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

Mastering the last mile - the Commercial Segway approach

B.Eng. Hannah Staub[1], Prof. Dr. Andreas Daberkow, B.Sc. Christoph Fessler

[1]*Heilbronn University, Max-Planck-Strasse 39, 74081 Heilbronn, Germany, hannah.staub@hs-heilbronn.de*

Abstract

Light electrical commercial vehicles are a key for solving urban transport issues and to enable electromobility. A current challenge is the reduction of long-term polluted air conditions and especially [1] particulate matter. An obligatory city ban on vehicles will influence commercial vehicle transport dramatically.

Consequently, the government of South-West Germany is promoting research on alternative commercial vehicle solutions. In this paper the results of a new testbed for Segway vehicles in commercial transport applications are described. Segway vehicles are two-wheelers with an electric drive for self-balancing, steering and propulsion. These vehicles are equipped with additional load containers.

A mid-size Energy Supply Company unit with 190 employees and a University facility management unit for 400 employees serve as a testbed for short-distance transport investigations. Both units have multiple locations and field maintenance sites that demand a transportation network of goods, tools and further supplies. Up to four Segways are integrated into the project to replace conventional combustion-engined transportation vehicles. All locations are distributed within a radius of 4200 m so that light electrical commercial vehicles can compete.

Up to now, more than 860 Segway km were made in different transportation situations. The project shows a considerable reduction of travel time between service locations up to 4 times per day. Excellent street, sidewalk and building interoperability is value-added with minimal need of parking space. The Segway vehicles are appreciated by their users. To enlarge the cargo hold, new removable cargo containers were designed for flexible management of different cargo containers. Finally, the paper shows an electric vehicle cost comparison between Segway, Cargo E-trike and Van.

Keywords

City traffic, freight transport, light vehicles, mobility concepts, special vehicles

1 Introduction

A considerable reduction of long-term polluted air conditions and especially of situations with particulate matter is one important goal of the German Environment Agency (UBA) and Baden-Württemberg Ministry of the Environment and Climate protection (UM). Consequently, more than 8 voluntary city bans on vehicles were imposed in the city of Stuttgart [1].

Alternative electrical vehicle solutions for private and commercial city traffic especially for “last-mile” transport are absolutely essential [2]. In this paper the results of a testbed for Segway vehicles in commercial transport applications are described, see also [3] and [4].

2 Testbeds

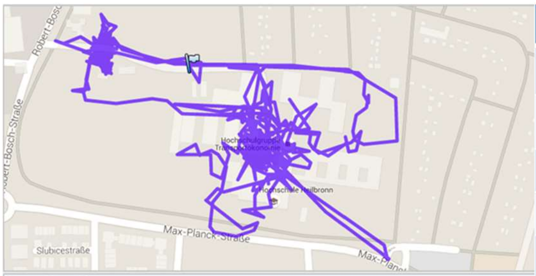
Both testbeds are in the area of Heilbronn, a city with a population of approximately 110,000 located 50 km north from Stuttgart. The Heilbronn-Franken region is an important industrial center in Southwest Germany. Both testbed facilities concentrate within a circle of 4 km radius.

2.1 Facility Management vehicle testbed

The Segway testbed in a University Facility Management (FM) unit for 400 employees and more than 8000 students serves to investigate short-distance transport. The aim is to replace combustion-engined FM vehicle traffic by frequent Segway usage. A Segway is an electrically propelled, self-balancing two-wheeler vehicle that uses single-wheel electrical drives for propulsion and balancing. The Segway vehicle is equipped with a GPS-Sensor to record velocity and track, the energy consumption is recorded separately. Test tracks between and in buildings range from 80 m to 4150 m. Typical FM tasks are maintenance and surveying of internal and external building installations, transport of parts, materials and tools, construction site control on foot or by light commercial vehicle to be replaced by Segway operation, see Fig. 1.

figure 1: Segway with cargo containers (left) and in typical Facility Management operation (middle and right)

Currently, 3 FM users were trained as personal Segway driving experts with one main user. Now, FM has covered more than 1200 Segway km since August 2015 in different transportation situations with an average energy consumption of 3.9 kWh/100km [5]. The recording of a typical FM operation day is shown in Fig.2.



