WHEN WE WOULD BENEFIT FROM PURCHASING MORE ENVIRONMENTALLY FRIENDLY PASSENGER CARS?
Costs, Emission and Safety Criteria During Life Cycle

by

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Protection of the society from the negative consequences of the road traffic is a global challenge. The greatest challenges are related to emissions of harmful combustion products and road safety. One of the possible solutions of this challenge is purchasing and using a new, more environmentally friendly passenger car (cleaner and safer). As a more environmentally friendly passenger cars, we considered electric and autonomous passenger cars. Although these cars are more environmentally friendly, their negative feature is high purchase costs. This paper aims to create a model for determining the period of use when the decision purchase a new, more environmentally friendly passenger car instead of a new, less environmentally friendly passenger car (petrol or diesel) would be beneficial. For that purpose, we analyzed costs, emission and road safety during life cycle. The developed model was applied on real data from Great Britain. Using the results of the model, stakeholders and customers of passenger cars would be able to reach better quality decisions related to purchasing the new passenger cars.

Key words*: passenger cars, life cycle, cost, emission, safety*

Introduction

The European Commission has planned to CO_2 emissions of passenger cars by 15% by 2025 and 37.5% by 2030 compared to 2021 [1]. The UN General Assembly has set a goal of reducing the number of road accidents and injuries globally by at least 50% by 2030 [2]. Purchasing new, cleaner, and safer passenger cars would be highly beneficial for achieving the set of goals. However, the new, cleaner and safer passenger cars has negative consequences, such as high purchase costs.

Stakeholders have the task to encourage customers for purchasing new, cleaner, and safer passenger cars. By purchasing an electric and autonomous passenger cars compared to a conventional (petrol or diesel) non-autonomous passenger cars, customers can reduce the environmental impact, the number and consequences of road accidents, and fuel/electricity costs [3, 4]. The cost of purchasing an electric and autonomous passenger cars is higher than a conventional non-autonomous one. Customers should be motivated by stakeholders to purchase a more environmentally friendly and safer passenger cars, even though it is more expensive than fossil-fuel (petrol, diesel) non-autonomous passenger cars.

Life cycle analysis of passenger cars can provide an answer to the previous question. Many authors considered the life cycle of the passenger cars, considering the different phases of the life cycle and analyzing the different criteria [4-10]. Kahane [11] found that advances in vehicle safety technology have positive impact reducing fatality risk. Autonomous vehicles

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can be a big step forward in this field. Namely, the automated driving system has a primary role in decision-making in autonomous vehicles (levels of autonomy –3, 4, and 5). Optimistic projections are that when autonomous vehicles reach 90% of the market share, road accidents, and fatalities will fall by 90% [12].

We concluded that future model needs to include several criteria based on the literature review. The previous research dominantly analyzed the costs and emissions of harmful combustion products. However, with significant technological progress in developing devices that allow passenger cars greater autonomy in the future, a considerable reduction in the number and severity of road accidents can be expected. For this reason, we have included a road safety analysis as a criterion in our research.

Based on the literature, we found a need for a complex life cycle analysis of passenger cars, including recognized and new phases of the life cycle of passenger cars. This paper aims to create a model for determining the period of use when the decision purchase a new, more environmentally friendly passenger cars (cleaner, safer, and more expensive) instead of a new, less environmentally friendly passenger cars would be beneficial. This research investigates the decision purchase a new electric and/or autonomous passenger cars instead of a conventional (petrol or diesel) non-autonomous one. In relation previous study [5], this paper also considers the criterion of road safety. The special significance of the model is in estimating the reduction of the consequences of road accidents in a country if the customer decides to purchase an autonomous vehicle (Level 3). This level of autonomy is adopted because the current technological development of autonomous vehicles is transitioning from Level 2 to Level 3 [13]. The model is practically applied to data from the Great Britain fleet. The data was used from references listed in section *Data*.

Using the results of this paper, stakeholders and customers of passenger cars would be able to reach better quality decisions related to purchasing the new passenger cars. For example, by applying the model, the customer and stakeholders can determine the period of use when the economic benefit obtained from reducing the environmental impact and the number and consequences of road accidents would be achieved. A significant contribution of the paper is applicability of developed methodology to continuously monitor the change of the period of use when they would take a benefit. Additionally, stakeholders will be able to determine the reduction of external costs of emissions and road accidents. Stakeholders can use these savings to stimulate the purchase of more environmentally friendly passenger cars.

Model

Life cycle framework of passenger cars

The life cycle framework of passenger cars should include all phases of the life cycle that are significant for solving the problem in question. By using such a framework and relevant criteria, passenger cars owners can make the right decision regarding buying a passenger cars. Also, stakeholders can influence the decision through their activities (correction of taxes, economic incentives for purchasing new, cleaner, and safer passenger cars). The new life cycle framework of passenger cars is shown in fig. 1.

