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Potential autonomous vehicle ownership growth in Hungary using the Gompertz model

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Abstract
Autonomous Vehicles (AVs) are anticipated to bring forth a multitude of advantages for upcoming mobility.These potential benefits and many others vary substantially by the market share of AVs. There are several articles that investigated AV market share with a variety of methods, however, they show a huge variation depending on the market specifications. The aim of this research is to calculate private AV adoption rates over time depending on the Hungarian automobile market characteristics. The research empirically estimates, using the Gompertz function, the projected growth rates of private autonomous passenger vehicles in Hungary using historical patterns of human-driven vehicle ownership data on the basis of projected per capita GDP.The study's findings suggest that, in an optimistic and moderate scenario, the Hungarian car market is projected to become saturated due to AVs by 2067 and 2076, respectively. However, a pessimistic estimation indicates that saturation is unlikely to occur before 2100. This study's contribution to the literature is through a mathematical approach that predicts AVs market penetration rate and saturation year, in which the assumptions and the used parameters of the model can be modified depending on different case studies, or they can be updated due to the advancement in technology and improvement in knowledge of the studied market.

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1. Introduction

Autonomous vehicles (AVs), also known as driverless or robotic vehicles, are defined as vehicles that operate by themselves without active control from a driver (Fagnant and Kockelman, 2015). AVs can drive using the information collected by their sensors, and they are not necessarily connected to the infrastructure or other vehicles (Talebpour and Mahmassani, 2016). According to SAE (SAE, 2022), AVs are classified into five levels of automation, starting with Level 0 (i.e., normal human-driven car) up to Level 5 (i.e., full automation). This research considers Level 5 AVs which operate under all conditions without requiring the driver to take over driving.

AVs are expected to introduce numerous benefits for individuals and overall future mobility. Autonomous vehicles, for example, are anticipated to enhance safety levels for all road users, including drivers, pedestrians, and passengers, by reducing the negative impact of human driving to the lowest possible extent and thereby minimizing road accidents.(Fagnant and Kockelman, 2015; Nadafianshahamabadi et al., 2021; Shatanawi et al., 2022). Besides safety, the integration of AVs is also likely to offer benefits to road congestion due to low reaction time and their full comprehension of road elements compared to human-driven vehicles (Talebpour and Mahmassani, 2016). These potential benefits and many others, however, vary substantially by the market share of AVs (Litman, 2022). The primary challenge lies in the fact that this emerging technology is not yet fully matured, making it difficult to predict adoption rates for AVs and their resulting traffic and environmental impacts Many researchers overcame this problem by creating several hypothetical scenarios (i.e., a certain number of possible market shares of AVs in a certain year), which consumes immense time and effort (see e.g., (Matalqah et al., 2022; Shatanawi and Mészáros, 2022). Because of this, estimating AV ownership rates can be of huge benefit to researchers, transport planners, and policymakers.

There are several published articles and reports that investigated this topic with a variety of methods as illustrated in the next section. However, they show that the share of AV ownership rates will differ significantly in various markets. The aim of this research is to calculate private AV adoption rates over time depending on the Hungarian automobile market specifications.

This research empirically estimates the projected growth rates of automated passenger vehicles in Hungary on the basis of historical patterns of human-driven vehicle ownership data. The study employed the Gompertz growth model and applied the proportion coefficient method to estimate the correlation between ownership of AVs and per capita gross domestic product (GDP) over time. Additionally, the study utilized robust, transparent, and openly available datasets, which could be the basis for forecasting methodology and effortlessly reached and checked (e.g., Hungarian Central Statistical Office (HCSO, 2021), European Statistical dataset (Eurostat, 2022), and the World Economic Outlook (World Bank, 2022)). Three AV ownership growth scenarios were investigated: optimistic, moderate, and pessimistic scenarios. Furthermore, the ARIMA model was utilized to forecast Hungary's annual GDP per capita up to the year 2080. The following sections discuss the literature review, the methodology and the data used to perform this research, and finally the results.

