the yaw moment of inertia (J_z).

3. To determine characteristic vehicle handling performance values.

4. To determine the balance of cornering stiffness of the front and rear axle in order to bring the vehicle behavior back to that of a reference vehicle or original conventional vehicle.

The EVPT consists of a specific model and a generic model. The specific model, a calculation and simulation package (with a vehicle dynamics

model, see Figure 2) is used to investigate the electrification of a specific vehicle. Here a large number of battery distributions and masses are evaluated and visualized.
In the generic model the calculated change of the mass and location of the center of gravity is used to assess the effects on vehicle handling. It is presented in a book of tables. These tables are categorized to the characteristic velocity v_{ch}, centre of gravity (CG) position and battery distribution.

The specific model which requires Matlab-Simulink is presented in the following paragraphs:

- The calculation and simulation package
- Driving tests and characteristic values
- The correction algorithm

The generic model is generic model is briefly described in Paragraph 2.4.

2.1 The calculation and simulation package

The steady-state and dynamic vehicle behavior for the linear range of the tyre-road interaction is described by the single-track vehicle model (Figure 2).

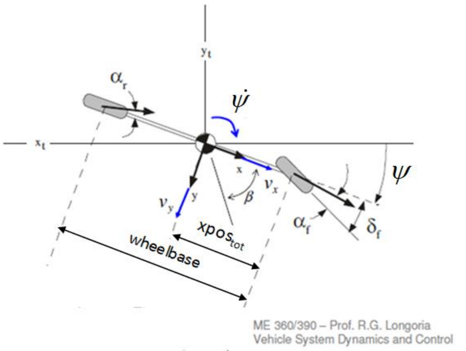

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Figure 2: Single-track model

The defining parameters for the steady-state behavior are:

- Vehicle mass: m_{tot}
- Cornering stiffness of the front axle and rear axle; $C_{fa,f}$, $C_{fa,r}$
- Wheel base : wb
- The location of the center of gravity (CG) in longitudinal direction. : $xpos_o$, $xpos_{rel}$

For the dynamic behavior the yaw moment of inertia is added.

The EVPT calculates all parameters based on the vehicle specification: dimensions, masses, performance and placement batteries. The tyre model estimates the cornering stiffness based on the wheel load, speed and road surface condition.
The EVPT consists of a preprocessing module for the vehicle model in which the vehicle dynamics parameters are determined, as well as a processing module for vehicle behavior in predefined tests by means of calculations and simulations; and a post processing module where the characteristic quantities are derived and exported. Calculations are made on 150 configurations per vehicle.
See Figure 3.

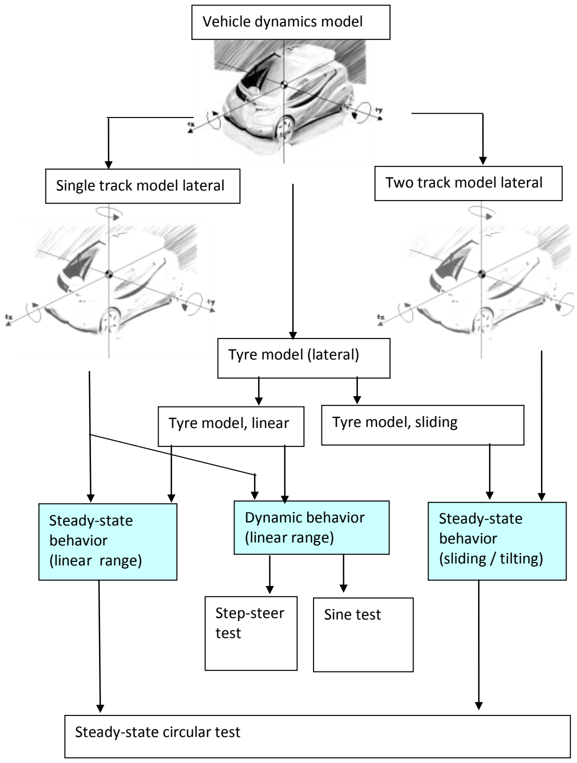


Figure 3: Vehicle dynamics calculation and simulation model

2.2 Driving tests and characteristic values

The EVPT focuses on the following pure lateral behavior:

- the steady state circular test
- the step-steer response test
- the sine test

Each configuration parameter set is recorded and a number of characteristic values and coefficients are determined. These are defined based on data which can be recorded in handling tests. A model based approach is defined in [5].

For the steady-state behavior we distinguish between the linear range and the level of maximum lateral acceleration.

- For the linear range, the self-steering gradient (EG) and the characteristic speed (v_{ch}) are calculated.
- The maximum lateral acceleration is determined at the moment one of the axles (front or rear) slide out of the circle.
- Furthermore, the maximum lateral acceleration to tilting is calculated.

The dynamic behavior is assessed on the basis of the step-steer test and the sine test.

- The following are determined with the step-steer test:
    - The response time $t_{\dot{\psi}_{\max}}$
    - The ratio between the maximum and steady-state yaw velocity (overshoot: $\frac{\dot{\psi}_{\max}}{\dot{\psi}_{stat}}$)
- The following are determined with the sine test:
    - The phase angle between the steering angle and the lateral acceleration φ_{ay}
    - The amplitude ratio of the lateral acceleration and the steering angle $\frac{a_{y\max}}{\delta_{\max}}$

The dynamic behavior of a vehicle is calculated by means of two transfer functions derived from the single-track model, in other words: yaw rate over steering angle and lateral acceleration over the steering angle. The parameters of the transfer function are collected too.