The life cycle starts with the manufacturing phase. The manufacturing included the following phases: material production, car's parts manufacturing, and assembling. More details about these phases were presented in [5]. During manufacturing phase, a certain amount of harmful combustion products is emitted [5]. After manufacturing, the manufacturer determines the suggested retail price [9]. After that, the passenger cars is transported to the passenger cars's dealer – the *Distribution of car* phase. Harmful combustion products are emitted during this

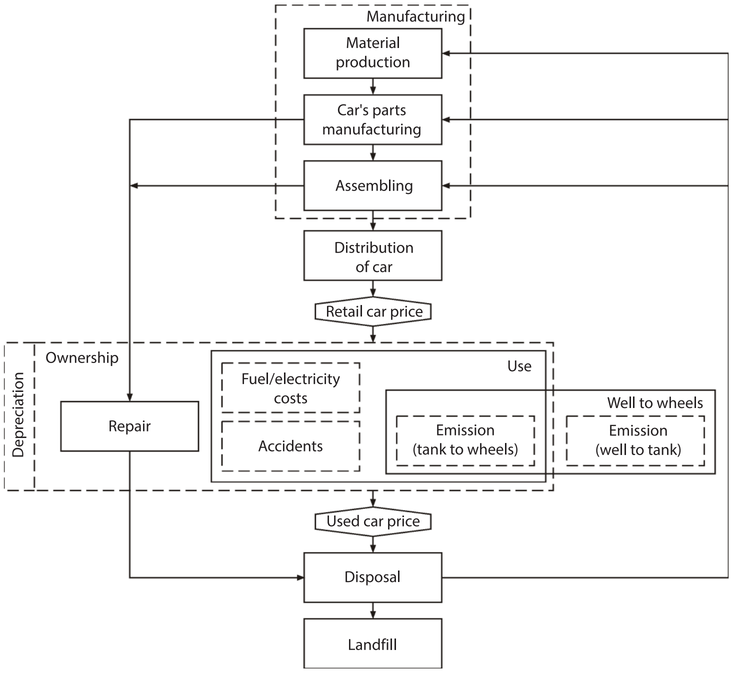

Figure 1. Life cycle framework of passenger cars

phase. In economic terms, the *distribution of car* phase is described with shipping costs [9]. Retail car price is the price paid by the passenger cars owner. Retail car price depends on the manufacturer's suggested retail price, shipping costs, and tax rate [9].

From the literature review, we concluded that many authors analyze the emission of harmful combustion products during the *Use* phase [4, 5, 7-10]. Based on the previous conclusions, we adopted a well-to-wheels approach. This approach included well-to-tank and tank-to-wheels analysis. Within the *Use* phase, fuel/electricity consumption was also recognized. De Clerck *et al.* [10] and Ahmadi [9] recognized the need to include this portion in the analysis. In our research, the impact of fuel consumption on the life cycle will be quantified using costs.

Fewer authors included the consequences of road accidents in the analysis of the life cycle of passenger cars [10, 14, 15]. The application of new technologies (*e.g.*, autonomous passenger cars) in road safety has a positive effect on reducing the number and consequences of road accidents [11, 12, 16].

The *Repair* phase includes repair and maintenance. Suitable maintenance ensures that the passenger cars can maintain the projected performance, fuel consumption, emissions of harmful combustion products, and road safety level during use. The adverse effects of this phase are the emission of harmful combustion products and the costs that the passenger cars owner pays for the realized maintenance activities. After the end of the *Use* phase, and before the passenger cars is forwarded to the *Disposal* phase, it is necessary to determine the *Used car price*. The *Disposal* is connected to the *Repair* and *Use* phases. The *Disposal* phase got used passenger cars parts and devices (*Repair*) and an old passenger cars that was withdrawn from use. The ecological and economic aim of the manufacturer is to return as much material as possible in the form of recycling, recovery, and reuse and to dispose of the minimum amount of waste (*Landfill*).

The following subchapters will present a detailed mathematical interpretation of each life cycle phase and a discussion that will further explain the impact of each of the phases on the life cycle of passenger cars.

