EVS30 Symposium
Stuttgart, Germany, October 9 - 11, 2017

Designing Light Electric Vehicles for urban freight transport

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Summary

The number of light commercial vehicles (LCV) in cities is growing, which puts increasing pressure on the liveability of cities. Small electric freight vehicles and cargo bikes can offer a solution, as they take less space, can manoeuvre easily and free from polluting emissions. Within the two-year LEVV-LOGIC project, (2016-2018) the use of light electric freight vehicles (LEFVs) for city logistics is explored. The project combines expertise on logistics, vehicle design, charging infrastructure and business modelling to find the optimal concept. This paper presents guidelines for the design of LEFV based on the standardized rolling container (length 800 mm, width 640 mm, height 1600 mm) and for the charging infrastructure.

Keywords: BEV (battery electric vehicle), freight transport, light vehicles, mobility concepts, smart charging

1 Introduction

The number of new light commercial vehicles[1] (LCV) registrations in Europe has increased from 1.3 million in 2009 to 1.7 million in 2015 [1]. In 2015, LCV accounted for approximately 11 percent in the total light duty vehicle market, compared to 8.5 percent in 2009. The London Assembly Transport Committee reported an increase of 11 percent in kilometres driven by LCV, while lorry traffic remained the same [2]. The increase of LCV in urban traffic is a result of the rising e-commerce market, the growth of inner city construction work, the increase of self-employed workers, and trends in the food, catering and hospitality market. The average shipment size in city logistics becomes smaller and deliveries are more time-critical [3]. As a result, the maximum capacity of freight vehicles is rarely needed [4].

The delivery of goods and services are in essence required for the functioning of cities, but the vehicles put increasing pressure on the city in terms of pollution, congestion, accessibility and loss of public space [5]. One of the opportunities for improvement may be found in the use of Light Electric Freight Vehicles (LEFV) in cities. The vehicles are smaller in size, can manoeuvre easily and are free from polluting emissions.

In recent years, various companies across European cities (such as DHL) have started to offer city logistics with LEFVs. However, logistic operators with LEFV only play a marginal role, while the number of LCV in city logistics continues to grow. Producers of LEFVs see limited growth in demand. There is no large-scale

[1] Gross vehicle weight below 3.5 metric ton. Also known as delivery vans.

production of LEFVs yet as the optimal vehicle specifications (per freight segment) has not been defined yet. This paper aims to support the understanding, design and applications of future LEFVs.

The LEVV-LOGIC project, introduced in Chapter 2, explores the current and future state in the transition to large-scale use of LEFVs in city logistics. The current state in electric freight vehicles is described in Chapter 3. Next, an inventory has been made on the current use of LEFVs in the Netherlands and the problems and challenges that users face (Chapter 4). The design assignment for future LEFV described in Chapter 5 starts from scratch. Chapter 6 describes vehicle design process. The results are described in Chapter 7 and consist of the customer and design requirements of LEFV, the design of a LEFV, the evaluation and guidelines for the design of LEFV and implications for the energy-charging infrastructure. The paper is completed with the conclusions and discussion (Chapter 8) and references (Chapter 9).

2 LEVV-LOGIC project

Within the LEVV-LOGIC project, the Amsterdam University of Applied Sciences, the Rotterdam University of Applied Sciences and HAN University of Applied Sciences work together with approximately 30 public and private organizations to explore how LEFV can be a financially competitive alternative for conventional freight vehicles. The research runs from 2016 to 2018 and has started by exploring the potential of LEFV for specific freight flows based on the characteristics of the logistics demand and according delivery profiles (e.g. freight conditions, customer services, delivery frequency, network density). Next, the optimal design of the vehicles is explored.

The LEVV-LOGIC project defines light electric freight vehicles as electrically powered or electrically assisted vehicles that are in size smaller than a LCV and have a maximum loading capacity of 750 kilogram. It includes electric cargo bikes and L-category vehicles.

This brings a first limitation of the current state vehicles (Figure 1) as large or heavy goods are not suitable to be delivered with LEFV. Next, LEFV have a limited range in terms of kilometres and speed and are consequently not suitable to drive on high ways. Depending on the intensity of use, the options for private and public infrastructure and replaceable batteries need to be considered to charge the batteries before or between trips.