2.3 The correction algorithm

The correction algorithm process consists of the following steps: (See Figure 4)

- Determination of the combinations of change to the front and rear axle cornering stiffness ($C_{f\alpha,f,rel}$ and $C_{f\alpha,r,rel}$) such that the steady-state behavior (the self-steering gradient) can be corrected to the value of the reference configuration.
- With each combinations the effect on the dynamic behavior is determined (response time $t_{\dot{\psi}_{\max}}$ at the step-steer test).
- The best combination can now be chosen.

The dynamic behavior of the vehicle is computed again to compare the original and corrected behavior of the vehicle.

Figure 5 shows an example of the reference vehicle with ICE. This vehicle is converted to an EV with the batteries near the rear axle. As a result, the vehicle yaw-rate response to sudden steering changes is slower. After correction of the cornering stiffness of the rear axle (multiplied by 1.05) and the front axle (multiplied by 0.9) the vehicle responds similarly to the original ICE configuration (see Figure 4).

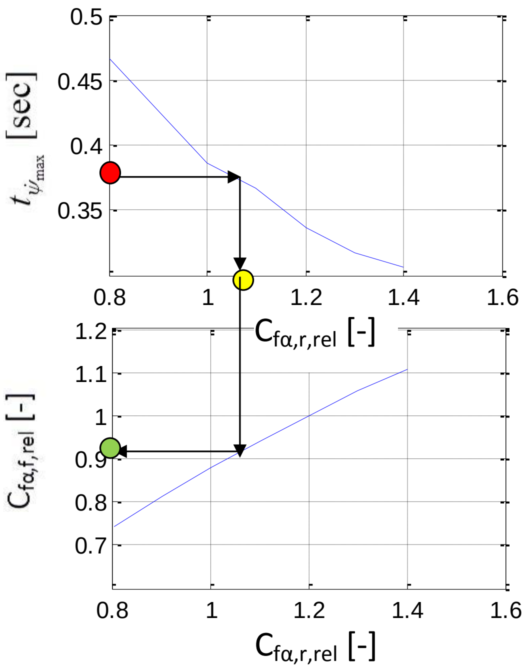


Figure 4: Correction algorithm principle

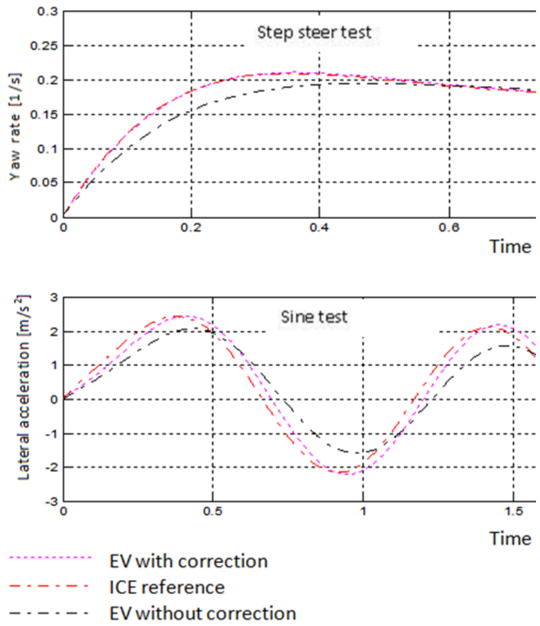


Figure 5: Correction algorithm results

2.4 The generic model

The generic model is a three dimensional polynomial of the variables $x_{pos,rel}$ and $m_{tot,rel}$ (relative change to the reference). The function is fitted for the characteristic values calculated in the specific model. A total 12 characteristic values is fitted.

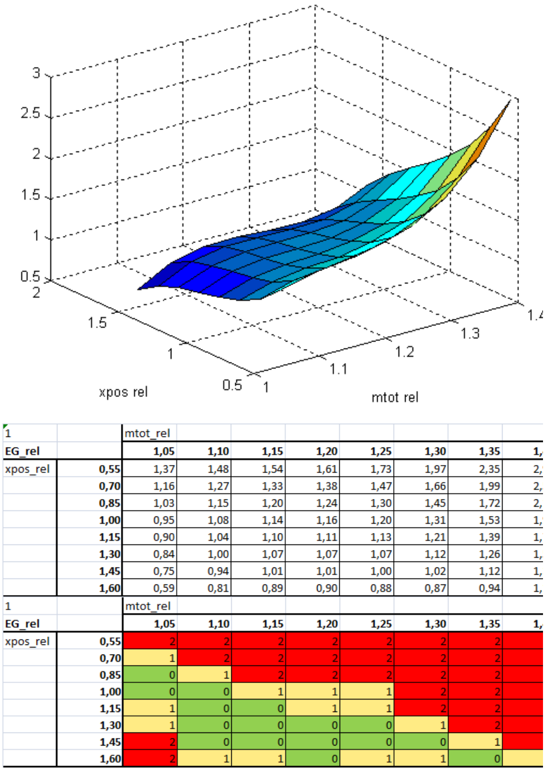
Figure 6 shows an example table. Here we can find that, for example an increase of the vehicle mass only will result in more understeer. A shift of the centre of gravity to the rear axle results in a vehicle with less understeer. It is obvious that one should try to find a packaging constraint in which EG_rel (EG_{rel}) is near to 1. A rapid interpretation of the tables is also presented in graded colors of green, yellow and red.