Costs

The passenger cars owner recognizes the retail car price (RCP) at the beginning and used car prices (UCP) and end of the ownership period, fig. 1. The most significant impact on RCP has the costs of the life cycle phases that come before the *Use* (material production, car's parts manufacturing, assembling, distribution of car). These costs are the basis for determining the manufacturer's suggested retail car price (MSRCP). After that, MSRCP is increased by shipping costs (CSHIPP) which depend on the passenger cars's weight [9]. The RCP is also influenced by value-added tax (VAT) and premium at purchase time (PREM) [10]. The PREM stimulates the purchase of cleaner and safer passenger cars. The RCP is given:

$$RCP = \left(MSRCP + CSHIPP\right)\cdot VAT - PREM \tag{1}$$

where UCP was calculated using the fixed percentage method [17]. The UCP after t years of use can be written:

$$UCP_{t,k} = RCP\cdot dep_k^t \tag{2}$$

where dep_k is the annual depreciation rate per vehicle technology (petrol, diesel, electric).

Fuel/electricity costs, $Cfe_{t,k}$, were definded by Mijailović *et al.* [6] and Petrović *et al.* [7]. These costs depend on the consumption and the unit price of the fuel/electricity. Burnham *et al.* [18] defined expression of repair costs per kilometer driven in the t_{th} year of use ($crep_{t,k}$). Repair costs during life cycle depends of the passenger cars's kilometer driven per year, S_t, and were calculated using:

$$Crep_{t,k} = \sum\nolimits_t S_t\cdot crep_{t,k} \tag{3}$$

Emission

Mijailović *et al.* [6] created a methodology that defined environmental benefits by considering the energy efficiency of passenger cars and their exhaust emissions. The authors found that the cost of fuel consumption represented approximately 91% of the total cost, external cost related to CO_2 was approximately 8% of the total cost, and external costs related to CO, HC, and NO_x were negligible (approximately 1%). Ahmadi [9] found similar findings regarding hybrid electric vehicles, plug-in hybrid electric vehicles, full battery electric vehicles, hydrogen fuel cell electric vehicles, and gasoline vehicles. Considering the previous results, CO_2 emissions could be selected as the primary emission of passenger cars.

The CO_2 emission during *Manufacturing* (ECO_2man), *Distribution of cars* ($ECO_2dis.c$), *Use* (ECO_2use), and *Disposal* (ECO_2disp) were defined by Mijailović [5] and Petrović *et al.* [7].

The CO_2 emission during *Manufacturing* depends on emission during material production, passenger cars's part manufacturing, and assembling.

The CO_2 emission during Ownership (ECO_2own) is the sum of the CO_2 emissions that occur during the phases *Use* (ECO_2use) and *Repair* (ECO_2rep):

$$ECO_2own_{t,k} = ECO_2use_{t,k} + ECO_2rep_{t,k} \tag{4}$$

According to Burnham *et al.* [18], repair costs increased with the passenger cars age. The previous conclusion can be explained by the fact that the reliability of passenger cars's components and assemblies decreases with the passenger cars's age. Because of the previous conclusion, the number of operations were conducted during the phase *Repair*, and the emission of harmful combustion products rise. Therefore, we introduced the assumption that the ratio of maintenance costs in the t_{th} year of use, $crep_{t,k}$, and *MSRCP* is equal to the ratio of the CO_2 emission during phase *Repair* in the t_{th} year of use, $rep_{t,k}$, and ECO_2man:

$$\frac{S_t \cdot crep_{t,k}}{MSRCP} = \frac{S_t \cdot rep_{t,k}}{ECO_2man} \tag{5}$$

By using the previous expression, the CO_2 emission per kilometer driven in the t_{th} year of use during *Repair* can be re-written:

$$rep_{t,k} = ECO_2man \cdot \frac{crep_{t,k}}{MSRCP} \tag{6}$$

The ECO_2rep was calculated:

$$ECO_2rep_{t,k} = \sum_t S_t \cdot rep_{t,k} \tag{7}$$

By eqs. (3) and (6), ECO_2rep can be expressed:

$$ECO_2rep_{t,k} = ECO_2man \frac{Crep_{t,k}}{MSRCP} \tag{8}$$

The external cost of the CO_2 emission depends on the CO_2 emission during life cycle and external costs per kilogram of the CO_2 emission, $ecCO_2$. They can be written in the form:

$$ECCO_2man = ecCO_2 \cdot ECO_2man, ECCO_2dis.c = ecCO_2 \cdot ECO_2dis.c \tag{9}$$

Safety

The safety criterion was applied to the *Use* phase. Road safety criterion quantifies road accidents' consequences: fatalities, serious injuries, and slight injuries. Linking between the consequences of road accidents was achieved by costs [19].