Figure 1: Examples of light electric freight vehicles (Urban Arrow, Stint, Goupil)

3 Research on electric freight vehicles

In European research and demonstration projects like DELIVER [6], FREVUE [7] and ENCLOSE [8] the potential of electric delivery vehicles has been explored extensively, from both a technical, financial, logistical and policy perspective. Despite the time and money spent on research and development, large-scale implementation of electric vehicles has not taken place yet. In fact, the development slows down [9]. While electric vans are considered to be credible [8], the share of electric vans in the total fleet of LCV is only 0.1% [9]. Neither sales figures are promising. Electric vans account for just 0.6% of all sales according to the European Environment Agency [10]. The EU project FREVUE concludes after four year of research that the business case of EV's remains a challenge. The environmental friendly vehicles do not offer sufficient operational advantages to compensate for the significant higher purchase price [11]. Next, there is a lack of efficient manufacturer support in case of breakdowns and development in charging infrastructure is needed.

In the meantime, the discussion on the negative impact of transport has developed into a broader debate including not only climate change, but also health issues (air quality and noise nuisance), public space occupancy and the attractiveness of cities in general. From that point of view, LEFVs offer an additional social benefit compared to conventional LCV as they are smaller in size. Next, LEFVs are competitive with conventional LCV in purchase price [12]. Also, operational benefits have been observed as the vehicles are faster in congested cities [13]. The vehicles are (often) allowed on cycle lanes and can park more easily and closer to the delivery address, i.e. save time searching for a place to park.

4 Design of LEFV

City logistics is very diverse in terms of type of goods, volumes, conditions and transport units. A survey among current users of LEFVs in The Netherlands shows the diverse usage of LEFVs in urban freight transport, see Figure 2, ranging from parcels to food and clothing. However, the respondents mention the lack of suitable LEFVs as the main barrier for up scaling. The main problems encountered are related to the capacity and battery/charging system.

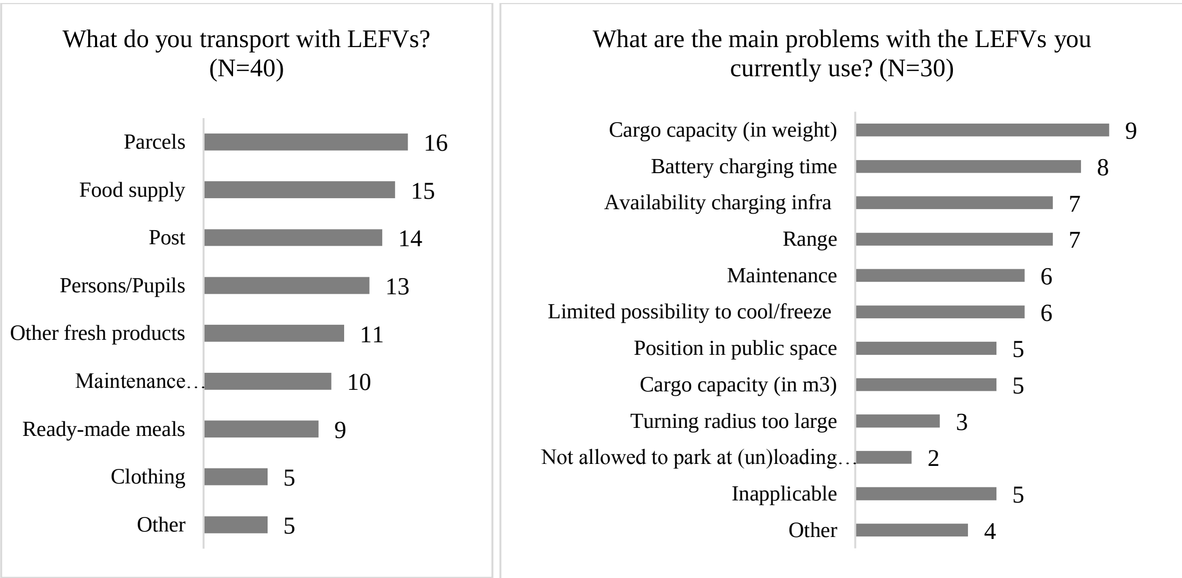

Figure 2: Results LEFV survey in The Netherlands (2017)

