Modeling Electric Mobility in Germany: A Policy Analysis Perspective

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Abstract

As a result of international negotiations, the European Union has a target of 20% reduction in greenhouse gas emissions by 2020 compared to 1990 levels. Road transport is the second largest greenhouse gas emitting sector in the Union and its emissions continue to rise. In this context, to reduce the CO_2 emissions from light-duty vehicles, the German Federal government plans to implement a set of new regulations including Regulation (EC) No 443/2009, super-credits, electric vehicle purchase incentives, and energy tax. In this research, different than the previous modeling approaches, by making use of simulation and optimization techniques simultaneously, a hybrid decision model is developed to assist policy makers and the corporate managers working in the automotive industry with evaluating the impacts of new regulations with respect to the changes in CO_2 emissions, electric vehicle sales, and costs of car manufacturers. In the developed model, while the simulation technique is utilized to build the interactions among the model entities and deal with uncertainty, the optimization technique is used to imitate the strategic decision making process of car manufacturers. Based on the model results, a general insight about the nature of new regulatory framework is provided and basic recommendations are made.

Keywords
Alternative fuel vehicles, greenhouse gas emissions, automotive industry, environmental policy analysis, hybrid decision support system

1. Introduction
In recent years, growing environmental concerns compel governments to act together in controlling and mitigating CO_2 emissions. As a result of international negotiations such as Kyoto Protocol, the European Union plans to pursue an objective of 30% reduction of greenhouse gas emissions by developed countries by 2020 (compared to 1990 levels) and that the Union itself makes a firm independent commitment to achieve at least a 20% reduction of greenhouse gas emissions by 2020 (compared to 1990 levels), irrespective of reductions achieved by other developed countries. In the Union, road transport is the second largest greenhouse gas emitting sector, and its emissions continue to rise (Regulation (EC) No 443/2009 2009). This leads the governments of the member states to focus on reducing the CO_2 emissions from light-duty vehicles and hence expediting the market diffusion of electric vehicles. Being one of the founding states of the European Union and having an automotive industry making worldwide vehicle production, Germany has a significant role in this new initiative, and the German Federal Government has a target of one million electric vehicles by 2020 and six million electric vehicles by 2030 in the German car market. In this context, to achieve the European Union's emissions standards at the state level and expedite the diffusion of electric vehicles into the market, the German Federal Government considers implementing a set of new regulations including Regulation (EC) No 443/2009, super-credits, electric vehicle purchase incentives, and energy tax. However, the potential impact of these policy instruments is still a question for policy makers and the corporate managers working in the automotive industry. For this reason, this paper aims to analyze the given policy instruments from a cost-benefit perspective, and make basic recommendations to policy makers and corporate managers with regard to the potential impacts of these policy instruments. To this end, different than the previous modeling approaches, by making use of simulation and optimization techniques simultaneously, a hybrid decision model is developed enabling policy makers and corporate managers to evaluate the impacts of new regulations with respect to the changes in CO_2 emissions, electric vehicle sales, and costs of car manufacturers. In the developed

model, while the simulation technique is utilized to model the interactions among the model entities and handle with the uncertainty in certain model parameters, the optimization technique is used to imitate the strategic decision making process of car manufacturers with a cost minimization submodel. In order to provide a general insight about the nature of new regulatory framework and make basic recommendations, the developed model is analyzed under different policy scenarios for the following 25 years.

The research presented in this paper makes a contribution to the literature not only methodologically but also as content. From the methodological perspective, developing a hybrid model to analyze the automotive industry is a relatively new approach. Simulation is dynamic, and allows modeling and analysis of the interactions among the entities in a complex system. In contrast, optimization is static, but provides the optimal solution for a predefined case. By combining the advantages of the two techniques, the developed hybrid model enables policy makers to test the impacts of various policy instruments from a cost-benefit perspective while enabling the corporate managers in the automotive industry to respond the regulations set by the government in an optimal way. In addition to the methodological contribution, the paper also makes a significant contribution to the literature as content. Presenting an analysis in the European context, the work presented in this paper differs from the previous automotive industry modeling studies since most of these studies focus on the U.S. car market and regulatory framework.