In the green area no significant change of vehicle handling properties are expected. In the red area the changes are unacceptable. Within the yellow area it is advised to change the setup of the vehicle using the tables determined with the correction algorithm.

3 Validation

The EVPT has been validated by:

- Literature research on effects on vehicle dynamics
- Vehicle handling experiments



1		mtot_rel							
EG_rel		**1,05**	**1,10**	**1,15**	**1,20**	**1,25**	**1,30**	**1,35**	**1,**
xpos_rel	**0,55**	1,37	1,48	1,54	1,61	1,73	1,97	2,35	2,
	0,70	1,16	1,27	1,33	1,38	1,47	1,66	1,99	2,
	0,85	1,03	1,15	1,20	1,24	1,30	1,45	1,72	2,
	1,00	0,95	1,08	1,14	1,16	1,20	1,31	1,53	1,
	1,15	0,90	1,04	1,10	1,11	1,13	1,21	1,39	1,
	1,30	0,84	1,00	1,07	1,07	1,07	1,12	1,26	1,
	1,45	0,75	0,94	1,01	1,01	1,00	1,02	1,12	1,
	1,60	0,59	0,81	0,89	0,90	0,88	0,87	0,94	1,

1		mtot_rel							
EG_rel		**1,05**	**1,10**	**1,15**	**1,20**	**1,25**	**1,30**	**1,35**	**1,**
xpos_rel	**0,55**	2	2	2	2	2	2	2	
	0,70	1	2	2	2	2	2	2	
	0,85	0	1	2	2	2	2	2	
	1,00	0	0	1	1	1	2	2	
	1,15	1	0	0	1	1	2	2	
	1,30	1	0	0	0	0	1	2	
	1,45	2	0	0	0	0	0	1	
	1,60	2	1	1	0	1	1	0	

Figure 6: The generic model, example EG relative (EG_rel)

3.1 Literature research on effects on vehicle dynamics

Literature on characterizing the lateral vehicle dynamics [8, 9,10,11,12] has been compared with the choices made for the EVPT. This is in general on change in vehicle behavior due to changes the centre of gravity, mass and moment of Inertia. For this purpose publication [8] and [10] appeared to be most relevant and are discussed in the following paragraphs.

3.1.1 Characterizing the lateral vehicle dynamics [8]

This paper presents a theoretical and experimental study on the effects on atypical moments of inertia, as is the case in conversion to or design of EV. It refers to research from the NHTSA inertial parameters database [13] and shows that the moment of inertia for the yaw can be normalized to

$$\bar{J}_{z,tot} = \frac{J_{z,tot}}{m_{tot}.(x_{pos,tot}.(wb - x_{pos,tot}))} \qquad (1)$$

The normalised inertial parameters from the database fall in the following range:

$$0.86 < \overline{J}_{z,tot} < 1.18 \qquad (2)$$

This narrow range represents the conventional vehicles. When changing to EV’s the normalised moment of inertia may fall outside this range.

By comparing the normalised yaw moment of the EVPT with this range the validity of EVPT is studied.

The EVPT calculates $J_{z,tot}$ from the position and the value of the individual masses.

- The $J_{z,bat}$ and the position of the CG of the batteries is calculated from the distribution between front, centre and rear area of the vehicle.
- The sum of all yaw moments of inertia is then the $J_{z,tot}$, so of the full vehicle.

To compare the normalized moments of inertia calculated by the EVPT with the range of for the NHTSA database results of three vehicle types have been selected:

- A compact car: The Citroen C1 EV ($m_{tot,unloaded}$ ICE: 900 kg)
- A small sports car: The Burton HR GTZero ($m_{tot,unloaded}$ ICE: 600 kg)
- A delivery van. ($m_{tot,unloaded}$ ICE: 1500 kg)

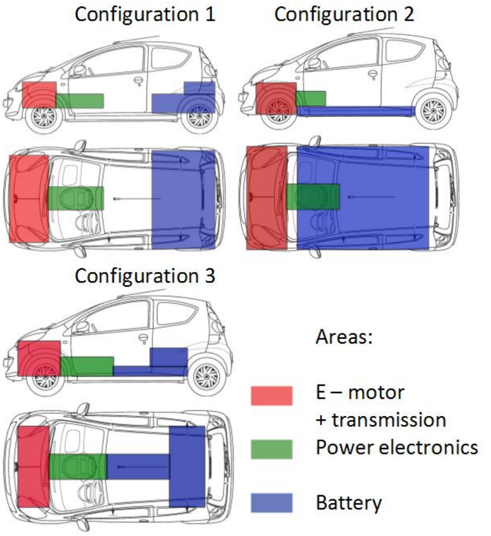


Figure 7: Configurations of the Citroen C1

For all vehicles three battery configurations have been calculated. The three configurations (Figure 7) for the Citroen C1 EV (battery mass 130 kg) have been described in the earlier paper [7]. The Burton HR GTZero (battery mass 150 kg) the configurations are battery front, centre and rear. This is also the case for the delivery van where the calculations have been done twice: for a battery mass of 250 kg and a battery mass of 500 kg.