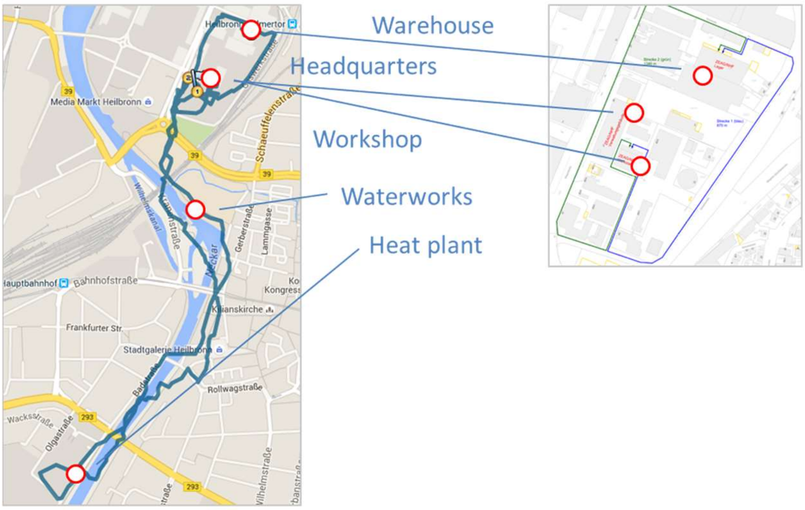
Track profile	
Overall time [h:m:s]	04:54:30
Vehicle time in movement [h:m:s]	01:26:51
Track length/covered distance [m]	10.3
Mean velocity [km/h]	7.08
Height gain [m]	+0 / -13

figure 2: Typical FM Segway operation record, GPS print (upper left), day record (upper right) and velocity plot [5]

The testbed evaluation shows a considerable reduction of travel time between service locations up to 4 times per day with excellent street, sidewalk and building interoperability. However, cargo container space is limited and additional containers reduce building interoperability of the vehicles [5].

2.2 Local Energy Provider vehicle testbed

Typical Energy Provider (EP) tasks to be replaced by Segway transport are pedestrian traffic between headquarters, warehouse and workshop, maintenance of waterworks and heat plant building installations as well as surveying and construction site control. Fig. 3 shows the corresponding company locations in Heilbronn.



Headquarters	Segway Distance [m]
Warehouse	500
Workshop	50
Waterworks	720
Heat plant	2550

figure 3: City map of company locations for Energy Provider Segway operation and travel distances

The EP company favors a shared Segway approach: After a brief internal driving instruction from externally trained Segway representatives an interested employee is allowed to check out and return a Segway vehicle at designated spots where charging is also carried out. More than 15 different Segway employees have been internally advised since June 2016 with a total of 66 Segway business rides across more than 160 km. Moreover in this EP testbed, Segway vehicles are appreciated by their users which vary from managers to workmen.

3 Comparison of the Segway with other transportation

To complete the testbed vehicle research further alternative transportation has been selected. The following vehicles are compared:

- Segway
- Bicycle
- Cargo bike (electrically propelled two- or three wheeler load carrying vehicle with bicycle design and additional cargo container device), see figure 4
- Pedelec (electrically assisted bicycle with different speed designs)
- (electric) car

figure 4: Cargo bike of Heilbronn university

3.1 Overview

The following table 1 gives an overview of identified advantages and disadvantages of the Segway compared to the other vehicles.

table 1: Overview of compared vehicles

Customer requirements	Requirement Detail	Segway3 bags	E-TrikeHeavy Duty	RenaultE-Kangoo	Cargo E-Bike
Operation costs	Costs of purchase in € (brutto)	9900	7500	25585	5500
	E-consumption kWh/100 km	3,92 kWh/100 km	6,27 kWh/100 km	15,50 kWh/100 km	1,69 kWh/100 km
	Consumption costs (0,25 €/kWh)	0,98 €/100 km	1,57 €/100 km	4,34 €/100 km	0,42 €/100 km
Weights	Curb weight with 75 kg - driver in kg	123	133	1580	107
	Zulässiges Gesamtgewicht in kg	166	300	2175	150
	Payload in kg	43	167	650	200
	Maximum Goods Volume in m^3	0,05 m³	1,456 m³	4 m³	0,350 m³
Driving performance	Maximum speed in km/h	20	25	130	35
	Max. acceleration up to 20 km/h	ca. 3 m/s²	ca 2 m/s²	2,5 m/s²	
Interoperability	Building trafficability	yes	no	no	no
	Street trafficability	yes, if no bikeway	yes	yes	yes
	Bikeway trafficability	yes	yes, vehicle width critical	no	yes
	Sideway trafficability	yes, slow speed	yes, curb critical	no	yes, slow speed
	Pedestrian zone trafficability	yes, slow speed	yes, sight critical	with exceptions	yes, slow speed
	Parking space claim m²	0,315	3	11,5	1,9
	Range in km	25	30	105	200
Vehicle Safety	Passive Safety	low	low	high	low
	Aktive Safety	low		high	low
Comfort	Rain shelter	no	moderate	yes	no
	HVAC	no	no	yes	no
	Driving pleasure	high	medium	medium	medium