Presently, LEFV concepts are being developed from two directions: up scaling bicycles and down scaling freight vehicles. For a successful transition to larger number of LEFVs in urban traffic, understanding of the fundamentals on functional requirements, performance and passive and active safety is crucial. During the first half year of the LEVV-LOGIC project, the functional (customer) requirements and challenges for the design of LEFV have been defined as follows:

- There is a need to design LEFV for larger loading capacity (mass and volume).
  In this paper we will focus on the two standardized rolling containers (Figure 3).
- There is a growing delivery market in the food sector, both B2B and B2C. As a result, the need for standardization in volumes, load units and cooling systems is growing as well.
- There is a need for easy battery replacement or fast charging.
- The interaction with other traffic and the existing infrastructure should be taken into account during the design phase as it currently creates uncertainty among users.

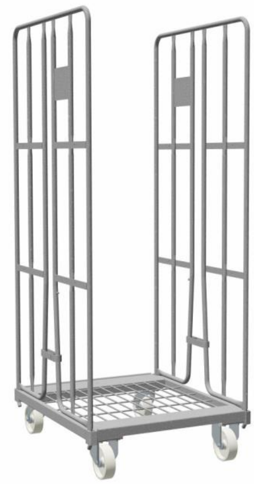

Figure 3: The standard roll container (length 800 mm, width 640 mm, height 1600 mm)

5 Design assignment for future LEFV

The inventory amongst vehicle suppliers brought up a number of questions with respect to the design, safety and homologation. Furthermore the analysis shown in the previous chapter shows that there is a need for an increase of the cargo capacity. The number of LEFVs increase and will further increase in the coming years, which affects traffic safety and logistics processes. The design assignment for future LEFV should therefore address:

- The understanding of the vehicle design process
- The (re)design and improvement of LEFVs
- The definition of guidelines for the design of LEFV
- The requirements and solutions for the logistic and energy and charging infrastructure

6 Vehicle development from the automotive perspective

The vehicle development process shown in Figure 4 consists of: the development of the design, detail engineering, prototyping and testing and production. In the decision point 1, 2 and 3 (D0, D1 and D2) the focus is on the design solution. The development of the design can be done with limited time effort, but will have large consequences on the product development process following up to production start D5 and the product performance and price. So when the development gets to decision point 2 (D2), it is a Go-no-go on scaling up the development.

This paper focuses on the development process up to decision point 2.

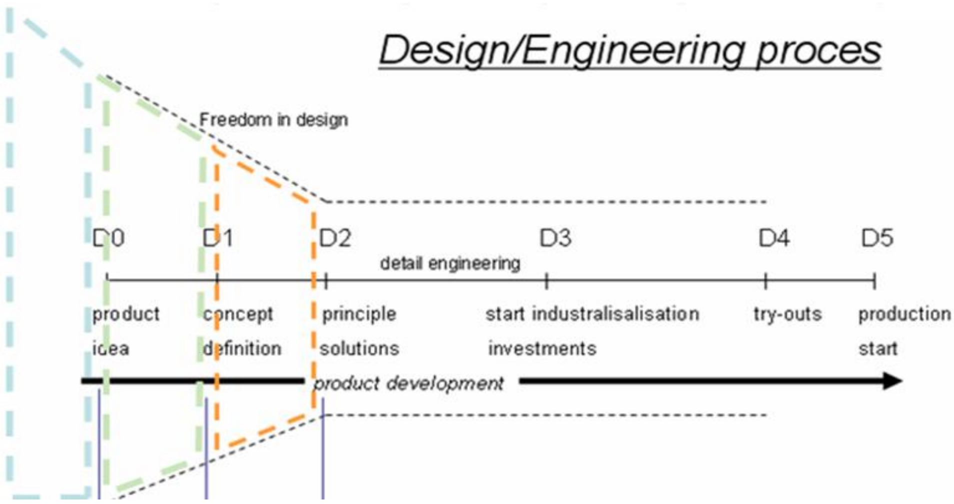

Figure 4. The vehicle design process

6.1 The product idea, from customer to design requirements

The product idea starts with a question which can be technology or market driven. It is the 'why' question answered here and brings both technology and market together. For example: the possible solution of LEFV in urban distribution transporting roll containers from a logistic hub to stores in the centre of the city because of the ambition to evolve to clean city centres. The product idea gives a glimpse of what the solution could be.