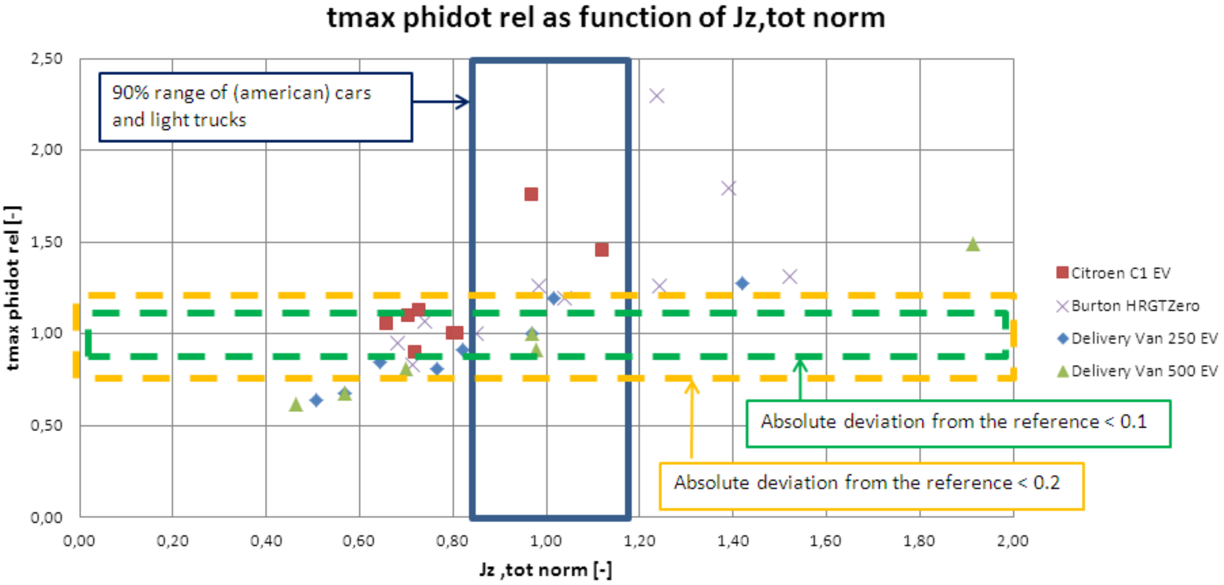


Figure 8: The response time relative to the ICE configuration as function of the normalized moment of inertia

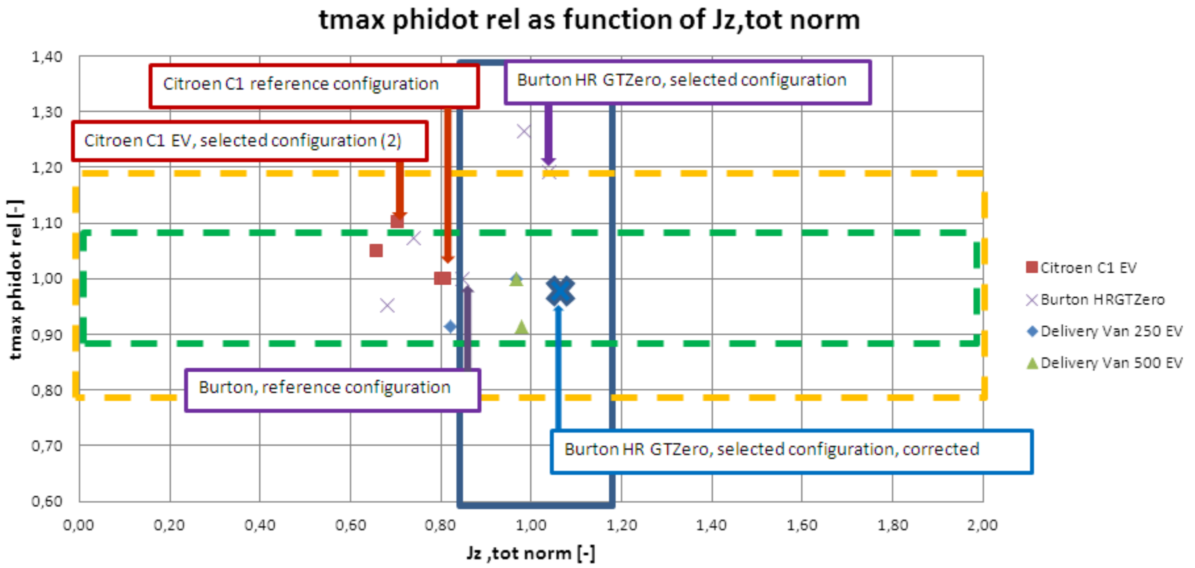


Figure 9: The response time relative to the ICE configuration as function of the normalized moment of inertia for selected and reference configurations

Figure 8 shows the complete set. On the horizontal axle the $J_{z,tot,norm}$ and on the vertical axle the response time $t_{\dot{\psi}_{\max}}$. The indicated range of normalized inertia, combined with the EVPT range green (absolute relative deviation < 0,1 from reference value) and yellow (idem, absolute relative deviation < 0,2 from reference value) show the desired range for acceptable vehicle handling.