2. Literature review

Researchers investigate the adoption rate of any new breakthrough technology in order to help in creating the necessary emergence policies. AV is no exception as numerous scholars studied its diffusion rate in various study cases and methods. These methods are varying between sales estimation, the growth pattern of vehicle's technologies, and the knowledge of field professionals (Talebian and Mishra, 2018). IHS Automotive (2014), utilizing the sales estimation, predicts that in the year 2050 almost all operating vehicles will be equipped with autonomous driving technologies. Litman (2022), on the other hand, uses a scenario-based method to predict the future market share of connected AVs depending on the growth pattern of vehicle's technologies such as airbags and integrated navigation technologies. According to the author's findings, in 2050, autonomous vehicles are projected to constitute 40-60% of newly purchased vehicles and form 20-40% of the total vehicle fleet. Using the knowledge of field professionals, a study conducted by experts of The Institute of Electrical and Electronics Engineers (IEEE) to predict the adoption of AVs finds that 75% of all the automobile market share will be autonomous by 2040 (Talebian and Mishra, 2018).

Several researchers used the Gompertz model to estimate the growth of civilian vehicles in the literature. Dargay et al. (2007a) introduced an extensive study to estimate a worldwide vehicle ownership model depending on the GDP per capita. Their study was performed using the historical trends of vehicle ownership between 1960 and 2002 for 45 countries, and their model forecasted the vehicle stock until 2030. Li et al. (2014) also conducted a research that predicts the ownership of electric vehicles in China using Gompertz and logistic models. They used the historical patterns of conventional vehicles and several anticipated electric car adoption rates in order to create their model.

Although the Gompertz function is a common prediction method in the literature for civilian car ownership, it is not for the prediction of AV adoption rates. Fig. 1. shows a graphical keywords map created using VOSviewer software (VOSviewer, 2022), illustrating the association between vehicle ownership and the Gompertz model in the Web of Science (WoS) database.

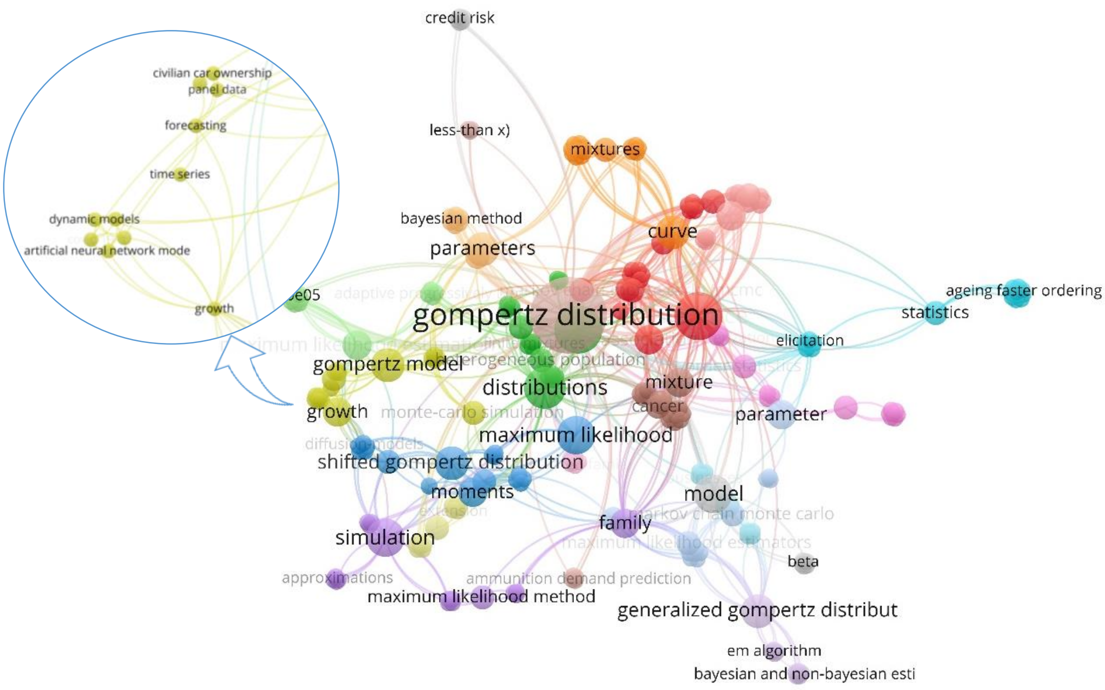

Fig. 1. Co-occurrence map of keywords associated with car ownership and Gompertz model