The cost of the road accidents per passenger cars for the analyzed country in the year T_x ($Cpc.acc_x$) was calculated as the sum of the costs of the fatalities, serious injuries, and slight injuries:

$$ECCO_2own = ecCO_2 \cdot ECO_2own, \;\; ECCO_2disp = ecCO_2 \cdot ECO_2disp \tag{10}$$

where N_x is number of passenger cars in the year T_x, $nfat_x$, $nsei_x$, $nsli_x$ – number of fatalities, serious injuries and slight injuries in year T_x, and *cfat*, *csei* and *csli* cost per fatality, serious injury, and slight injury

According to the literature, the new life-saving technologies introduced in passenger cars have positive impact on road safety. The NHTSA [20] found that autonomous vehicles have the potential to exclude human error from the road accidents contributors, which will help to protect the drivers, passengers, cyclists and pedestrians. Pilet *et al.* [21] concluded that the maximum value of the percentage of avoided fatal crashes is 62.8%. Considering road accidents with autonomous vehicles analyzed in previous research [16, 22, 23], we concluded that autonomous vehicles are still in the testing phase and that the authors did not identify many cases. As a result, it was not possible to make reliable predictions about their future impact on the road safety.

Human has the most important role in driving passenger cars. As mentioned previously, more significant contributions to road safety are expected from autonomous vehicles. Since testing of autonomous vehicles (Level 3) has been currently taken, we analyzed their impact on reducing the road accidents consequences in this paper.

The first step was to identify road accidents contributing factors. Most road accident databases recognize contributing factors such as human (driver, pedestrian*, etc.*), road, vehicle, and environment. Some databases monitor the characteristics of road accidents in more detail and identify many contributing factors. A good example is the Great Britain database, which contains about 80 contributing factors [24]. Using data from this database, we recognized contributing factors of road accidents. We assessed whether autonomous vehicles (Level 3) would be able to exclude contributing factors as the cause of road accidents. The assessment was made based on the conclusions of previous research in this area [16, 21-23].

The second step was to estimate the actual consequences of reducing road accidents if an autonomous passenger cars replaced the existing passenger cars. In particular, this procedure was applied in the case of Great Britain [24] for the period from 2016 to 2020. The Great Britain was chosen as an example of a country with a high level of the road safety. The public risk of road accidents in Great Britain is among the best in the world and amounts to 2.8 [25]. In the year 2019, autonomous passenger cars could potentially reduce 56% of fatalities (*afat*), 56% of serious injuries (*asei*) and 62% of slightly injuries (*asli*).

According to the previous conclusions from this chapter, the eq. (10) is expanded by introducing the estimation of road accidents reduction by introducing autonomous passenger cars:

$$Cpc.acc_x = \frac{1}{N_x}\left[nfat_x \cdot cfat(1-afat) + nsei_x \cdot csei(1-asei) + nsli_x \cdot csli(1-asli)\right] \quad (11)$$

Finally, the expression which determines the costs of the road accidents consequences per passenger cars in the period since its purchase, T_{buy}, by applying expression (11) is:

$$Cpc.acc_t = \sum_{T_x=T_{buy}}^{T_{buy}+t} \frac{1}{N_x}\left[nfat_x \cdot cfat\left(1-afat\right) + nsei_x \cdot csei\left(1-asei\right) + nsli_x \cdot csli\left(1-asli\right)\right] \quad (12)$$

Cost comparison

At the beginning of using a new passenger cars, *i.e.* at the time of purchase (t = 0; t – age of the passenger cars), the owner has the cost of RCP. As the age of the passenger cars increases, the value of the passenger cars decreases due to its depreciation. Also, during the use of a passenger cars, there are the external costs of CO_2 emissions during *Ownership*, costs of road accidents, fuel/electricity costs, repair costs, and other costs. Purchasing of new passenger cars results in CO_2 emissions that can be described by the sum of the CO_2 emission during the new passenger cars's manufacturing and the CO_2 emission during the distribution of the new passenger cars.

The cost of a passenger cars as a function of its age, t, per k vehicle technology is calculated using:

$$\begin{aligned} C_{t,k} &= RCP + ECCO_2man + ECCO_2dis.c + ECCO_2own_{t,k} + \\ &+ Cpc.acc_t + Cfe_{t,k} + Crep_{t,k} + Cother_t - UCP_{t.k} \end{aligned} \quad (13)$$

The period of use when we would benefit, t_b, from purchasing a new, more expensive, cleaner, and safer passenger cars ($k = k_2$, *autonomous)* instead of purchasing a new, cheaper, less clean, and less safe passenger cars ($k = k_1$, *non-autonomous*) determined by:

$$C_{t_b,k_1,\text{non-auton}} = C_{t_b,k_2,\text{auton}} \quad (14)$$

Results

Data

The model was applied to the example of the passenger cars fleet in Great Britain for 2019. This year was chosen as the last year before the COVID-19 pandemic.