It becomes obvious that Pedelec and Segway vehicles are very similar in use. Concerning cargo bikes and cars there are wider differences.

3.1.1 Pedelec and bicycle

In the leisure sector, a Pedelec is probably the most obvious alternative to a Segway. Above all, the significantly lower acquisition costs attract a potential customer as well as the lower maintenance costs. However, when it comes to a commercial use, many of Segway's benefits gain importance.

In the case of a frequent change of location, a remarkable advantage is the trafficability of buildings including elevators and building corridors as well as the elimination of the search for parking lot. This requirement is met best by Segways as explained in section 3.3. In a business use case it is an advantage that a Segway ride relates to only very small physical effort. Thus, for example, a ride uphill is less tiring and possible with business clothing.

In addition, especially outdoors or in crowded and complex construction site situations, the elevated viewing position is an advantage in comparison to the bike. In the case of monitoring trips or the use by law enforcement or emergency responders, visibility and a better sight in crowds are very important.

3.1.2 Cargo bike

The use cases of a Cargo bike and a Segway differ greatly. The Segway is suitable for transporting people with light luggage. However, the transport of the person is the main purpose. Load bicycles are designed to transport heavy loads. Therefore, a user will hardly have to decide between these two devices. The application determines clearly which transport medium fits better.

3.1.3 (Electric) car

Currently, an electric car is far more expensive than a Segway. The purchase price of an electric small car without special equipment amounts from approx. 22000 € [6] to 23400 € [7] for a Nissan leaf or Renault ZOE Battery-Electric Vehicle (BEV). The use of the Segway also creates great potential for saving time and thus costs. The economic advantages are discussed in more detail in the Chapter 3.3.

A disadvantage of a Segway in comparison to a car is, that it cannot be used in all year weather conditions. If it is too cold or if it rains, another means of transport must be taken into consideration or even different vehicles alternatives must be made available.

In comparison to (combustion-engined) cars a Segway has the enormous advantages that it is possible to drive directly to the destinations in inner cities, without loss of time for searching a parking lot or walking from the car to the destination. Environmental driving bans do not apply for Segways, as they are electrically propelled.

3.2 Economically viable range

In general, the time needed from the starting point to the final destination is divided into several periods of time as follows:

(1) Departure from individual starting point (e.g. office desk)
(2) Walkway to the vehicle
(3) Get ready to go
(4) Driving time
(5) Search for the possibility to park the vehicle
(6) Vehicle parking period
(7) Walkway to the intended destination

These different phases of the travel time vary according to which transport means is used. The mere driving time is proportional to the distance covered, apart from disturbances by the environment. The duration of the other phases has no reference to the distance traveled, such as searching for a parking lot. Therefore, these related time periods (1) – (3) and (5) – (7) are defined as the *overall set-up time* of a transportation.

The *overall set-up time* of a transportation should be kept as low as possible, especially if very short distances are required. However, these time periods are mostly long in urban areas, where the distances are short but the traffic volume is high or the accessibility and parking is restricted. The Segway has the most advantages in these areas, as the overall set-up time can be shortened or even eliminated.

The time periods (1) and (2) can be minimized as the Segway can be parked right near or in the office, as it can drive in buildings. This eliminates the footpath to the vehicle. The time required to prepare the vehicle and fastening the seat belt is replaced by putting on a helmet and attaching a possible bag. There is no need for a search for the possibility to park the vehicle, since it is possible to drive in the building and since the Segway can be parked almost everywhere with very little parking space. The actual vehicle shutdown lasts only a few seconds. The way to the specific meeting place (7) is clearly shorter in comparison to the other means of transport.