A co-occurrence network was constructed and a general query was employed to examine all instances of the use of the Gompertz model in the literature, that is: ALL FIELDS = (Gompertz model). However, this query was applied with specific constraints to be applicable to the scope of this research. To do that, the searched results were refined depending on the "Web of Science Categories". Three main categories were considered: Economics, Transportation, and Statistics. Depending on these conditions, 161 publications were selected. The map shows the relation among a set of 257 keywords from the chosen studies depicted in clusters, these clusters display the connection between keywords. The bubble size represents the keyword occurrences and the links between those bubbles are showing the relatedness strength. With a total of 20 clusters and 1300 links, the diagram confirms that car ownership predictions using the Gompertz model were used in the literature, however, for civilian cars not for AVs. Therefore, this study was conducted due to the lack of literature that examines the prediction of AV ownership rates using the Gompertz model. As well as to investigate the expected AV adoption ratios and saturation time in Hungary using historical patterns of conventional passenger vehicles from 1980 and anticipated AV adoption rates from the literature.

3. Methodology and data

This section introduces the framework for investigating AV ownership growth rates in Hungary using the Gompertz curve. In addition, it discusses the historical trends of human-driven vehicles from 1980 in order to be used in the estimation model.

3.1. Methodology

Vehicle ownership prediction methods can be categorized into two common models: the equilibrium model, and the well-known and used method; the demand model (Li et al., 2014; Majerova, 2022). The latter method can also be divided into a set model that is used for long-term predictions, and a non-set model which is often utilized in practice for short-term predictions (Li et al., 2014). In this research, the Gompertz curve, classified as a saturation level limit method that is part of the set model, was employed to estimate AVs ownership growth in Hungary as it is, compared to the logistic model, more flexible to estimate. Named after the British statistician and mathematician Benjamin Gompertz in 1825, the Gompertz model was first employed in the biological field, and it showed a noticeable performance in estimating growth and mortality and therefore the lifespan (Talebian and Mishra, 2018). After nearly a century, the model became more popu**larly utilized in product life cycle analysis when R. Prescott,** an American researcher, used it to estimate the market demand. As used in several previous studies, the general mathematical form of the Gompertz function is as follows:

$$A_t = \lambda e^{-\alpha e^{-\beta G_t}} \alpha, \beta > 0 \quad (1)$$

where, A_t and G_t are vehicle ownership (veh/1000 people) and GDP per capita in year t, respectively, λ is the upper limit of A_t (i.e., the saturation level), α and β are parameters that define the curvature of the function. It is worth mentioning that, by analyzing the model analytically, the sensitivity parameter on how GDP is influencing car ownership rates is β.

Equation (2) is produced by taking the logarithmic operation on both sides of equation (1):

$$ln\, A_t = ln\, \lambda - \alpha e^{-\beta G_t} \quad (2)$$

Equation (3) is obtained next by log-linearizing equation (2):

$$ln\left(ln \frac{A_t}{\lambda}\right) = ln(-\alpha) - \beta G_t \quad (3)$$

Based on equation (3), $ln(-\alpha)$ and β can be calculated using the ordinary least square method (OLS) for time series data. The elasticity of car ownership, on the other hand, with respect to GDP can be determined as follows:

$$E = \alpha\beta G_t e^{-\beta G_t} \quad (4)$$

Fig. 2. illustrates the positive trend between motorization level and per capita GDP in an S-shaped curve, which is divided into four stages (Wang et al., 2012).