In the following sections of this paper, first, a brief literature review is provided explaining the contribution of the paper as a comparison of the study with previous studies in terms of methodology and content. After the policy instruments analyzed in this research are shortly described, in the Methodology section, the development of the hybrid model is explained by providing a visual representation of the simulation model together with the formulation of the optimization submodel. The model results obtained under certain assumptions and simplifications are then presented, followed by the interpretation of the results and basic recommendations. Finally, the paper is concluded with a discussion of the verification, validation and limitations of the developed model and potential future research directions.

2. Literature Review

In the literature, there are various optimization models developed to analyze the automotive industry and related decisions. Often, these models focus on cost minimization or profit maximization. In their study, Michalek et al. (2004) and Shiau et al. (2009 and 2010) investigate the impact of fuel efficiency and CO_2 emissions standards to vehicle design and specifications from a profit-loss perspective, and introduce the optimal vehicle design concept to the literature. While Michalek et al. (2004) utilize linear programming, Shiau et al. [4] use mixed-integer nonlinear programming. The U.S. Environmental Protection Agency (EPA) (2010) evaluates the relative costs and effectiveness of alternative transport technologies (gasoline, diesel, electric, etc.) with an optimization model by minimizing the cost of meeting a specified CO_2 emissions target. In his study, Ozdemir (2011) analyzes the effect of different transport technologies, economic, environmental and political conditions in Germany on the costs, efficiencies, greenhouse gas emissions and land area requirements for biofuel production by using a linear optimization model that minimizes the cost of satisfying the energy demand of German transport sector. Ines et al. (2011) focus on a different aspect of electric vehicles and study the optimal location of electric vehicle charging stations for an area of Lisbon, Portugal where there is a strong concentration of population and employment. Their methodology is based on a maximal covering model to optimize the demand covered within an acceptable level of service, and to define the number and capacity of the stations to be installed. Finally, Sioshansi (2012) analyzes the impacts of electricity tariffs on the charging, costs, and emissions of plug-in hybrid electric vehicles with the support of optimization models that minimize the energy generation cost, and the charging and refueling costs of plug-in hybrid vehicles.

In addition to the optimization models, the literature also provides simulation models that can be used in the analysis of the decisions related to the automotive industry. Generally, these simulation models are dynamic models that provide a system perspective and focus on the relations and interactions among the entities in the automotive industry. In most of these models, the objective is to analyze the system under different input scenarios instead of finding an optimal solution for a specific variable under several constraints as it is the case in the optimization models. For instance, by using agent-based simulation, Kieckhäer et al. (2009) model the automotive industry from a system perspective and provide an analysis of the strategic decisions related to the development of vehicle product portfolio (i.e., which vehicle technology to introduce, at which time, in which vehicle class). Similarly, Wansart and Schnieder (2010), and Sullivan et al. (2009) develop simulation models, and provide an analysis of the car market under a variety of consumer, economic and policy conditions to analyze the market diffusion of electric vehicles. And finally, in contrast to the optimization approach of Ines et al. (2011), Sweda and Klabjan (2011) make use of agent-based simulation to identify patterns in residential electric vehicle ownership and driving activities, and hence to enable strategic deployment of new charging infrastructure by focusing on Chicago area.

The optimization models developed for the automotive industry provide optimal results for a predefined case. However, since these models are typically static models, they ignore the dynamic and uncertain nature of the automotive industry. On the other hand, while the simulation models enable to model the relations and interactions among the entities in the automotive industry and test a specific case, they do not provide any information about whether it provides the optimal solution. For this reason, the models using only optimization or simulation technique are somewhat inadequate in modeling the automotive industry which has a highly complex nature. To fill this gap, in recent years, researchers have started to focus on developing hybrid models that make use of simulation and optimization techniques simultaneously. An example of these models might be the one that is developed by Zhang et al. (2011). In their study, by using the hybrid model that they developed, Zhang et al. (2011) examine the basic mechanisms that affect the market diffusion of electric vehicles into the U.S. car market.