Parameters of new passenger cars (petrol, diesel) represent real passenger cars purchased in 2019 [26, 27]. The values of the new electric passenger cars were taken from [9]. The value of increased price of a new passenger cars because of the Level 3 of autonomy was 10874 EUR [26]. We introduced the assumption that passenger cars have the same driven kilometers every year, regardless of age. The average value of passenger cars kilometers driven per year in Great Britain was 11909 km [28]. Annual depreciation rate for petrol and diesel passenger cars were adopted from Lebeau *et al.* [29]: $dep_{\text{petrol}} = 0.845$, $dep_{\text{diesel}} = 0.827$. Element energy limited [30] stated that the depreciation rates for electric passenger cars and petrol passenger cars are approximately equal. Considering the limited number of studies related to the annual depreciation rate for electric and/or autonomous passenger cars, we assumed that the depreciation rates for conventional non-autonomous and electric and/or autonomous passenger cars are equal. Other data was obtained from following sources: Mijailović [5], Petrović *et al.* [7], Ahmadi [9], Burnham *et al.* [18], Wijnen *et al.* [19], Mickunaitis *et al.* [31], Department for Business Energy and Industrial Strategy [27, 32-34], Department for Transport statistics [27, 35, 36], and Diaz [37].

Application of the model

In this chapter, we present the results of the model application on real data. These results will allow stakeholders and customers to understand the dependencies between the analyzed period t_b and some of the variables that can help them make decisions regarding buying the new passenger cars.

The impact of emission

The technology of electricity production was incorporated using the emission factor of electricity production, *CE*. Lower values of *CE* represent cleaner technologies for producing electricity (*e.g.* wind power plants). Figure 2 shows the relationship between t_b and *CE* for the case of petrol, diesel, and electric non-autonomous passenger cars, in order to better observe the ecological impact of electric passenger cars on t_b. The distribution of economic benefits, Δ_{eb}, obtained from reducing the environmental burden and reducing the number and consequences of road accidents can be claimed by stakeholders and customers. This parameter ranges from 0 to 1. In the case where stakeholders retain all the economic benefits, Δ_{eb} is 0, while in the case where all the economic benefits are transferred to the customers, the value of Δ_{eb} is 1. Figure 2 also presents the impact of Δ_{eb} on t_b. In this study, we did not consider the way of the division of Δ_{eb}.

Considering that the analyzed case does not consider the autonomous passenger cars, economic benefits from reducing the number and consequences of road accidents cannot be expected. The period t_b increases with an increase in *CE*. Namely, the reduction in environmental impact obtained by purchasing an electric passenger cars instead of a fossil-fuel passenger cars decreases with increases of *CE*. In the case where stakeholders retained the economic benefits obtained from reducing the environmental burden for themselves ($\Delta_{eb} = 0$) compared to the case where stakeholders fully transfer the economic benefits to customers ($\Delta_{eb} = 1$), the period t_b for Great Britain increases from 6.9 to 7.6 years (petrol – electric passenger cars) and from 10-11 years (diesel – electric passenger cars) – an increase of approximately 10%.

The ecological benefits of choosing an electric instead of a fossil-fuel passenger cars were not carried out for high values of *CE* [7]. Therefore, the critical value of *CE* at which the ecological benefits of purchasing an electric instead of a fossil-fuel passenger cars are not reached it is important to determine. Based on fig. 2, we concluded that for *CE* > 500 gCO_2/kWh (petrol) and *CE* > 420 gCO_2/kWh (diesel), there were no ecological benefits of purchasing an electric passenger cars instead of a fossil-fuel passenger cars.

Figure 3 presents the impact of RCP of electric passenger cars on t_b when stakeholders fully transfer the economic benefits to customers (Δ_{eb} = 1). Reducing the RCP of electric passenger cars would positively impact reducing t_b. Based on the obtained results, we concluded that the application of cleaner technology for electricity production has a more negligible impact on t_b than RCP of electric passenger cars.

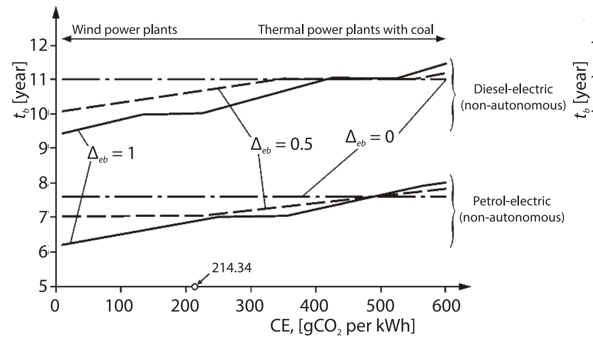

Figure 2. Impact of the emission factor o f electricity production, *CE*, and distribution of economic benefits, Δ_{eb}, on t_b