1) Slow increment of ownership rates with increasing per capita GDP,
2) Fast increment of vehicle ownership while increasing per capita income,
3) Slower growth compared with stage 2,
4) Saturation state, where vehicle ownership does not increase with increasing per capita GDP.

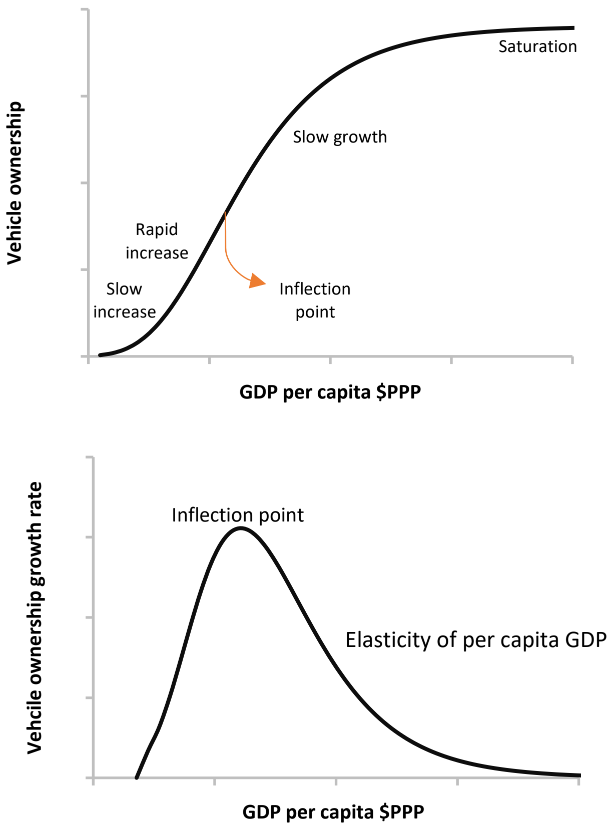

Fig. 2. Relationship between economic development and mobility level (Adopted from Wang et al., 2012)

The elasticity, on the other hand, is always positive for all levels of GDP per capita, and reaches its maximum value at GDP = 1/β (also known as the inflection point) and declines gradually while approaching the saturation level (Kutasi, 2022). The inflection point is of high importance as it defines the transition limit between the rapid increase stage and the slow growth stage. Accordingly, the Gompertz curve is split into two mathematical behaviors around the inflection point as follows:

$$A_t = \begin{cases} quadratic, if\, G_t < inflectionpoint \\ logarithmic, if\, G_t > inflectionpoint \end{cases} \quad (5)$$

The inflection point also represents the per capita GDP level that achieves the maximum elasticity, see Fig. 2. By taking the second derivative of equation (1) and setting it equal to 0, the inflection point will take place at GDP = $\frac{ln\, \alpha}{\beta}$.

As the automated technology is not yet matured and is still under development, historical data on AV ownership is not available to predict future projections. However, as above-mentioned, the growth of motorization, modeled by the Gompertz function, follows the S-shaped curve, which is proved by several studies, see for example (Dargay et al., 2007b; Li et al., 2014; Litman, 2022; Talebian and Mishra, 2018; Wang et al., 2012). Therefore, the ownership development of different types of vehicles such as conventional, hybrid, electric, and even autonomous can be all described by Gompertz's S curve. Based on that, this research employed the recent years' data of human-driven vehicles in Hungary in order to obtain their curve fitting using the Gompertz function, then calculated the proportion of AVs from the predicted human-driven automobiles using the proportion coefficient method based on the behavior of the Gompertz curve shown in equation (5).

3.2. Data

According to (Rota et al., 2016), the saturation level of civilian car ownership in Hungary will reach 570.2 vehicles per 1000 capita, representing λ in equation (1). Then, according to the Hungarian Central Statistical Office (HCSO, 2021), Eurostat (Eurostat, 2022), and the World Economic Outlook (World Bank, 2022), the data for human-driven car ownership rates and per capita GDP in Hungary are collected and demonstrated in Fig. 3.