For the Burton HR GTZero and the delivery van both methods correspond well, meaning that the green (+yellow) area of the EVPT is in the range of the normalised moments of inertia. In case of Citroen C1 the points seem to be shifted to the left. This car is small and compared to its length relatively heavy leading to a lower value of the normalised moments of inertia. Especially when adding the battery. Refer also to (1). Furthermore this car is outside the range of cars covered in the NHTSA database.

For both the Citroen C1 and the Burton HR GTZero the packaging is chosen using the EVPT. Figure 9 show that the chosen packaging for the HR GTZero (33% of the batteries on the front axle and 67%) of the batteries on the rear axle increase the response time $t_{\dot{\psi}_{\max}}$ in to the yellow area. However by increasing the $C_{f\alpha,f}$ and $C_{f\alpha,r}$ the response time $t_{\dot{\psi}_{\max}}$ recovers again to the value of the reference configuration. In case of the C1 the configuration 2 with the battery under the floor would be favourable but cannot be realized in the vehicle body. For this reason the design team has chosen for configuration 3.

The paper also quantifies the effect on the transient response of the vehicle. The centre of rotation is defined as the distance behind the CG: [14].

$$c^* = \overline{J}_{z,tot}.(wb - x_{pos,tot}) \qquad (3)$$

In case c*=b the centre is on the rear axle. It moves forward in case c* decreases and backwards in case c* increases. A low value of c* corresponds with a low value of the response time $t_{\dot{\psi}_{\max}}$

In order to be able to compare the vehicles we use the normalised value:

$$\overline{c^*} = \frac{c^* - (wb - x_{pos,tot})}{wb} \qquad (4)$$

The tendencies shown in Figure 10 to Figure 12 show that:

- $\overline{c^*}$ is 0 around for acceptable vehicle handling.
- A value of $\overline{c^*}$ negative corresponds faster response and larger overshoot
- A value of $\overline{c^*}$ negative corresponds slower response and smaller overshoot

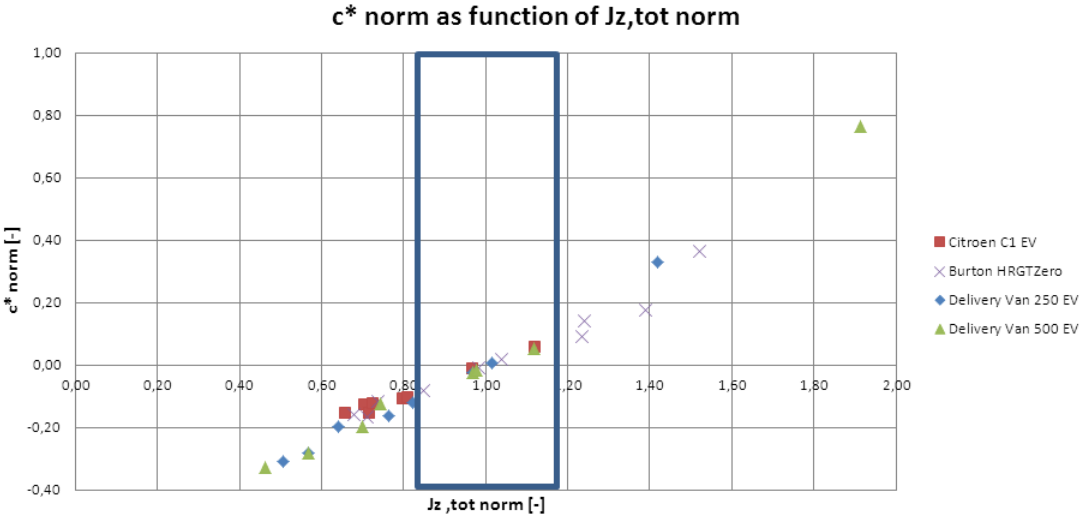


Figure 10: c* normalised as function of the $J_{z,tot}$ normalised

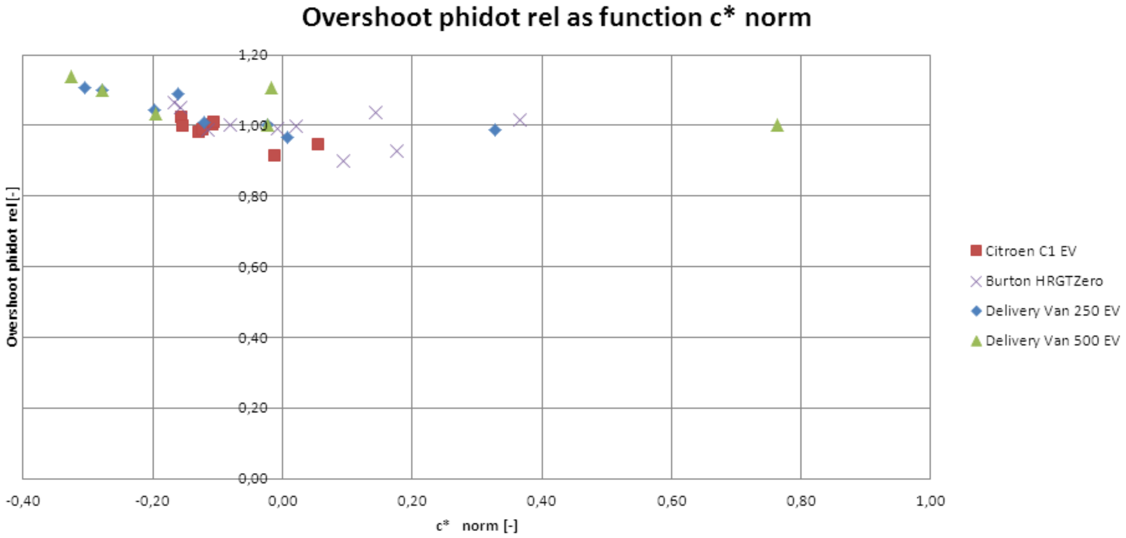


Figure 11: Overshoot in the yaw velocity, relative to the reference, as function c* normalised