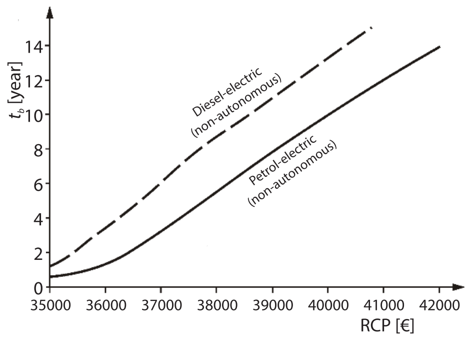

Figure 3. Impact of the RCP electric passenger cars on the period tb

The impact of road safety

The introduction of autonomous passenger cars will decrease the number and consequences of road accidents and, subsequently, reduce the costs of road accidents per passenger cars. On the other hand, implementing devices that will enable the autonomy of passenger carswill increase the RCP. In order to better understand the impact of road safety on t_b, we analyzed the comparison between petrol non-autonomous – petrol autonomous (Level 3) passenger cars and diesel non-autonomous – diesel autonomous (Level 3) passenger cars when stakeholders fully transfer the economic benefits to customers (Δ_{eb} = 1).

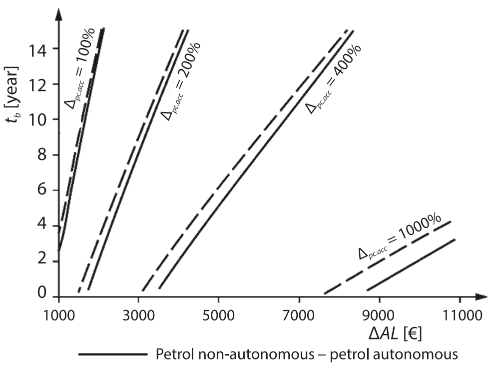

Figure 4. Impact of the value of increasing the price of a new passenger cars because of the Level 3 of autonomy, ΔAL, and changes in costs of road accidents per passenger cars, $\Delta pc.acc$, on the period t_b

Figure 4 shows the dependence of t_b on the value of increasing the price of a new passenger cars because of the Level 3 of autonom,y ΔAL, and changes in costs of road accidents perpassenger cars ($\Delta pc.acc$). Based on the results presented in fig. 4, we conclude that t_b increases with the value of increased the price of a new passenger cars because of Level 3 of autonomy, ΔAL. The analyzed period, t_b, will have a practically acceptable value only in the case of significant multiple descrease of the ΔAL.

If the public risk of road accidents had high values, t_b would be lower, fig. 4. The decrease in the period t_b with increasing size $\Delta pc.acc$ can be explained by the fact that with higher costs of consequences of road accidents have a more significant potential to reduce them. We concluded that the justification for the introduction of autonomous passenger cars increases with the reduction of road safety levels.

The common impact of emission and safety

Many predictions assume that most autonomous vehicles will be electric [3]. Based on that, a comparison between petrol non-autonomous and electric autonomous, and diesel non-autonomous and electric autonomous passenger cars was made.

An important piece of information is the relationship between savings in emissions, road accident consequences, fuel/electricity consumption, and repairs. For this reason, the cost difference of the mentioned factors between electric autonomous and fossil-fuel (petrol, diesel) non-autonomous passenger cars was analyzed, fig. 5, $\Delta ECCO_2md$ – difference between external costs of CO_2 emission during new passenger cars's manufacturing and its distribution, ΔCP_t – difference between passenger cars depreciation; $\Delta ECCO2own_t$ – difference between external costs of CO_2 emission during *ownership*, $\Delta Cpc.acc_t$ – difference between costs of road accidents, ΔCfe_t – difference between fuel/electricity costs; $\Delta Crep_t$ – difference between repair costs.