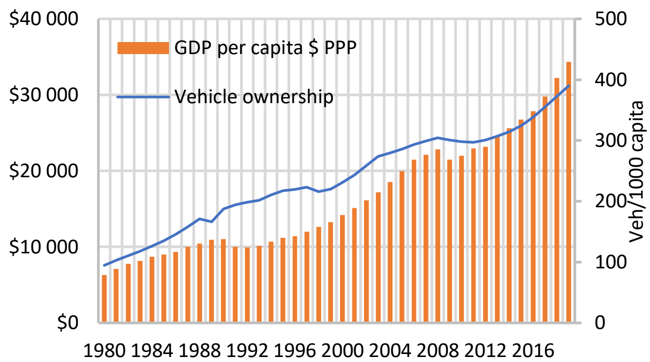

Fig. 3. Human-driven vehicle ownership rates and per capita GDP in Hungary between 1980 and 2019

Using the OLS method, α and β parameters were estimated using equation (3) based on the available statistical data collected, thus, the growth model of civilian vehicle ownership in Hungary on the basis of per capita GDP can be described as in equation (6), which is also demonstrated in Fig. 4. It is worth mentioning that Microsoft Excel was used for regression analysis and 95% confidence interval was set, thus in this model maximum of 5% error is allowed. Moreover, the model shows, using the coefficient of determination (R^2), a goodness of fit of more than 0.92, meaning that this regression model is sufficient and valid for describing the historical data of car ownership in Hungary, also to be assumed and adopted for future estimations.

$$A_t = 570.2e^{-1.979e^{-4.987\times10^{-5}G_t}} \quad (6)$$

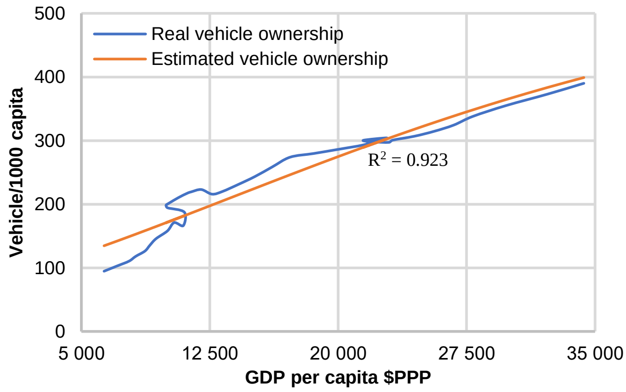

Fig. 4. Real and estimated vehicle ownership rates in Hungary between 1980 and 2019 based on per capita income

The inflection point for the Hungarian vehicle ownership rates will occur at $13,687 per capita GDP $PPP by deploying the obtained α and β parameters. This means that the inflection point for AV ownership in Hungary is also expected to appear after an increment of approximately $14,000 in the per capita income because they are expected to follow the same growth patterns as civilian cars. Fig. 5. displays the elasticity of car ownership in Hungary on the basis of GDP/capita, which is also shown as a time series to better understand the behavior of the historical rates of motorization.