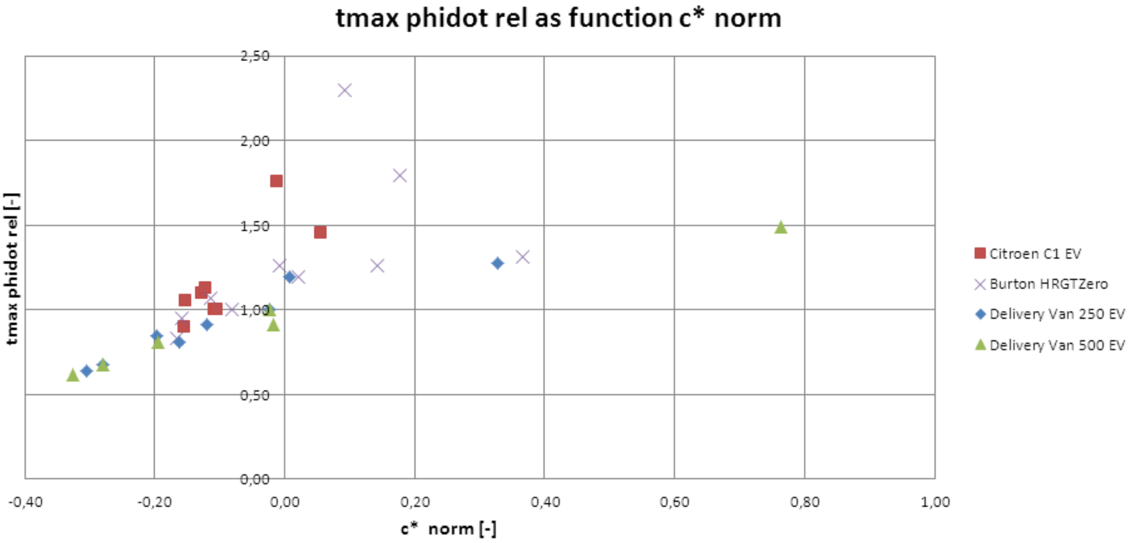


Figure 12: Response time $t_{\dot{\psi}_{\max}}$, relative to the reference, as function c* normalised

The investigations here have proven the validity of the EVPT with respect to:

- the estimation of $J_{z,tot}$
- the classification on the non critical and critical battery packaging compared to the $J_{z,tot,norm}$
- the response depending on the center of rotation c*

3.2 An enhanced generic single track vehicle model and its parameter identification for 15 different passenger cars [10]

The paper describes an enhanced single track vehicle model by adding:

- steering compliance
- relaxation length of the tyre
- tyre model beyond 0.4 g lateral acceleration

The EVPT uses a steering compliance factor for the front axle also as a fixed value per vehicle. It is calculated from the steering gradient (without compliance factor) and the typical steering gradient corresponding to the v_{ch} for the reference configuration (cruising speed~80 km/h for a passenger car).

The relaxation length has not been included in the EVPT, but it is expected that this is compensated by the pure step steer (without time delay). In line with this hypothesis the average value of the response time $t_{\dot{\psi}_{\max}}$ of the EVPT corresponds to the value in [10].

The tyre model beyond 0.4 g has been prepared to be a basic Magic Formula as presented in [10] but is not yet functioning.

The research in this paper uses values of the $J_{z,tot}$ from the NHTSA database [13] as the paper discussed in the previous paragraph. The results of the simulation have been compared to the experimental data of 15 different passenger cars for the ISO 7401 step steer test which is also used in the EVPT.
The paper concludes that *'the the proposed single track model is generally suitable for describing the vehicle response for different loading configurations when load dependencies are included in the tyre description and vehicle inertia properties.*'

3.3 Vehicle handling experiments

Sensitivity studies have investigated the effect of change of mass, centre of gravity and moment of Inertia on the vehicle handling. [15]
The vehicles under tests are the BMW 3 Touring (2007) and the VW Golf 6 (2013)

3.3.1 BMW 3 Touring

To the unloaded vehicle mass has been added. (0 kg, 120 kg, 200 kg and 300 kg) behind the rear axle.
The stationary response of a_y on the δ has been measured as well as the dynamic response in a step steer test at 0,4 g at a vehicle speed of 80 km/h according to ISI 7401.
From the data the steering gradient EG and the response time $t_{\dot{\psi}_{\max}}$ have been calculated.
The tested configurations have also been simulated by the EVPT using the specific model.

Table 1 shows the results: the relative change of the characteristic value by adding 300 kg behind the rear axle. Thus $J_{z,tot}$ increases from 3000 kgm^2 to 3500 kgm^2 and the m_{tot} increases from 1700 kg to 2000 kg.

The accuracy has been estimated based on the deviation in the repetition of individual measurements. Respecting this limited accuracy of the experiments it is clear that the EVPT performs well.