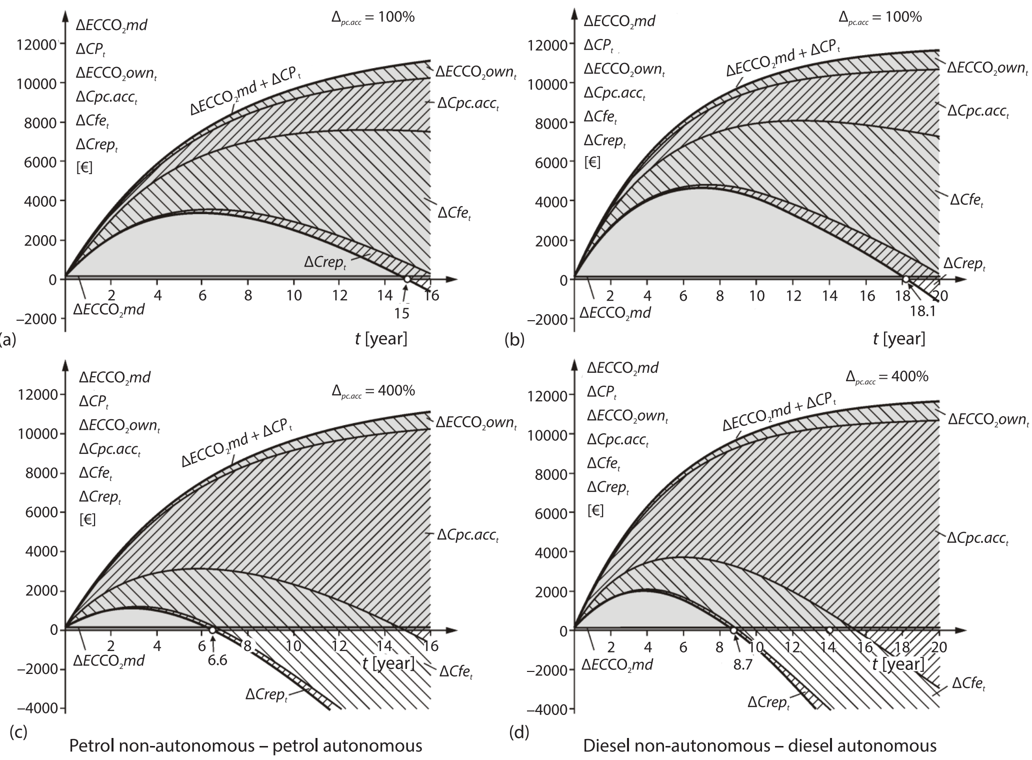

Figure 5. Dependence $\Delta ECCO_2md$, ΔCP_t, $\Delta ECCO_2own_t$, $\Delta Cpc.acc_t$, ΔCfe_t , and $\Delta Crep_t$ on passenger cars age

Since t_b was greater than 20 years for the value of ΔAL = 10874 €, the further analysis considered savings in emissions, road accident consequences, fuel/electricity consumption, and repairs for a lower value of ΔAL, specifically ΔAL = 5437 € (reducing the device price by 50%). In the previous chapter, we concluded that the justification for the introduction of autonomous passenger cars increases with the reduction of road safety levels. Because of that, fig. 5 presents results for different values of public risk of road accidents: public risk of road accidents in Great Britain ($\Delta pc.acc$ = 100%) and four times higher public risk of road accidents ($\Delta pc.acc$ = 400%).

Higher costs ($\Delta ECCO_2md$, ΔCP_t) that arise from purchasing a new, more expensive, cleaner, and safer passenger cars (electric autonomous) instead of purchasing a new, cheaper, less clean, and less safe passenger cars (petrol non-autonomous) were mostly neutralized after 15 years of use by reducing fuel/electricity costs (around 62%) and reducing costs of road accidents (around 23%). Important information is the fact that the average age of passenger cars in Great Britain was 8.3 years [36]. Further increase in the public risk of road accidents led to a situation where the reduction in costs of road accidents becomes greater compared to the reduction in fuel/electricity costs. The same conclusions were reached for the comparison of diesel non-autonomous – electric autonomous passenger cars. The reduction in costs of road accidents, $\Delta Cpc.acc$, was greater compared to the reduction in external costs of CO_2 emissions during *ownership*, $\Delta ECCO_2own$. For the value of the public risk of road accidents in Great Britain, $\Delta pc.acc$ = 100%, the ratio of $\Delta Cpc.acc$ and $\Delta ECCO_2own$ was greater than 3. In the case of higher values of the public risk of road accidents, the previous ratio increases.

Based on these results, we found that customers achieve greater safety benefits than emissions by purchasing an electric autonomous passenger cars instead of a fossil, non-autonomous one. On the other side, the ratio of safety benefits to fuel/electricity costs depends on the public risk of road accidents. Specifically, for higher values of the public risk of road accidents, safety benefits become more significant than fuel/electricity cost reduction. However, the main problem in achieving an acceptable period of use for customers' benefit is the high value of the increased price of a new passenger cars due to Level 3 of autonomy.

Conclusion, limitations, and future research

In this paper, we have proposed a model for determining the period of use when the decision purchase a new, more environmentally friendly passenger cars (cleaner, safer, and more expensive) instead of a new, less environmentally friendly passenger cars would be beneficial. We analyzed the decision purchase a new electric and/or autonomous passenger cars instead of a conventional (petrol or diesel) non-autonomous one. As the key criteria in the model, we adopted costs, emission and road safety. By applying the proposed model to real data from Great Britain, we have identified the following key findings:

- The ratio between road safety benefits and emission benefits increases with introducing autonomous passenger cars.
- Retail car price of passenger cars have a more significant impact than the application of cleaner technology for electricity production on the period of use when we would benefit.
- The justification for the introduction of autonomous passenger cars increases with the reduction of road safety levels in the area.