Furthermore, the influence of the travel distance is examined where the overall set up time isn’t considered more closely. For economical transportation, it is advised to determine a lower and upper limit distance, within which the use of a Segway is efficient. Therefore the traffic volume, available shortcuts, the influence on the travel time by other traffic participants or traffic lights, as well as geographical features such as large inclines must be taken into consideration. The limit distances depend on the location or environment and can vary from city to city. This paper presents the limit distances in Heilbronn.

3.2.1 Viable initial conditions

A lower limit for the use of Segways in comparison to walking is estimated by empirical measurements from the Heilbronn university testbed, as seen in diagram 1. It is about 340 m.

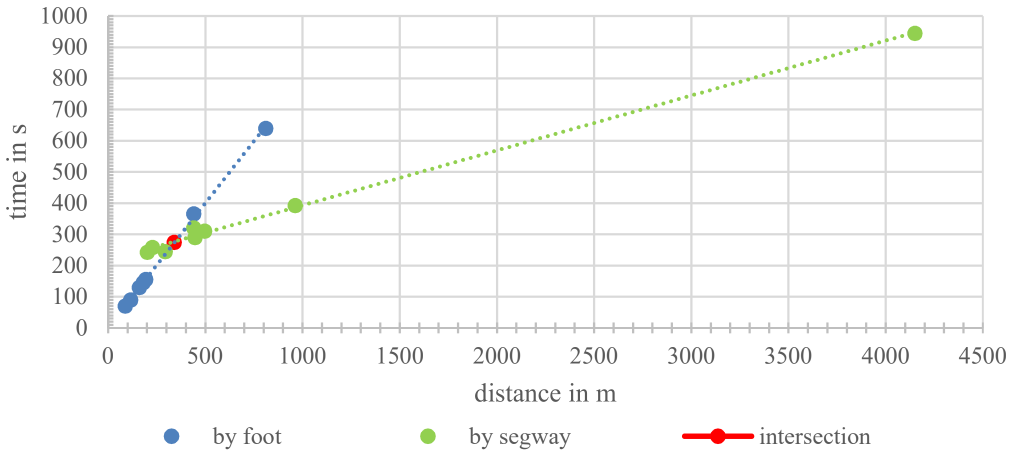


diagram 1: Economically viable range in comparison to walking

3.2.2 Segway and bicycle

In further test drives the Segway and bike drove the same route within a time interval of less than 5 minutes. The overall set-up time was not investigated. All results are affected by traffic conditions, such as waiting at traffic lights or at crossroads. Some measured values are shown in diagram 2.

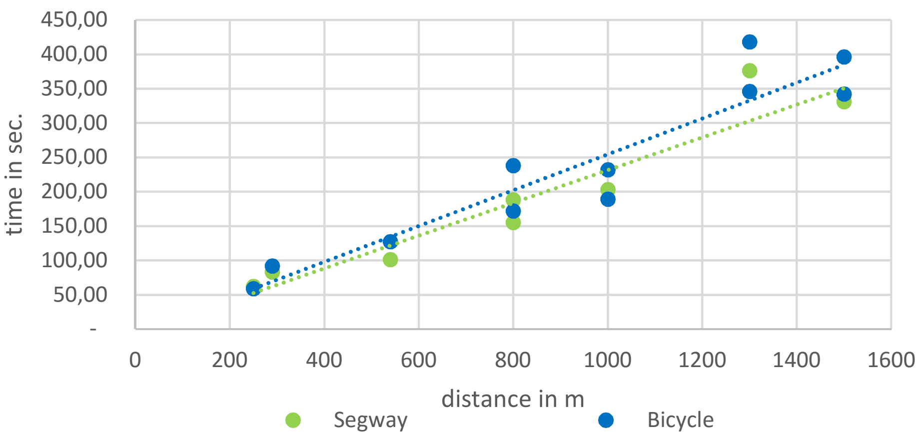


diagram 2: Economically viable distance of a Segway in comparison to a bicycle

The drive evaluations yield that the Segway reached an average speed of 15.5 km/h. The Segway is not slower than a bicycle. The top speed of the vehicle is less important in urban areas, as it is hardly reached due to the high traffic volume. Looking at the overall set-up time, a Segway can significantly save time. For a transportation decision making help, the authors propose an *economically viable distance* limit.