To get the focus on the development we need to come to a specification on the customer level. So if we decide to develop a LEFV for transporting roll containers we need to define for example that: the vehicle can be part of the traffic flow within constrains of safety and interaction with other modalities, should fit in a homologation category, should be sustainable, easy to drive, etcetera.

Customer requirements define the 'what' in the development from the perspective of marketing (user, governments, legislation, homologation), operations (manufacturing), product development and after sales/maintenance.

Customer requirements come from stakeholders outside the design process and should be converted to design requirements inside the design process. Design requirements defining the 'how' are a specific and measureable assignment to the design-team.

For the design requirements we distinguish several categories:

- The functional requirements define what should be transported and how, ie.: the load capacity number of passengers including driver followed by the how, the range and speed.
- The safety requirements define the criteria for active and passive safety.

The customer and design requirements are part of the so called QFD (Quality Function Deployment). Here a customer requirement (for example 'good braking') is converted to design requirement (for example 'vehicle deceleration of 7 m/s^2'). The customer and design requirements are interlinked in a matrix. Furthermore a weighting factor sets the importance of the customer requirement, and next, the number of cross links between design and customer requirements is defined. Basically the QFD is a calculation sheet which results in the program of demands for the vehicle development.

6.2 The concept definition

The concept definition starts with a blank sheet of paper and the design requirements and should end with the vehicle packaging. The vehicle packaging defines the layout of the vehicle including the major components. In general the challenge is to come to a new product using components commercial off the shelf where possible. In most cases the vehicle manufacturer integrates components in the design and assemblies supplied components and subsystems.

One proper approach is to apply a methodical approach (morphological approach to product design) in the design to get to the best and traceable solution efficiently. Herewith the concept definition consists of the following steps:

- Diverging: What are the possibilities based on the functional demands?.
- Converging: What are the most feasible solutions?
- Design, calculation and integration: fit of the design to the design requirements resulting in selection, specification and integration in the vehicle 'concept definition'.

Diverging starts with the functional decomposition in which the main function “transporting” is divided in sub functions: propulsion, steering, braking, carrying, protecting. In a morphological chart all possible solutions for each sub function are defined. The design structure is set by combining the solutions. These design structures should differ as much as possible to postpone design choices as long as possible. Based on the design requirements design solutions are being selected. This is the converging process. Following towards integrated solutions we proceed the following steps:

- Define the possible vehicle packaging within the frame of the homologation category;
- Dimensioning of the propulsion based on driving cycle, performance and longitudinal forces on the vehicle (aerodynamic drag, rolling resistance, slopes);
- Select possible components (batteries, electric machines, etcetera);
- Redefine the vehicle packaging and analyse the active safety in stationary and dynamic behaviour;
- Define solutions for tyres, suspension and steering and select possible components.

The process to an integrated solution is iterative and results in options within the frame of the design requirements. It can also bring up the discussion if for example the 'best' solution does not fit in the current vehicle type homologation categories If so, changing the rules here is quite a 'hazardous operation' but maybe necessary for the long term feasibility. The vehicle integration (in person or as department) manages this process and understands and interprets the essence of getting to the best compromise.

6.3 The principle solutions

In the stage "principle solution" all packaging components and functions are being connected to a virtual prototype. In the state of the art product development, information technology sets the standards for integral design. This means that all designers and system development, prototyping and production engineers are linked to the same design. The principle solutions stage delivers a virtual prototype in a virtual production process and the projected logistic solution. After the principle solution decision point D2 all choices and dimensions are set and fixed.

7 Results

The results consist of the customer and design requirements of LEFV (Paragraph 7.1), the design of a LEFV (Paragraph 7.2), the evaluation of its design (Paragraph 7.3), the guidelines for the design of LEFV (Paragraph 0) and solutions for the energy-charging infrastructure (Paragraph 7.5).