To provide a more realistic and comprehensive modeling approach, similar to Zhang et al. (2011), this research also adopts a hybrid modeling approach by making use of simulation and optimization techniques simultaneously. In that sense, it provides one of the first hybrid decision models in the literature making a significant methodological contribution to the literature. In addition to the methodological contribution, this research also makes a remarkable contribution to the literature as content. In their study, Zhang et al. (2011) focuses on the U.S. car market and considers Corporate Average Fuel Economy (CAFE) as the only possible policy instrument for the government. On the other hand, this research focuses on the German car market, and provides an analysis of Regulation (EC) No 443/2009 together with the other policy instruments such as super-credits, electric vehicle purchase incentives, and energy tax. Besides, while the transport technologies considered in the model of Zhang et al. (2011) is limited to three alternatives - gasoline, hybrid and electric, this research provides a broader perspective by extending the alternatives to seven technologies, namely diesel, gasoline, LPG-CNG, hybrid, electric, hydrogen and biofuel.

3. Policy Background

Before proceeding with the methodology, this section provides a brief description of the policy instruments that are considered in the developed model.

Regulation (EC) No 443/2009: The main objective of Regulation (EC) No 443/2009 is to set emissions performance standards for new passenger cars. With this regulation, the average CO_2 emissions for new passenger cars is set to 130 g/km, and from 2020 onwards, a target of 95 g/km is determined as the average emissions for the new car fleet. The car manufacturers whose average emissions of CO_2 exceed the target levels are required to pay an excess emissions fee, and these excess emissions fees are considered as a revenue item for the government budget. Based on Regulation (EC) No 443/2009, the calculation of the excess emissions fees is performed as the following:

- From 2012 until 2018:
    - where the manufacturer’s average specific emissions of CO_2 exceed its specific emissions target by more than 3 g/km:
      ((Excess emissions – 3 g/km) × 95 €/g/km + 1 g/km × 25 €/g/km + 1 g/km × 15 €/g/km + 1 g/km × 5 €/g/km) × number of new passenger cars.
    - where the manufacturer’s average specific emissions of CO_2 exceed its specific emissions target by more than 2 g/km but no more than 3 g/km:
      ((Excess emissions – 2 g/km) × 25 €/g/km + 1 g/km × 15 €/g/km + 1 g/km × 5 €/g/km) × number of new passenger cars.
    - where the manufacturer’s average specific emissions of CO_2 exceed its specific emissions target by more than 1 g/km but no more than 2 g/km:
      ((Excess emissions – 1 g/km) × 15 €/g/km + 1 g/km × 5 €/g/km) × number of new passenger cars.
    - where the manufacturer’s average specific emissions of CO_2 exceed its specific emissions target by no more than 1 g/km:
      (Excess emissions × 5 €/g/km) × number of new passenger cars.
- From 2019:
    - (Excess emissions × 95 €/g/km) × number of new passenger cars.

Super-credits: By defining the super-credits, in the calculation of the average CO_2 fleet emissions, it is planned that each new passenger car with an emission of less than 50 g/km to be counted as 3.5 cars in 2012 and 2013, 2.5 cars in 2014, 1.5 cars in 2015, and 1 car from 2016.

Electric vehicle purchase incentives: These incentives are considered as a subsidy of the government for the consumers, and based on this initiative, a subsidy of €3000-€5000 per vehicle is planned to be given to the consumers for the first 2,250,000 electric vehicles.

Energy tax: Energy tax is an excise tax imposed on the sale of fuel. In Germany, energy tax is around €0.4704 per liter for diesel and €0.6545 per liter for gasoline, plus value added tax (19%) on the fuel itself and the energy tax. In order to expedite the market diffusion of electric vehicles, an increase in the energy tax is considered as a policy option.