3.2.3 Economically viable distance formula

Looking at the static components, a Segway can significantly save time, which is why a *limit distance formula* is proposed as follows:

$$d_{limit} = \frac{v_a \cdot v_{Seg} \cdot (t_a - t_{Seg})}{v_a - v_{Seg}} \quad (1)$$

where v_a is the velocity of vehicle to be compared, v_{Seg} is the travel velocity of the Segway, t_a the overall set-up time for the vehicle a to be compared and t_{Seg} the overall set-up time for the Segway.

The saved overall set-up time describes how much this period is reduced by using the Segway. For example, when driving by car takes 2 min to walk to the car and 3 min to park the car, the result is an overall set-up time of 5 minutes. With the Segway a walking period is no longer necessary or minimized and the overall set-up time is only 1 minute which leads to a saved setup time of 4. table 2 shows some examples that result from formula (1).

table 2: Examples of calculated economically viable distance

	comparative vehicle: overall set-up time [min]	comparative vehicle: average speed [km/h]	Segway: overall set-up time [min]	Segway: average Speed [km/h]	Economically viable distance [m]
Pedelec (theoretically)	10	35	3	20	1556
Pedelec (real)	4	25	1	15.7	2110
Car (real)	5	35	1	15.7	4271

The following assumptions were made for calculating in table 2:

- The average speeds in European cities are shown in table 3. The limit distance is calculated with the value of 35 km / h.
- The average speed of the Segway of 15.7 km / h (in Heilbronn city) results from the comparative journeys.
- The average speed with a Pedelec is assumed to be 25 km / h. [8]
- For Pedelecs with a top speed of 45 km / h, an authorization is necessary in Germany.

table 3: Average speed in European cities [9]

	London	Berlin	Warschau	Manchester	Edinburg	Rom	Glasgow	Bristol	Paris	Belfast	München	Amsterdam	Dublin	Birmingham	Barcelona
average speed in km/h	19	24	26	28	30	30	30	31	31	32	32	34	35	35	35

The following diagram 3 shows the theoretical recommended limit distance (vertical axis) as a function of the saved set-up time (horizontal axis). The speeds of the two means of transport must be specified for this purpose.

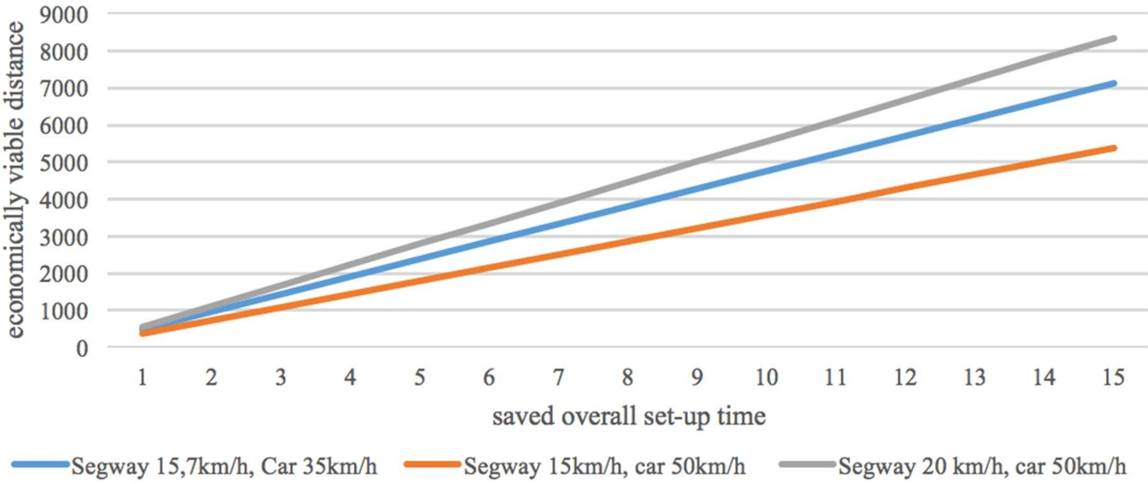


diagram 3: Calculated economically viable range

3.2.4 Viable range conclusion

The speed of a Pedelec will be approximately equal to that of a Segway, since the higher end speed is rarely possible in the inner city. Assuming a 5-minute timesaving by omitting the search for a parking spot and walking, the calculated economically viable distance for the use of a Segway is estimated to 2370 m in inner cities (Segway 15.7km/h, car 35km/h).

3.3 Further economic assessment

This chapter shows further perspectives on the economic use of Segways.

The following chart shows the saved labor costs. Basis for the calculation is the consideration how much faster a certain distance is traveled. The saved time is then charged with the hourly wage. The respective speeds can be found in the legend of the diagram.