7.1 Customer and design requirements of LEFV

Chapter 4 has introduced the customer requirements. The research on vehicle design will explore standards to enable efficient transfer of goods from larger to smaller modalities. Three standards have been selected as vehicle loading: euro pallets, roll containers and a standard small container. This paper focuses on the roll containers.

The size and mass (maximum loading of 750 kg) requires driving power much higher than is possible with human powered vehicle. This forces us to a vehicle homologation category with a maximum speed of 45 km/h (cruising speed around 30 km/h). The vehicle category according to the existing standards is the light quadri-mobile for transport (L6e-BU) (LWH3000 x 1500 x 2500 mm)(v<=45 km/h). This category has a motor power limited to 6 kW. Based on this motor power a 2 kWh battery at 3C discharge rate would be the minimum. This is lower than 4 kWh battery capacity (estimated value) we need for the 50 km driving range. In order to minimise the battery costs, we have chosen to allow for replaceable batteries with units of 4 kWh.

7.2 Explorative design solutions, within current vehicle type approval categories

The assignment has been carried out by students Automotive Engineering of the Rotterdam University of Applied Sciences. For the understanding of the vehicle design process and the design possibilities, feasible solutions have been investigated for the power train, the passive and active safety and the chassis. Together this results in the vehicle packaging and basic design. Figure 5 shows an example of the vehicle design with two rolling containers [16].

Figure 5: The vehicle design with two rolling containers

The vehicle has a closed body and the rolling containers (with swiveling wheels) are behind each other on the lowest floor level possible. To enable this packaging in wheel motors are used. The batteries are under the floor of the driver compartiment. The current design dimensions are close to the maximum dimensions for the homologation category so there (seems to be) no alternative solution for the position driver, batteries and containers. The calculated propulsion (Table 1) represents the "worst case" with full vehicle loading, 70 km range and an air drag coefficient of 0.9.

Table 1: Vehicle specification (worst case) [16]

Specification	Design	Homologation maximum value
Length [m]	2.830	3.000
Height [m]	1.990	2.500
Width [m]	1.380	1.500
Wheelbase [m]	2.300	Not specified
Motor power [kW], at 45 km/h	2*3	6
Battery capacity [kWh], 75 km range at velocity 30 km/h	8	Not specified
Battery voltage [V]	96	Not specified

7.3 Design evaluation

The goal of the design evaluation is to optimise the propulsion (minimise energy and power) and the vehicle packaging (maximise the vehicle handling performance) based on calculations and simulations.

<u>Optimisation of the propulsion</u>

We explore what could be the range of the components if we optimise the vehicle in shape (0,4 for comparable vehicle body shapes like VW Transporter [17]) and reduce the load to what is expected for the rolling containers (100-150 kg each [18]). Furthermore the vehicle cruising velocity is varied (20, 30 and 40 km/h). The estimated empty vehicle mass is 250-300 kg and the rolling resistance coefficient 0.01. The calculated battery capacity in the nominal range (30 km/h at 50 km range) is 3 to 4 kWh. At the maximum velocity (45 km/h) and maximum loading (750 kg) the battery power should be circa 3.5 kW. See Table 2.

Lowering the battery capacity may also decrease the voltage. Standard battery packs of 48 V and circa 2 kWh [19] are available as are also several in wheel motors with a maximum power of 2-3 kW however these should possibly be reconstructed for higher wheel loads.

Table 2: Battery capacity [kWh] with varying velocities, loads and range

Cruising velocity [km/u]	Load[kg]	Driving range [km]		
		30	50	70
20	200	1.2	2.0	2.9
20	400	1.5	2.5	3.6
20	600	1.8	3.0	4.2
30	200	1.6	2.7	3.8
30	400	1.9	3.2	4.5
30	600	2.2	3.7	5.2
40	200	2.2	3.7	5.1
40	400	2.5	4.2	5.8
40	600	2.8	4.7	6.5

Optimisation of the vehicle packaging

The maximum vehicle width and height will also effect the roll over stability. Table 3 shows the resulting lateral acceleration in g (1 g=9.81m/s^2) with increasing height of the centre of gravity and increasing track width where the vehicle will roll over while driving a stationary circle. For the dynamic response we should add the result of the overshoot on the yaw velocity. Assuming the friction based maximum lateral acceleration will 0.8 g with 0.2 g margin the safe area can be indentified. This calculation underlines the need to put the load on the minimum floor level (as in the proposed design) and to maximise the track width to the allowed limits.