4. Methodology

As previously mentioned, the model developed in this research is designed as a hybrid model and makes use of the simulation and optimization techniques simultaneously. In the development of the model, using Goldsim simulation software (2011), first a simulation model is built as the main model, and then an optimization model is embedded as a submodel into the simulation model. In the following paragraphs, the simulation model and the optimization submodel are briefly described as the two components of the developed model.

Simulation model: A visual representation of the scope and main structure of the simulation model is shown in Figure 1. As seen from the figure, the simulation model is composed of four basic entities - the government, the car manufacturers, the consumers, and the energy providers. The development of the model is based on the relations and interactions among the four basic entities. For instance, the government is connected to the car manufacturers with Regulation (EC) No 443/2009 and super-credits. When the government sets tight emissions standards, the car manufacturers can respond the government's regulation in two ways. First, they improve the average fuel efficiency of the car fleet by improving the fuel efficiency of internal combustion engines and launching electric vehicles; second, if they exceed the CO_2 emissions allowance set by the government, they pay the excess emissions fees (especially when it is less costly than the cost of improving the fuel efficiency of the car fleet). In a similar way, through purchase incentives and energy tax, the government is also connected to the consumers and the energy providers, respectively. While the purchase incentives reduce the electric vehicle prices that consumers face, the energy tax increases the operating costs of conventional vehicles. Inside the model, to make a prediction for the consumers' preferences (i.e., purchase decision), a discrete choice model developed by Achtnicht et al. (2009) that focuses on the German car market is utilized. The utilized discrete choice model is based on various attributes such as vehicle price, energy price, availability of charging stations, etc. affecting the purchase decisions of consumers. Depending on the changes in market conditions, the consumers make their purchase decisions, and the system output is cumulated as a cost or benefit from the triple bottom line perspective (i.e., economic, environmental and social). In the model, the overall objective of the government is considered as to create a balance in the distribution of the costs or benefits among the remaining three entities.

Optimization submodel: The reaction of the car manufacturers to the government's regulation is a complex decision. For this reason, to imitate the strategic decision making process of the car manufacturers, an optimization submodel is developed with an objective of cost minimization, and embedded into the simulation model. The parameter set and formulation of the optimization submodel is provided as the following:

t	:	Time in years ($1 \leq t \leq T$)
i	:	Fuel type ($1 \leq i \leq I$)
j	:	Vehicle type ($1 \leq j \leq J$)
e_{ij}^t	:	CO_2 emissions per km
l_{ij}^t	:	Lower limit for CO_2 emissions per km
u_{ij}^t	:	Upper limit for CO_2 emissions per km
Imp_{ij}^t	:	Amount of fuel efficiency improvement (g/km)
F_{emi}^t	:	Average CO_2 fleet emissions

A_{emi}^t	:	Allowance for average CO_2 fleet emissions
T_{emi}^t	:	CO_2 emissions tax
q_{ij}^t	:	Number of vehicles sold
SC_{ij}^t	:	Super-credits
C_{emi}^t	:	Total cost of excess emissions
C_{Imp}^t	:	Total cost of fuel efficiency improvement
$f_{ij}^t(Imp_{ij}^t)$	:	Fuel efficiency improvement cost function