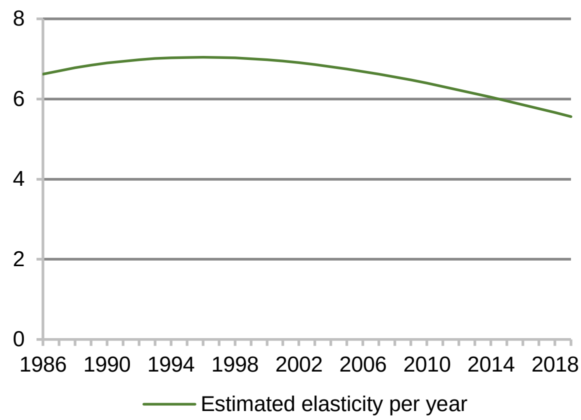

Fig. 5. Elasticity of human-driven vehicle ownership in Hungary

4. Results

After obtaining the growth model of civilian car ownership in Hungary based on historical data until 2019, we can deploy equation (6) to estimate the future projections of ownership rates. The Hungarian GDP per capita growth rate, however, needs to be estimated to conduct the empirical analysis depending on these forecast findings. In this research, the autoregressive integrated moving average (ARIMA) model was used to forecast Hungary's annual GDP growth rate in order to get the independent variable G_t in the Gompertz function. Considering the stationarity of the time series, autocorrelation plot (ACF) and partial autocorrelation plot (PACF), ARIMA (1,1,1) model was used to forecast the annual Hungary's GDP per capita until the year 2080. Fig. 6. shows the resulting S-shaped growth curve of the human-driven vehicle ownership in Hungary forecasted until reaching the expected saturation level, which is expected to occur at approximately $97,000 per capita GDP. Also, as calculated above, the inflection point in Hungary occurred at $13,687 GDP per capita.

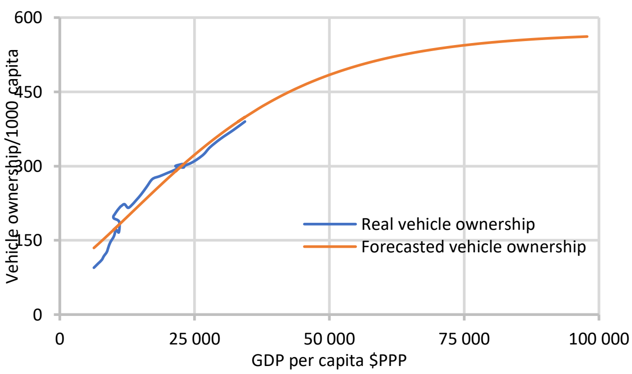

Fig. 6. Real and forecasted vehicle ownership rates in Hungary between 1980 and 2060 based on per capita income

According to (Litman, 2022) autonomous vehicles are expected to form 1-2% of the car market fleet in 2030, and 20% and 40% in 2040 and 2050, respectively. More optimistic predictions by IEEE found that AV penetration rate will be 75% in 2040 (Talebian and Mishra, 2018), and 90% in 2050 (Silva et al., 2021). To this end, we created three scenarios depending on the above literature to predict Hungary's AV growth model:

1. Pessimistic scenario (PS): 1%, 20%, and 40% in 2030, 2040, and 2050, respectively.
2. Moderate scenario (MS): 1.5%, 47.5%, and 65%, in 2030, 2040, and 2050, respectively.
3. Optimistic scenario (OS): 2%, 75%, and 90%, in 2030, 2040, and 2050, respectively.

As mentioned in the previous section, the inflection point for AV ownership in Hungary is expected to appear after an increment of nearly $14,000 in the per capita income because they are expected to follow the same growth patterns as civilian cars. In 2030, the GDP per capita is expected to be nearly $57,000, and $71,000 in 2040 (as forecasted using the ARIMA model). Thus, it is estimated that Hungary's AVs ownership will be in the stage of accelerating growth between 2030 and 2040, and in the slow growth stage after 2040. Depending on this analysis and equation (5), we can make AVs ownership occupation ratio in 2030-2040 quadratic curve fitting, and logarithmic curve fitting after 2040 as follows:

$$AV_t = \begin{cases} q_s . A_t, \text{if} G_t < inflectionpoint \\ l_s . A_t, \text{if} G_t > inflectionpoint \end{cases} \tag{7}$$

where AV_t is AV ownership (veh/1000 people) in year t, q and l are AVs occupation ratios in the fast and slow growth stage, respectively, for scenario s. The growth models for all scenarios can then be summarized in equation 8, where A is the period between 2030 to 2040 and B is the period between 2040 to 2050.