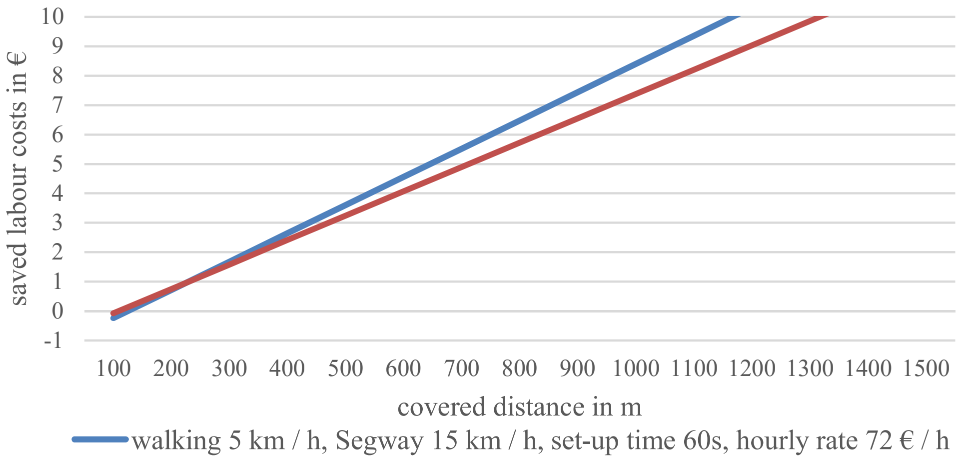


diagram 4: Saved labour costs due to time saving related to covered distance

A first *break even analysis* is derived from the three consecutive diagrams, which show the costs saved by using the Segway. Thus, the break-even point is reached when the counts cut the line of the purchase price of the Segway.

- The saved labor costs (solid line) are calculated from the saved time using the Segway multiplied with the labor costs per hour.
- The dashed line assumes that an existing car is not moved and therefore no fuel costs are incurred. The operating costs of the Segway are also considered. The consumption costs can be neglected in comparison to the labor costs due to the short distances.
- The dotted line represents the scenario that a Segway is procured instead of a car. The leasing rate of the car can therefore be added to the saved costs.

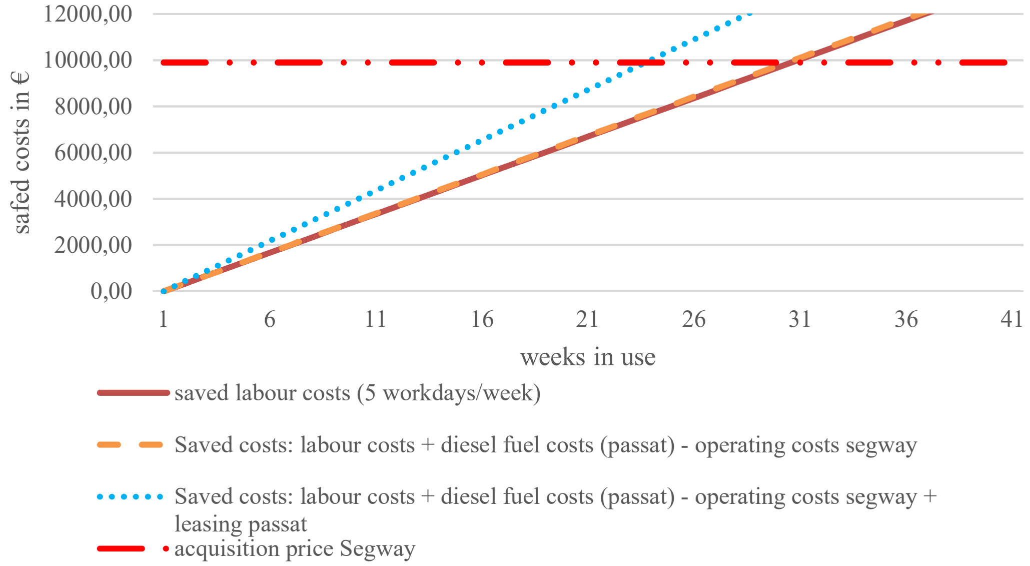


diagram 5: Break even analysis

For the assumptions made for the calculation, see table 4 and table 5.