Table 3 : Roll over lateral acceleration [g] with increasing track width and height of centre of gravity

Height of centre of gravity [m]	Track width [m]			
	1.2	1.4	1.6	1.8
0.6	1.0	1.2	1.3	1.5
0.7	0.9	1.0	1.1	1.3
0.8	0.8	0.9	1.0	1.1
0.9	0.7	0.8	0.9	1.0

Preventing for rolling over is one of the active safety aspects. Others are the maximum longitudinal acceleration and maximum lateral acceleration and the combined case (braking in a turn).

For the longitudinal acceleration the wide range of loads requests a proper brake force distribution. Because of its importance for the vehicle packaging, this publication will focus on the dynamic lateral vehicle behaviour. Two packaging possibilities are being compared here:

1. The proposed vehicle design with different load levels (P1)
2. An alternative vehicle design with different load levels placed in the vehicle centre (P2)
   For example by placing two rolling containers next to each other.

The calculations have been made using the Electric Vehicle Packaging Tool ([20] and [21]) adapted for the packaging design of Light Electric Freight Vehicles. For characterising the stationary and dynamic vehicle handling the important quantities are:

- For the stationary circle simulation:
  - Characteristic velocity v_{ch}
  - Steering Gradient *EG*
- For the dynamic response simulation:
  - Time constant *Tau*
  - Damping ratio *D*

Figure 6 show the results for P1 and P2

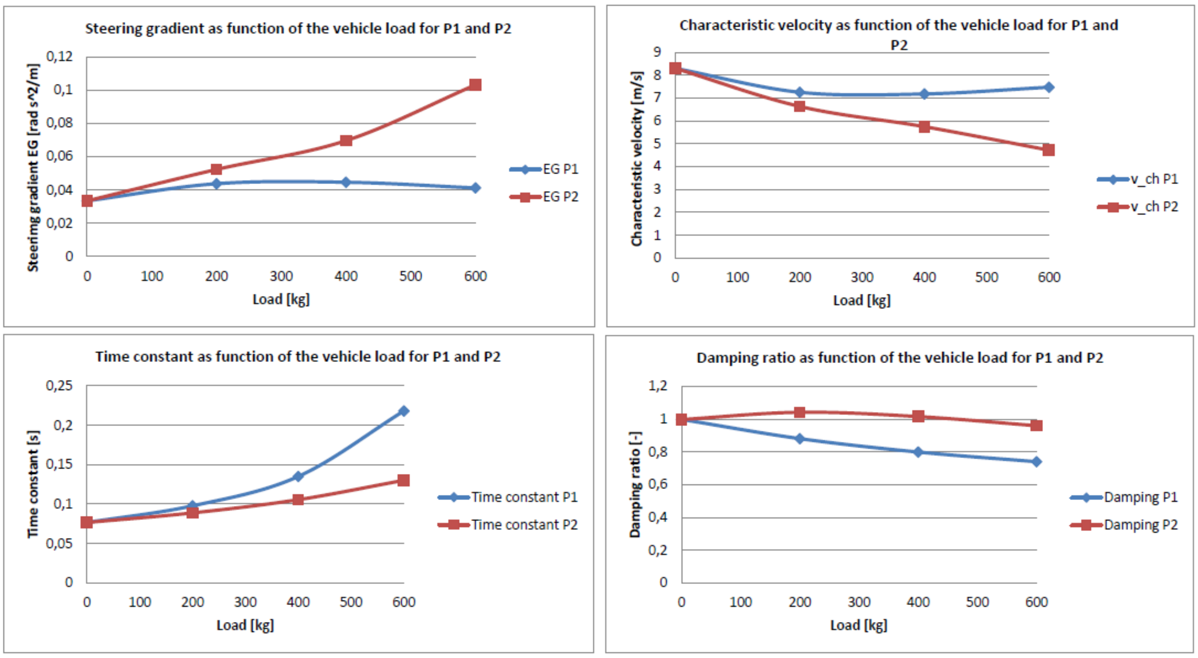

Figure 6: Stationary and dynamic lateral vehicle performance for two vehicle packagings P1 and P2

The change in steering gradient and the characteristic velocity show that the vehicle will become more understeered in the stationary circle for both P1 and P2. However because of the higher load change on the front axle te change is larger for the P2 packaging.