Table 1: BMW 3 Touring: The relative change of the EG and $t_{\dot{\psi}_{\max}}$ by added 300 kg mass behind the rear axle of a vehicle. Experiments and simulations compared

	EG	$t_{\dot{\psi}_{\max}}$
Experiment	0.89±0.06	1.12±0.04
Simulation	0.84	1.12

3.3.2 VW Golf 6

Similar tests have been executed with a VW Golf 6. This unloaded vehicle has been loaded with 200 kg behind the rear axle.

Herewith the mass increases from 1350 kg to 1550 kg. The $J_{z,tot}$ increases from 2300 kgm^2 to 2600 kgm^2.

See table 2. Also here the EVPT performs well.

Table 2:VW Golf 6: The relative change of the EG and $t_{\dot{\psi}_{\max}}$ by added 200 kg mass behind the rear axle of a vehicle. Experiments and simulations compared

	EG	$t_{\dot{\psi}_{\max}}$
Experiment	0.76±0.06	1.14±0.04
Simulation	0.85	1.14

4 Applications of the EVPT

The EVPT in its preliminary form has been evaluated in de electric vehicle development project and has been introduced in the automotive engineering education.

4.1 Development of an electric sports car: HR GTZero

For the Electric Sports Car Build-Off (ESCBO) co-creation competition, powered by Siemens, the Rotterdam University of Applied Sciences has developed a full electric vehicle based on the Burton car body and the Citroen 2CV chassis. [17].
See Figure 13.

Figure 13: HR GTZero under test

The goal of the project was to get the best compromise in performance, costs and development time. For this goal the EVPT has been used according to the process described in Figure 1.

Step 1: The reference vehicle is the Burton with an ICE mounted in front of the front axle.

Step 2: The preprocessing defines 150 configurations of battery mass and packaging.

Step 3: The results of step 2 and 3 are then combined in one workbook to generate the graphs. Following to this basis calculation different possibilities for the vehicle packaging have been worked out. Based on this a second more precise run has been prepared starting with step 1.

Step 4: For the selected configuration the foreseen correction on the effective $C_{f\alpha,f}$ and $C_{f\alpha,r}$ is calculated. Here it is concluded that the effective cornering stiffness of the front and rear axle should be increased. This achieved by increasing the roll stiffness of the suspension by increasing the springs stiffness.

In June 2013 the vehicle handling performance has been approved by the Dutch homologation organization as part of the single vehicle approval. Furthermore this HR GTZero has been approved to be used on the public road and fulfills all the R100 safety standards of an electric ‘single build’ vehicle.

4.2 Application in automotive engineering education

The EVPT-tool will be integrated in the Automotive Engineering education, as part of the eMobility-Lab, with the results becoming available to be exploited further in the eMobility-Lab activities.

5 The added value of the EVPT

There are a number of alternatives for the use of the EVPT. In general we distinguish three levels:

1. General simulation software (like Matlab Simulink)
2. Dedicated vehicle simulation software (like Carsim)
3. Multi body simulation software (like Adams, or Adams Car)

These packages offer all the possibilities for vehicle dynamics simulation so have a broader scope than the EVPT. The quality of the output is directly related to the quality of the input, i.e. a correct calculation of the parameters of, vehicle, tyre and power train.

The EVPT was designed to be a basic easy to use robust simulation tool specifically suitable for a study on the effects of changes in the vehicle packaging. The number vehicle parameters which has to be defined is therefore very limited and easily understandable for a general engineer. The EVPT has a number of smart characteristics like the accurate calculation of mass and moments of inertia, the calculation of the mass of batteries from the vehicle driving range, a simple, robust, tyre model and an automatic calculation of the compliance factor of of the front axle. For a rapid evaluation 150 different configuration are processed and exported in standard MS Excel import files.
The first evaluation of a vehicle packaging thus takes less than one hour! (including programming of the parameters)
Another unique functionality is the correction algorithm which supplies direct information on the requested change in the vehicle setup to compensate for the change in the vehicle packaging.
The specific model of the EVPT uses Matlab Simulink as simulation environment which might limit the use by (small) vehicle conversion companies. For this reason a generic model, as a book of tables, is also available
This EVPT helps to avoid basic mistakes at the earliest beginning of the design process and can lead to safer electric vehicles as a result. Our credo is: Better be safe, than sorry!

6 Conclusions

The methods applied in the EVPT are valid with respect the type of model used as well as the calculation of the important moment of inertia around the vertical axis. These other models have been validated in with experimental data.
Vehicle handling tests were performed and the data both in the stationary and in the dynamic range was compared to the results of the EVPT. The results show a good qualitative and quantitative match of the simulation and measured characteristic values.
The EVPT has been used in an ICE to EV conversion project and has shown its usability in making design choices. The vehicle in development has been tested extensively by the Dutch homologation organization and has been approved for use on the public road.

Finally, when comparing the EVPT to other software packages the main conclusion is that the key values added are especially valuable in the field of design rather than in the field of the vehicle dynamics. This lies mainly in the ability to calculate the necessary change in the cornering stiffness of front and rear axle.