table 4: Assumptions made for break even analysis

		unit
Time saving of the employee per trip	10	min
Number of stations per day	5	
Number of trips per day	6	
Distance traveled per trip	2.5	km
previous Time per station (without Segway)	1.42	h
Time saving per employee per day	60	min
Number of kilometers traveled per day	15	km
Labor costs employee per hour	72	€
Working time per day	7.72	h
Working days per week	5	d
contingency allowance	7	%
Saved labor costs per day	66.96	€

(green)	freely selectable value
(grey)	preselected Value, adjustable
(white)	Calculated value

table 5: Costs caused by the chosen car VW Passat

	Diesel Con-sumption (combined) [l/100km]	diesel fuel price [€/l]	consuption costs [€/100km]	Leasing rate/ month incl. Service [€/month]	total costs of leasing over period [€]	period of leasing contract [months]	cost/week: consumption + leasing [€/week]
VW Passat	4.1	1.05	4.31	396	19020	48	99.1

A Segway procurement is reasonable for a vehicle fleet manager if short distances must be covered frequently, and by using a Segway labor costs can be saved to a high degree, for example, in the case of monitoring tasks such as patrols by the police, regulatory office , construction site control or rescue forces.

4 New Cargo Container adaption design

With a total of 0.05 m^3, see left in figure 4 the overall volume of potential Segway cargo containers is limited. Consequently, an easy-to-clip-and-fold cargo mechanism has been developed that allows versatile Segway usage even in narrow elevators, see figure 4.

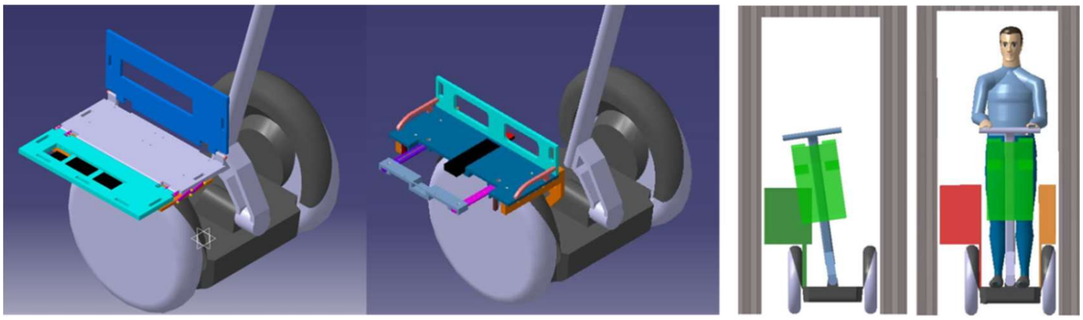


figure 4: New easy-to-clip-and-fold cargo adapter (left two images) and full 3D collision analysis (right)

The project team has decided to evaluate only cargo container solutions that will match the government Segway vehicle regulations. The maximum vehicle width of 0.73 m can only be exceeded by removable cargo containers. Moreover, these containers must match standard sizes e.g. for document folders and load carriers. The paper also explains which cargo container design alternatives were taken into consideration and finally tested in daily Segway operation [10].

5 Conclusion and further work

All Segway project vehicles in operation are appreciated by their users in the testbeds. The Segways are in frequent usage without accidents also in transitional weather seasons.

Also in America (e.g. Albuquerque, New Mexico) the Segway approach is used for policemen and first responders and accepted as a great help [11]. Since 2015, the facility manager at Heilbronn University has traveled a total of more than 1200 km. The ordinance of Heilbronn owns two Segways and has covered 3900 km and 4245 km since 2012.

It becomes obvious that one priceless advantage of a Segway operation is the reduction of travel time between service locations. Here, a time reduction of up to factor 4 was observed. For transportation decision-making help, an economically viable distance formula is proposed. Also, an economic assessment template to compare a potential Segway purchasing to other transportation means is provided. To enhance the load capacities of the Segway, a new cargo container adaption mechanism has been developed and tested. In comparison to the equipment variant with one normal cargo container (able to use elevators) an increase of 165% can be achieved

The use of Segways within the economically viable range greatly increases productivity. Unfortunately, the purchase price of the Segway is still very high. Nowadays, significantly more reasonable alternatives working with the same principle are available, which indicates that the price will fall in the future.