Based on these conclusions, key activities that stakeholders should undertake to achieve the benefits as early as possible include:

- Reducing the cost of electric and autonomous passenger cars (*e.g.*, technology development, production incentives, customer stimulation).
- Introducing electric passenger cars in areas with lower values of the emission factor of electricity production.
- Introducing autonomous passenger cars in areas with lower road safety levels.

- Encouraging the increased use of environmentally friendly passenger cars (*e.g.*, car-sharing concepts).

During the research process, certain limitations were noticed. Specifically, limited access to data for model application limited its use in areas where such data is unavailable. However, the conclusions drawn for the analyzed case of Great Britain are relevant regardless of the research area. Additionally, the model will provide precise values for other areas when necessary data becomes available. Another limitation is the lack of empirical research on the impact of autonomous passenger cars on the number and consequences of road accidents. The results obtained in future research can be easily incorporated into this model (*e.g.*, reducing price of new technologies, a new data about road accidents, *etc.*).

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Nomenclature

afat – percentage reduce of fatalities, [–]
asei – percentage reduce of serious injuries, [–]
asli – percentage reduce of slightly injuries, [–]
$C_{t,k}$ – cost of a passenger cars as a function of its age, *t*, per *k* vehicle technology, [€]
CE – emission factor of electricity production, [$gCO_2kW^{-1}h^{-1}$]
cfat – cost per fatality, [€]
Cfe – fuel/electricity costs, [€]
Cpc.acc – cost of the road accidents per passenger car for the analyzed country, [€]
Crep – repair costs, [€]
crep – repair costs per kilometer driven, [$€km^{-1}$]
csei – cost per serious injury, [€]
CSHIPP – shipping costs, [€]
csli – cost per slight injury, [€]
dep_k – annual depreciation rate per car technology
ΔAL – increasing the price of a new passenger cars because of the Level 3 of autonomy, [€]
ΔCfe_t – difference between electric autonomous and fossil-fuel non-autonomous fuel/electricity costs, [€]
ΔCP_t – difference between electric autonomous and fossil-fuel non-autonomous depreciation, [€]
$\Delta Cpc.acc_t$ – difference between electric autonomous and fossil-fuel non-autonomous costs of road accidents, [€]
$\Delta Crep_t$ – difference between electric autonomous and fossil-fuel non-autonomous repair costs, [€]
Δ_{eb} – distribution of economic benefits, [–]
$\Delta ECCO_2md$ – difference of $ECCO_2man$ + $ECCO_2dis.c$ between electric autonomous and fossil-fuel non-autonomous passenger cars, [€]
$\Delta ECCO_2own_t$ – difference of $ECCO_2own$ between electric autonomous and fossil-fuel non-autonomous passenger cars, [€]
$\Delta pc.acc$ – changes in costs of road accidents per passenger cars, [€]
$ecCO_2$ – external cost of the CO_2 emission, [$€kg^{-1}$]
$ECCO_2dis.c$ – external cost of the CO_2 emission during *Distribution of cars*, [€]
$ECCO_2man$ – external cost of the CO_2 emission during *Manufacturing*, [€]
$ECCO_2own$ – external cost of the CO_2 emission during *Ownership*, [€]
$ECCO_2use$ – external cost of the CO_2 emission during *Use*, [€]
$ECO_2dis.c$ – CO_2 emission during *Distribution of cars*, [kg]
ECO_2disp – CO_2 emission during *Disposal*, [kg]
ECO_2man – CO_2 emission during *Manufacturing*, [kg]
ECO_2own – CO_2 emission during *Ownership*, [kg]
ECO_2rep – CO_2 emission during *Repair*, [kg]
ECO_2use – CO_2 emission during *Use*, [kg]
k – car types/technology, [–]
MSRCP – manufacturer's suggested retail car price, [€]
nfat – number of fatalities, [–]
nsei – number of serious injuries, [–]
nsli – number of slight injuries, [–]
PREM – premium at purchase time, [€]
RCP – retail car price, [€]

rep – CO_2 emission during *Repair* per kilometer, [kgkm^{-1}]
S_t – car's kilometer driven per year, [km]
t – car's age, [year]
t_b – period of use when we would benefit from purchasing a new, more expensive, cleaner, and safer passenger cars instead of purchasing a new, cheaper, less clean, and less safe PC, [year]
UCP – used car prices, [€]
VAT – value-added tax, [–]

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