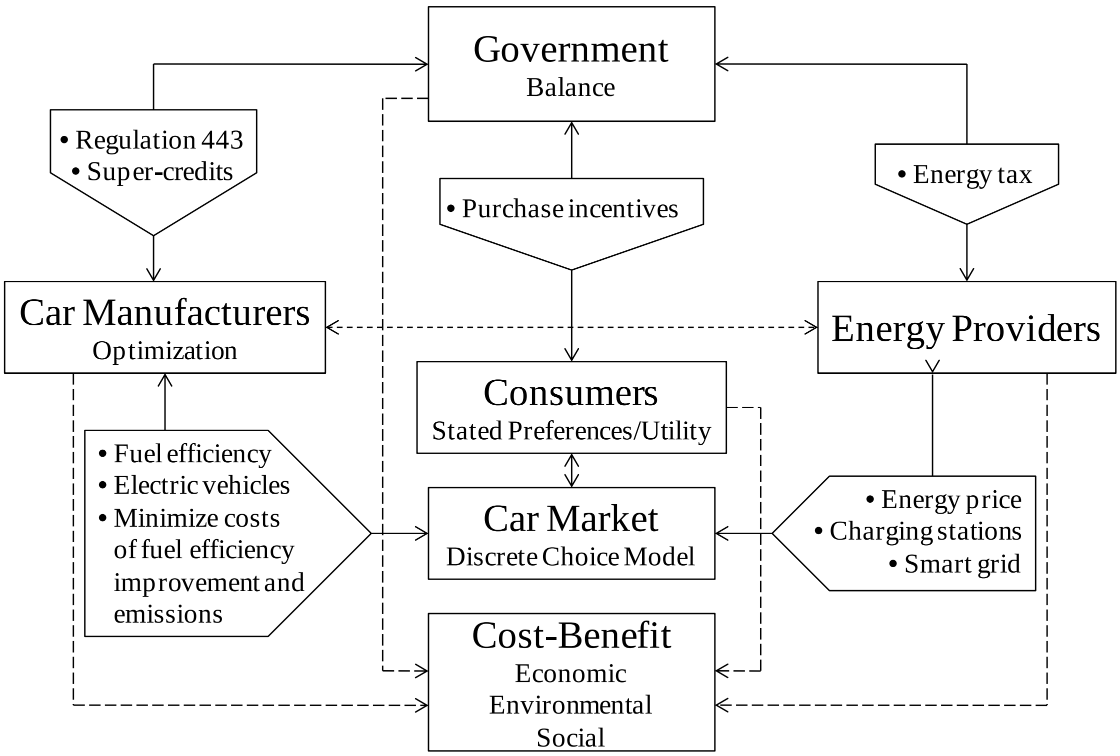

Figure 1: Simulation model diagram

To provide a clear description of the optimization submodel, some of the model parameters are presented in a tabular format in Figure 2. While the rows of the table represent fuel type (i), the columns represent vehicle type (j). For each cell, four parameters are defined, namely CO_2 emissions per km (e_{ij}^t), amount of fuel efficiency improvement (Imp_{ij}^t), super-credits (SC_{ij}^t), and fuel efficiency improvement cost function ($f_{ij}^t(Imp_{ij}^t)$).

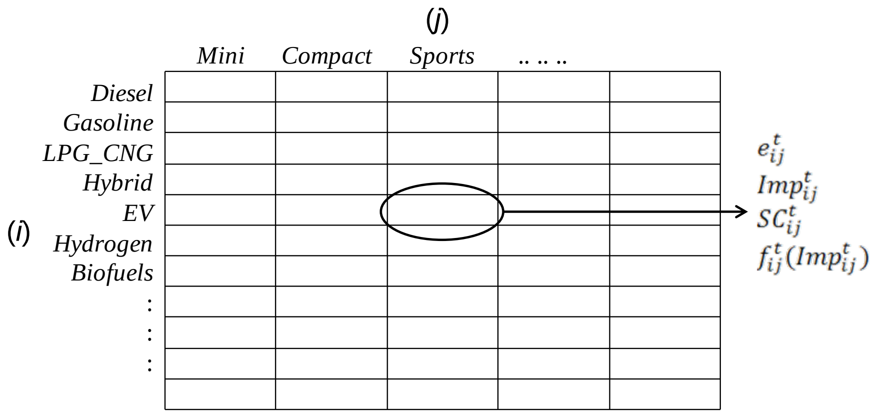

Figure 2: Some of the model parameters in tabular format

Equations (1), (2), (3), (4) and (5) provide the formulation of the optimization submodel. As provided in the formulation, it is considered that the car manufacturers have two main cost items - the cost of excess emissions (C_{emi}^t) and the cost of improving the fuel efficiency of conventional vehicles (C_{Imp}^t), and the objective of the optimization submodel is set to minimization of the total cost. In the cost minimization process, the amounts of fuel efficiency improvement for different fuel types and vehicles types (Imp_{ij}^t) are considered to be the decision variables whose optimal values are looked for.