7 Nomenclature

Parameters		
Symbol	**Dimension**	**Desciption**
c^*	m	Centre op rotation behind the CoG
$\overline{c^*}$	-	Centre op rotation behind the CoG, normalised
m_{tot}	kg	Vehicle mass
m_{bat}	kg	Battery mass
$J_{z,tot}$	kgm^2	Yaw moment of intertia
$\overline{J}_{z,tot}$	-	Yaw moment of intertia, normalised
$xpos_{tot}$	m	Longitudinal position of centre of gravity relative to front axle
$zpos_{tot}$	m	Vertical position of centre of gravity relative to the road.
wb	m	Wheelbase
$C_{f\alpha,f}$	N/rad	Cornering stiffness front axle
$C_{f\alpha,r}$	N/rad	Cornering stiffness rear axle

Parameters generic model		
Symbol	**Dimension**	**Desciption**
$xpos_0$	%	Longitudinal position of centre of gravity relative to front axle relative to wheelbase
$xpos_{rel}$	-	Longitudinal position of centre of gravity relative to front axle
v_{ref}	km/h	Velocity category vehicle
J_{z1}, J_{z2}, J_{z3}	-	Battery (added mass) distribution: central, evenly, on axles.
$m_{tot,rel}$	-	Relative change vehicle mass

Characteristic values steady-state vehicle behavior		
Symbol	**Dimension**	**Desciption**
EG	rad.s^2/ m	Self steering gradient or understeer coefficient
EG_{rel}	rad.s^2/ m	Self steering gradient or understeer coefficient, relative to reference configuration
v_{ch}	m/s	Characteristic velocity

Characteristic values dynamic vehicle behavior		
Symbol	**Dimension**	**Desciption**
$t_{\dot{\psi}_{\max}}$	sec	Time from start of step steer test to maximum of the yaw velocity. ‘tmax phidot’
$\frac{\dot{\psi}_{\max}}{\dot{\psi}_{stat}}$	-	Ratio between the maximum dynamic and steady-state yaw velocity on a step steer test. ‘overshoot’
φ_{ay}	rad	Phase angle between the steering angle and the lateral acceleration on a sine test

$\frac{a_{y\max}}{\delta_{\max}}$	m/rad.s^2	The amplitude ration of the lateral acceleration and the steerng angle on a sine test

References

[1] Frank Rieck; *Project proposal eMobility-lab*; Rotterdam University of applied sciences; March 2009 (in Dutch)

[2] Dr.Ing. Adam Zomotor; *Fahrwerktechnik: Fahrverhalten* (*Vehicle dynamics*); Vogel Buchverlag 1991; ISBN 3 8023 0774 7

[3] Hans Pacejka; *Tyre and Vehicle Dynamics*; Butterworth-Heinemann, 2002; ISBN 0750651415

[4] Roeland.M.M.Hogt, Eelco Rietveld; *Exploration safety EV*; Rotterdam University of applied sciences; March 2010 (in Dutch)

[5] Tetsushi Mimuro et. al.; *Four Parameter Evaluation Method on Lateral Transient Response*; SAE-paper 901734, 1990

[6] F.G. Rieck; *Exploration driving electric, Chapter: Safety and environment*; D-Incert 2010 (in Dutch)

[7] Roeland M.M.Hogt et al; *Electric Vehicle Packaging Tool (EVPT)*; Rotterdam University of applied sciences; November 2012; EEVC 2012

[8] Carrie G. Bobier et al; *Transient Responses of Alternative Vehicle Configurations: A Theoretical and Experimental Study on the Effects of Typical Moments of Inertia*; Stanford University; June 2008; 2008 American Control Conference, paper WeA07.3

[9] David A. Renfroe et al; *Quantitative measure of transient oversteer of road vehicles*; Engineering Institute, LLC. United States Paper Number 07-0217

[10] Bart Niessen, Sven Jansen et al; *An enhanced generic single track vehicle model and its parameter identification for 15 different passenger cars*; TNO/Eindhoven University of Technology; AVEC'12

[11] H. Mazumder et al; *Effect of mass distribution on cornering dynamics of retrofitted EV*; Faculty of Engineering and Industrial Sciences, Swinburne University of Technology ,Victoria, Australia; Electric Vehicle Conference (IEVC), 2012 IEEE International Conference: 4-8 March 2012

[12] Jaehoon Lee et al; *Full Vehicle Dynamic Modeling for Chassis Controls*; School of Automotive Engineering, Kookmin University, South Korea; F2008-SC-021

[13] Gary J. Heydinger et al; *Measured Vehicle Inertial Parameters-NHTSA's Data Through November 1998*; NHTSA; SAE World Congress, 1999, 1999-01-1336

[14] W.F. Miliken and D.L. Miliken; *Chassis Design: Principles abd Analysis*; Warrendale, PA USA: Society of Automotive Engineers; 2002

[15] Francesco Bergisch, Marwin Jansen, Michael Visser; Vehicle handling experiments, development and practice; Rotterdam University of applied sciences; June, 2013 (in Dutch)

[16] Martijn Koedijk; Application EVPT on packaging design of the *HRGT Zero*; Rotterdam University of applied sciences; November, 2013 (in Dutch)

[17] *www.burtoncar.com*

About

The eMobility-lab investigates electric mobility concepts operating in the Rotterdam area, contributing to a sustainable, safe and economic solution for clean transportation. www.emobilitylab.nl

The (Research Design and Manufacturing) RDM Campus is a place where students and companies collaborate in an open environment and focus on new economic activity and sustainable and innovative solutions in the markets Building, Moving&Powering.
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