For the dynamic behaviour we observe the larger change for the P1 configuration. Here the time constant is a measure for the response time on a sudden steering input. So this will be higher for P1. The damping ratio is a measure for oscillation after a step input (ie. steering). The higher damping ratio makes the vehicle response on a sudden steering input easier to handle. The damping ratio of 1 is the 'ideal' reference for this. The lower the damping ratio the more difficult it is to handle the vehicle after a sudden steering input because of the oscillating yaw velocity.

The difference between P1 and P2 is most clear when observing the response on a sine test (Figure 7). Here it is clear that the change in case of P1 is much larger then for P2.

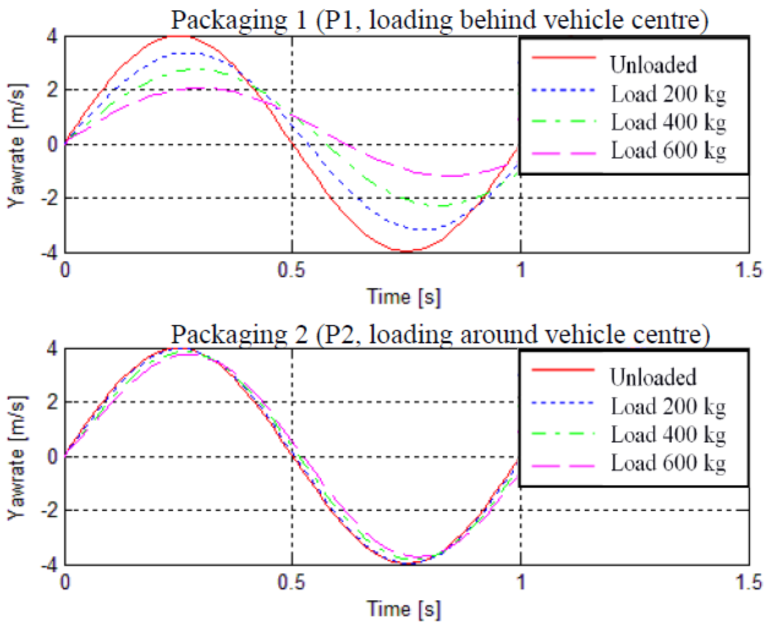

Figure 7: Sine test response of the yaw velocity (yawrate) for two vehicle packagings P1 and P2

7.4 Guidelines for applied design of LEFV

From the previous paragraph these are the important design guidelines:

1. With respect to the propulsion:
    a. Take care of reducing vehicle driving force (air drag and rolling resistance)
    b. Choose the components for the regular user profile and take measures to prevent for worst case scenario's. So for example by being able to replace or charge a battery when the capacity is to low.
2. With respect to the packaging:
    a. Put the load on the lowest floor level close to the vehicle centre and design the vehicle around this load.
    b. Maximise the vehicle track width within the allowed range (1500 mm vehicle width)

7.5 Requirements and solutions for the logistic and energy charging infrastructure

The increase in the use of LEFV will also give an increase in the load on the electric power network. This network should be strong enough to support the expected growth. There is a difference in private and public grid connections.

For private companies the maximum possible connection value is a limiting factor. Charging a single 4 or 8 kWh battery overnight will not be a problem, but there is a limit on the amount of vehicles that can be loaded at once. In the Figure 8 the load on the power network is given for a typical distribution company in the Netherlands with most energy consumption during daytime. Up to now most LEFV are charged at night and used in daytime without additional charging because stop times are too short to do sufficient battery charging. Charging at night can become a problem when the electrical fleet becomes bigger and too many vehicles need to be charged simultaneously. Most fleet owners do not know at what number of vehicles this will really become a problem. The LEVV-LOGIC project develops a tool that will give insight in the needed capacity and the amount of vehicles that can be charged without investing in extra grid capacity. This will include measures like delayed and smart charging, additional battery charging in daytime, and installation of solar systems. For the coming years electric batteries will be the main energy source but alternatives like fuel cells will be considered as they have potential to relieve the power grid.