Pedelecs and Segways can be many times faster in the city center than cars, as they can use shortcuts and the traffic affects them less than a car. The Segway in comparison to a Pedelec is especially well-suited for certain applications where the following aspects are particularly important:

- The building trafficability e.g. on company premises
- The increased viewing position (especially in the case of monitoring tasks such as patrols by the police, construction site control or rescue forces)
- Carrying small devices to the workplace / destination

Under these conditions a Segway is the preferred choice to travel short distances, as it reduces the overall set-up time. The possibility of carrying light luggage increases the usability further and makes the use of Segways for companies appealing.

6 References

[1] J. Löhle, „Das Handwerk warnt vor Fahrverboten.,“ *Stuttgarter Zeitung ,* 22 03 2016.

[2] McKinsey&Company, „Delivering change - The transformation of commercial transport by 2025,“ 09 2016. [Online]. [Zugriff am 12 12 2016].

[3] C. Dorn, Alternativer Warentransport: Kann ein Segway Personal Transporter herkömmliche Methoden ersetzen?, Hamburg: Diplomica Verlag, 2010.

[4] K. Hyvönen, P. Repo, M. Lammi, „Light electric vehicles: substitution and future uses,“ *Transportation Research Procedia,* Nr. 19, p. 258 – 268, 2016. (ich glaube hier stimmen die Namen nicht)

[5] A. Daberkow and K. Rösinger, *Self-Balancing Two Wheelers – urban duty vehicles of the future?,* I. f. F. FTG, Hrsg., Graz , 2016.

[6] Renault, „Preisliste Renault ZOE,“ 2017. [Online]. Available: https://www.cdn.renault.com/content/dam/Renault/AT/downloadcenter/zoe/PL_ZOE.pdf. [Zugriff am 17 05 2017].

[7] Nissan, „DER NISSAN LEAF - ZERO EMISSION,“ 2017. [Online]. Available: https://www.nissan.de/fahrzeuge/neuwagen/leaf.html. [Zugriff am 17 05 2017].

[8] S. Jacobs, „Vergleich zwischen Tempo 25 und 45: Wie schnell soll das E-Bike sein?,“ 11 05 2015. [Online]. Available: http://www.tagesspiegel.de/wirtschaft/pedelecs-im-test-vergleich-zwischen-tempo-25-und-45-wie-schnell-soll-das-e-bike-sein/11715088.html. [Zugriff am 14 06 2017].

[9] Forbes, „Europäische Städte mit der niedrigsten Durchschnittsgeschwindigkeit im Straßenverkehr,“ 2008. [Online]. Available: https://de.statista.com/statistik/daten/studie/37200/umfrage/durchschnittsgeschwindigkeit-in-den-15-groessten-staedten-der-welt-2009/ . [Zugriff am 14 06 2017].

[10] M. Schneichel, Bachelorthesis: Konstruktionsvarianten eines Gepäckträgers für einen Segway, Heilbronn, 2017.

[11] J. McKay, „Balancing Act: Segway scooters have become a favorite tool among some cops and medics.,“ *Justice,* pp. 52-53, 12 2006.

7 Acknowledgements

The research team would like to thank the Baden-Württemberg Ministry of Economics, Labor and Housing for its support.

8 Authors

Hannah Staub

From 2012 to 2015, Hannah Staub completed her bachelor's degree in mechanical engineering at the corporate state university Baden-Württemberg Karlsruhe. Afterwards she worked for half a year as a junior development engineer with an automotive supplier. In March 2016 she started her current engineering master's program at Heilbronn University of applied science. In addition, she is working on a University project on Segway operation in future urban transport.

Andreas Daberkow

Prof. Dr.-Ing. Andreas Daberkow received his PhD at Stuttgart University in 1992. He started his career at the Frankfurt Research Center of a large autom [10]otive manufacturer. From 1999 to 2001 he was responsible for supplier integration tasks at the heavy truck development center in Stuttgart and continued to work in the field of IT and data management for electric/electronic development issues. Since 2009, Prof. Daberkow lectures in the Automotive Systems Engineering degree program of Heilbronn University. He is doing research on electromobility with light vehicles in urban-regional operation.

Christoph Feßler

From 2012 to 2016, Christoph Feßler completed his bachelor's degree in mechatronics at Hochschule Mannheim - University of applied science. During that time, he also worked as a co-author with Prof. Dr.-Ing. Peschges on a book addressing the team-based development. In September 2016, he started his current master's program in mechatronics at Heilbronn University. Morover, he is working on a University project on Segway operation in future urban transport.