$$AV_t = \begin{cases} PS \begin{cases} \left(\left(0.01 + 0.72 \times 10^{-9}(G_t - 57{,}000)\right)^2\right) 570.2e^{-1.979e^{-4.987\times10^{-5}G_t}}, forA \\ \left(1.19\, ln(G_t) - 13.13\right) 570.2e^{-1.979e^{-4.987\times10^{-5}G_t}}, forB \end{cases} \\ MS \begin{cases} \left(\left(0.015 + 1.77 \times 10^{-9}(G_t - 57{,}000)\right)^2\right) 570.2e^{-1.979e^{-4.987\times10^{-5}G_t}}, forA \\ \left(1.04\, ln(G_t) - 11.19\right) 570.2e^{-1.979e^{-4.987\times10^{-5}G_t}}, forB \end{cases} \\ OS \begin{cases} \left(\left(0.02 + 2.83 \times 10^{-9}(G_t - 57{,}000)\right)^2\right) 570.2e^{-1.979e^{-4.987\times10^{-5}G_t}}, forA \\ \left(0.89\, ln(G_t) - 9.25\right) 570.2e^{-1.979e^{-4.987\times10^{-5}G_t}}, forB \end{cases} \end{cases} \tag{8}$$

Fig. 7. illustrates the results of equation (8); however, further optimization is needed in order to have the curves better represented by the Gompertz function. We fitted the composite function (i.e., quadratic and logarithmic) into a Gompertz model considering the minimum squared error depending on the α and β parameters. Hungary's AV growth models are expressed as follows:

$$AV_t = \begin{cases} 570.2e^{-4.072e^{-4.84\times10^{-5}G_t}}, PS \\ 570.2e^{-7.640e^{-1.04\times10^{-5}G_t}}, MS \\ 570.2e^{-10.10e^{-1.49\times10^{-4}G_t}}, OS \end{cases} \tag{9}$$

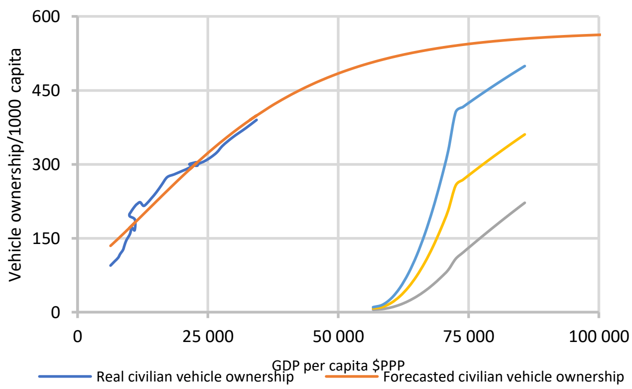

Fig. 7. Estimated AV ownership rates in Hungary based on per capita income

It should be noted that the study assumes a 100% market saturation share for AVs due to their numerous benefits and positive impact on the public and the overall transportation system Fig. 8. shows that in an optimistic situation, 92% of Hungary's automobiles will be autonomous at an $85,000 per capita income, and 100% at a GDP of $105,000, which corresponds to the 2067 year. In a moderate scenario, AVs are expected to form 50% of Hungarian cars at a per capita GDP of $76,700 and will reach market saturation in 2076. On the other hand, according to the pessimistic model, Hungary is expected to reach a market share of 50% of AVs in 2055 which the moderate scenario anticipates happening 12 years earlier. Furthermore, the pessimistic scenario model showed that there will not be a full emergence of AV in Hungary before the year 2100 and a $140,000 GDP per capita.

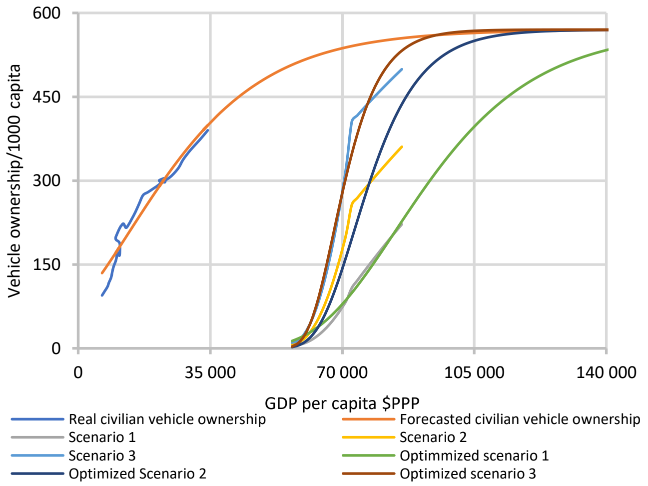

Fig. 8. Optimized forecasting of AV ownership rates in Hungary based on per capita income

The curves in Fig. 9. indicate the annual growth of AV ownership per one thousand capita in Hungary for the three studied scenarios, which helps to comprehend deploying behavior of AVs into the market. It is important to note that the elasticities of AV ownership on the basis of income follow a basic non-monotonic pattern; getting higher over the low GDP per capita levels and decreasing over higher levels of income, but always remaining positive.