$$\text{Min } Z = C_{emi}^t + C_{Imp}^t \quad (1)$$

s.t.

$$F_{emi}^t = \sum_i^I \sum_j^J \left[q_{ij}^t \times \left(e_{ij}^t - Imp_{ij}^t\right)\right] / \sum_i^I \sum_j^J \left(SC_{ij}^t \times q_{ij}^t\right) \quad (2)$$

$$l_{ij}^t \leq Imp_{ij}^t \leq u_{ij}^t \quad (3)$$

where

$$C_{emi}^t = [(F_{emi}^t - A_{emi}^t) \times T_{emi}^t] \times \sum_i^I \sum_j^J q_{ij}^t \quad (4)$$

and

$$C_{Imp}^t = \sum_i^I \sum_j^J \left[f_{ij}^t(Imp_{ij}^t) \times q_{ij}^t\right] \quad (5)$$

5. Assumptions and Policy Scenarios

Before running the developed model, several assumptions and simplifications are made. First of all, for the fuel types, seven categories are considered, namely gasoline, diesel, LPG/CNG, hybrid, electric, hydrogen and biofuel. Among these seven categories, it is assumed that the fuel efficiency improvement is possible only for the fuel types of gasoline, diesel, LPG/CNG and hybrid. And, the cost function for the fuel efficiency improvement ($f_{ij}^t(Imp_{ij}^t)$) is assumed to be convex and increasing in the fuel efficiency improvement amount (Imp_{ij}^t). In addition to that, it is assumed that the car manufacturers reflect the costs of emissions and the fuel efficiency improvement to the consumers by increasing their vehicle prices. As the main objective of this research is to analyze the impacts of the given policy instruments, for simplicity, the vehicle sales in different segments (mini, compact, sports, etc.) are not tracked in the model. Finally, since there is no significant fluctuation in the sales of light-duty vehicles in Germany, a constant demand is assumed with a total sales of 317,500 vehicles per month.

Under the given assumptions and simplifications, the model is run for five different policy scenarios whose details are provided in Table 1. Policy scenario 1 represents the base case scenario where there is no regulation and the CO_2 allowance is set to a value which is higher than the current average fleet emissions of German car manufacturers. In policy scenario 2, CO_2 allowance is set to 95 g/km from 2020 and the super-credits are applied as described in Section 2. Policy scenario 3 is similar to policy scenario 2 with a CO_2 allowance of 95 g/km from 2020; however, it does not involve the super-credits. Policy scenario 4 has a CO_2 allowance of 95 g/km from 2020 with the super-credits; but different than policy scenario 2 it provides a subsidy of €8,000 for the first 2,250,000 electric vehicles sold as a purchase incentive for the consumers. Finally, policy scenario 5 is designed similar to policy scenario 4; but in addition to the policy instruments considered in policy scenario 4, it involves some extra energy tax on gasoline and diesel such that with this scenario, the energy tax is increased from €0.6545 per liter to €0.7545 per liter for gasoline and from €0.4704 per liter to €0.5704 per liter for diesel.

6. Model Results

Under the assumptions and simplifications specified in the previous section, the model is run until 2025, and the total number of electric vehicles sold, CO_2 emissions and the costs of car manufacturers are tracked. The model results are presented in Table 2. As mentioned before, the primary objective of Regulation (EC) No 443/2009 is to reduce the CO_2 emissions from light-duty vehicles by setting certain emissions standards for the car manufacturers. In that sense, it is not a direct incentive for the consumers to encourage them to purchase electric vehicles, and hence does not provide a significant amount of increase on the sales of electric vehicles as seen in Table 2. Setting tight emissions standards ends up with some reduction in CO_2 emissions; however, it creates a high amount of cost on the car manufacturers. For instance, when the policy scenario 2 is selected instead of policy scenario 1, the cumulative cost of CO_2 emissions for the car manufacturers increases from €273,692,640 to €12,791,392,256, and similarly, the cumulative cost of fuel efficiency improvement increases from €121,940,240 to €18,626,011,136. Even though Regulation (EC) No 443/2009 has a direct impact on the car manufacturers compelling them to reduce their CO_2 emissions and the excess emission fees collected from the car manufacturers creates a considerable amount of revenue for the government, the regulation has an indirect impact on the consumers when the car manufacturers reflect their increasing costs to the consumers by increasing their vehicle prices with the aim of keeping their profits at the same level.