Use of public chargers is low by most logistic companies because of the time it takes, and the low availability at relevant locations. Practice is that delivery routes are chosen such that the battery is sufficient to complete the route, or to a lesser extent, an additional replaceable batteries is carried on the route. This however, reduces the maximum loading capacity of the vehicle. Investigations will be done to what extend smart charging strategies, range extenders or additional fast charging points can improve the business case of LEFV and can accommodate the envisaged growth in LEFVs up to 2025.

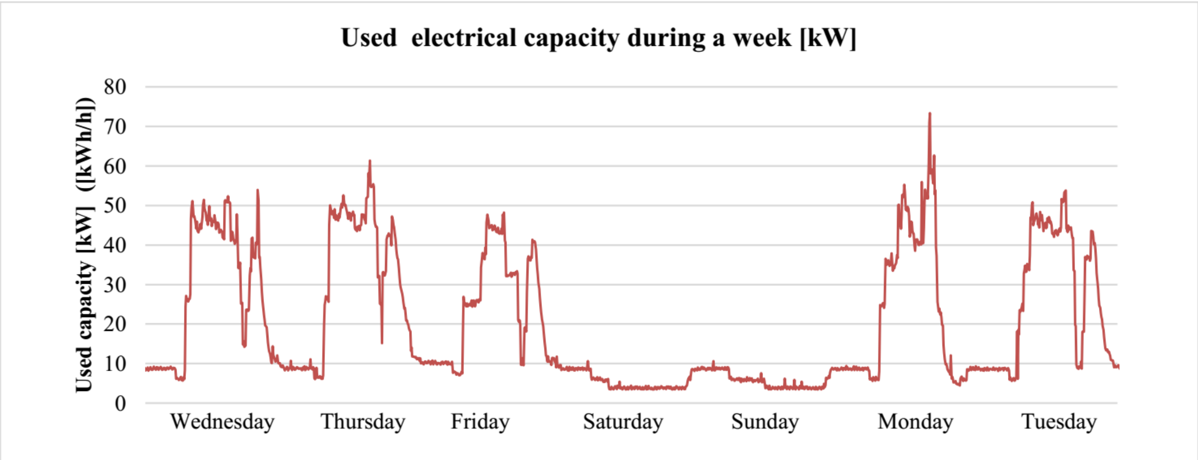

Figure 8: Example of power capacity during a week

8 Conclusion and discussion

The research shows the feasibility of the design of LEFV for different freight flows and the potential of LEFV in the development towards more efficient and sustainable city logistics. The maximum velocity of 45 km/h and maximum loading capacity of 750 kg makes LEFV a vehicle category in between the current vehicle categories like bicycles/mopeds/scooters and cars/vans/trucks. Especially the interaction with these categories in dense urban traffic requires proper standards for the design, production, maintenance and application of LEFVs.

The design assignment has led to a new design of LEFV which can fill the gap between

- the delivery bicycles/tricycles, light urban transport concepts like Kurt [22] and STINT [23] and
- the light electric vans and small trucks.

Of importance is that this design focuses on rolling containers. None of the other vehicles is capable for transporting the standard rolling containers because of mass and/or loading height (how to get the rolling containers in and out the vehicle) and the maximum vehicle height. For example in case of the light electric vans (like Goupil G4 [24]) the loading height is 800 mm and the vehicle height is 1993 mm so it cannot transport the standard rolling container with the height of 1600 mm.

It is possible to focus on adapting on these concepts but this should be done within the constraints of the vehicle design as presented in this paper. Furthermore choosing the light electric vans or small trucks would lead to a change to a larger vehicle outside the segment of LEFV.

Finally the business case development and logistic design must answer the question which vehicle category and charging infrastructure strategy is favourable for the short and long term development of zero emission city logistics.

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