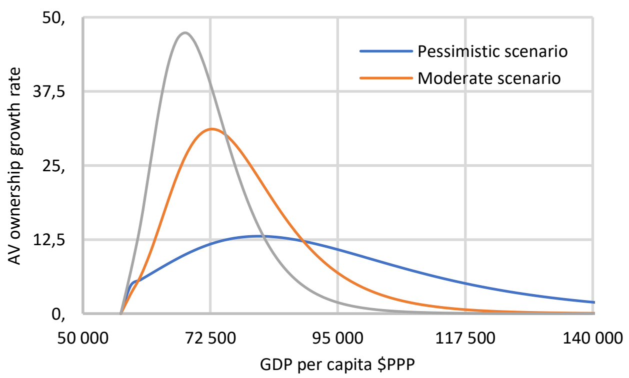

Fig. 9. Estimated AVs ownership elasticity in Hungary

5. Conclusion

This research estimated Hungary's AV ownership growth model by employing the recent years' data of human-driven vehicles in Hungary in order to obtain their curve fitting using the Gompertz function, Three AV growth scenarios were considered: optimistic, moderate, and pessimistic scenarios. We found that the Hungarian automobile market will reach AV saturation in 2067 and 2076 in an optimistic and moderate situation, respectively, and not before 2100 in a pessimistic estimation.

Although this research introduces a mathematical approach that predicts AVs market penetration rate and saturation year, it faces some limitations. For simplification and generalization, Level 5 automation technology was used, and it was not differentiated from Level 4 as they are both very advanced technologies. Also, since the driver is expected to occasionally take control of the car in specific circumstances, Level 3 automation technologies have not been considered as the individual benefit is anticipated to be significantly lower. The data that has been gathered about vehicle ownership and GDP are discrete data points, meanwhile, we build up a continuous regression model. This is because we represented car ownership rates on the basis of GDP, not as a time series, thus a continuous regression model was assumed and used to forecast future vehicle ownership rates as it will be easier to comprehend. The adopted scenarios in this research do not take into account that AVs could significantly change the assumed vehicle market saturation level, however, this is subject to future research.

The applied parameters and the used assumptions can be easily altered or updated depending on different study cases or changes in the market. Moreover, this study with its initial estimates can be further developed by considering different growth models and comparing their performance in predicting AV ownership growth in Hungary, and by incorporating additional variables besides GDP such as consumer preferences. It would be also interesting to integrate system dynamics as it offers a complete approach and considers feedback loops and time lags.

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预测

摘要
潜在的好处和其他方面因自动驾驶汽车的市场份额而大不相同。已有多篇文章探讨了不同方法下的自动驾驶汽车市场份额，但由于市场规格的不同，它们显示出巨大的变化。本研究的目的是根据匈牙利汽车市场的特征，计算私人自主驾驶汽车随时间的采用率。本研究使用 Gompertz 函数在经验上估计匈牙利的私人自动驾驶客车的预计增长率，基于预计的人均 GDP 的历史人力驱动车辆拥有数据模式。我们发现，在乐观和中等情况下，匈牙利汽车市场将在 2067 年和 2076 年达到自动驾驶汽车饱和，而在悲观的估计中不会在 2100 年之前饱和。本研究的贡献在于采用数学方法预测自动驾驶汽车的市场渗透率和饱和年份，其中模型的假设和使用的参数可以根据不同的案例研究进行修改，也可以根据技术进步和市场研究的提高进行更新。