Table 1: Policy scenarios

<table>
<tr><th rowspan="2">Policy Scenarios</th><th colspan="2">Policy Instruments on Car Manufacturers</th><th>Policy Instruments on Consumers</th><th colspan="2">Policy Instruments on Energy Providers</th></tr>
<tr><th>CO_2 Allowance (g/km)</th><th>Super-credits</th><th>Purchase Incentive for EVs (EUR)</th><th>Gasoline Fuel Tax (EUR/liter)</th><th>Diesel Fuel Tax (EUR/liter)</th></tr>
<tr><td>1</td><td>170 g/km from 2020</td><td>Without</td><td>0</td><td>No extra tax (0.6545)</td><td>No extra tax (0.4704)</td></tr>
<tr><td>2</td><td>95 g/km from 2020</td><td>With</td><td>0</td><td>No extra tax (0.6545)</td><td>No extra tax (0.4704)</td></tr>
<tr><td>3</td><td>95 g/km from 2020</td><td>Without</td><td>0</td><td>No extra tax (0.6545)</td><td>No extra tax (0.4704)</td></tr>
<tr><td>4</td><td rowspan="2">95 g/km from 2020</td><td rowspan="2">With</td><td rowspan="2">8,000 for the the first 2,250,000 EVs sold</td><td>No extra tax (0.6545)</td><td>No extra tax (0.4704)</td></tr>
<tr><td>5</td><td>Extra tax (0.7545)</td><td>Extra tax (0.5704)</td></tr>
</table>

Table 2: Results under different policy scenarios

Policy Scenarios	Number of EVs by 2025	Cumulative CO_2 Emissions by 2025 (tonnes)	Cumulative Fuel Efficiency Improvement Cost by 2025 (EUR)	Cumulative CO_2 Emissions Cost by 2025 (EUR)	Cumulative Total Cost by 2025 (EUR)
1	1,451,896	1,798,606,208	121,940,240	273,692,640	395,632,896
2	1,493,475	1,665,398,528	18,626,011,136	12,791,392,256	31,417,405,440
3	1,537,183	1,652,734,208	21,096,486,912	26,330,413,056	47,426,895,872
4	2,325,583	1,655,035,008	17,858,357,248	7,606,248,960	25,464,606,720
5	2,384,281	1,652,785,920	17,639,155,712	7,688,781,824	25,327,939,584

Super-credits play a critical role in the application of Regulation (EC) No 443/2009. At a first glance, it might be expected that the super-credits will encourage the car manufacturers to produce more electric vehicles by assigning extra credits to the vehicles whose emissions are less than 50 g/km. However, they have a reverse effect such that while calculating the average fleet emissions, counting the electric vehicles more than one car enables the car manufacturers to achieve target emissions levels by producing less number of electric vehicles. Essentially, super-credits phase Regulation (EC) No 443/2009 between 2012 and 2016 by loosening the tight standards of the regulation. In that sense, they provide a smooth transition to tight emissions standards between the given years resulting with a reduction in the costs of car manufacturers and slow down in the market diffusion of electric vehicles as observed in Table 2 when the results of policy scenario 2 and policy scenario 3 are compared.

Providing purchase incentives creates a significant increase in the sales of electric vehicles as seen from the results of policy scenario 4 and policy scenario 5. It makes the electric vehicles more affordable and hence encourages the consumers to purchase electric vehicles instead of conventional ones. However, since it is a costly policy instrument for the government, it has limitations and its impact would potentially be temporary.
The energy tax on gasoline and diesel has an impact on the operating costs of vehicles. Higher energy taxes cause the consumers to prefer electric vehicles as they increase the operating costs of conventional ones. For this reason, even though policy scenario 5 is similar to policy scenario 4, as a result of the extra energy tax on gasoline and diesel, it provides a higher electric vehicle penetration into the car market.

7. Policy Recommendations

An ideal policy scenario to achieve the target CO_2 emissions from light-duty vehicles would be the one that will facilitate the market penetration of electric vehicles with minimum or no cost to the involved entities (i.e., government, car manufacturers, consumers and energy providers). In that sense, while setting effective policy instruments to reduce the CO_2 emissions, it is important to minimize their side effects by using other complementary policy instruments. For instance, with the current state of Regulation (EC) No 443/2009, it might be possible to reach low emissions levels by setting tight standards. However, as the regulation gets tighter, the amount of cost on the car manufacturers increases tremendously. As explained before, as a reaction of increasing costs, to keep their profitability, the car manufacturers will potentially respond this regulation by increasing their vehicle prices. To offset this side effect, the government may adopt a push-pull strategy. With such a strategy, the government can push the car manufacturers to a technology shift by setting tight emissions standards and at the same time pull the consumers to the new technology (i.e., the electric vehicles) by giving the collected emissions fees to the consumers as purchase incentives.

As it is seen in Table 2, increasing the energy tax on gasoline and diesel ends up with higher electric vehicle sales. However, most of the time, it is unlikely to make a change at the current levels of the energy tax due to political reasons. For this reason, keeping the energy tax on gasoline and diesel at their current levels would be a more realistic approach in this case.

Finally, the electric vehicles are emissions-free vehicles as long as they are charged with the electricity generated from renewable energy resources. Hence, in order to obtain effective results in terms of CO_2 emissions, recommended regulations should be supported with the policy instruments that will encourage the energy providers to go with renewable energy resources.

8. Verification, Validation and Limitations

Verification and validation of a decision model is a challenging process, and most of the time, it is difficult to fully validate a theoretical model. However, in general, while verification involves the correct implementation of a theoretical model in the computer environment, validation answers the question of whether the model is an accurate representation of the real system. In this case, to verify that the developed model produces reasonable results, the model is run and tested under the base case scenario (policy scenario 1) for a variety of settings of the input parameters. On the other hand, to validate the model, the results obtained with the model are compared with the results of other models found in the literature, and the model is calibrated as needed. In addition to that, collaboration with other researchers, policy makers and corporate managers working in the automotive industry also provides a noteworthy reference and can be a considered as a form of face validity.

Even though the developed model is verified and validated to some degree, it has two major limitations. First, running an optimization submodel in a simulation model is a costly process and takes time. Particularly, as the size of optimization submodel increases, the solution time increases tremendously. To deal with this limitation, the model is designed to focus on the strategic decision making process of car manufacturers instead of focusing on their tactical or operational decisions. And, by assuming that strategic decisions are typically made annually, the optimization submodel is run once per year throughout the planning horizon while taking the model runs.

Another limitation of the model is its complexity. Since the model provides a system approach, in theory, it is possible to analyze the automotive industry at a very detailed level by considering all the entities and interactions in the industry. However, it is obvious that this will create a high amount of computational burden. For this reason, to determine which parameters are important and which interactions should be kept in the model, several sensitivity analyses are performed, and the results of these analyses are evaluated by considering the Pareto Rule (roughly 80% of the effects come from 20% of the causes).

9. Conclusions and Future Work

To mitigate the CO_2 emissions from light-duty vehicles and achieve the target emissions set by the European Union, German Federal government plans to implement a set of new regulations including Regulation (EC) No 443/2009, super-credits, electric vehicle purchase incentives, and energy tax. This paper provides an analysis of these regulations by developing a decision model that can be used by policy makers and the corporate managers working in the automotive industry. As an output of the analysis, the paper presents a general insight about the nature of new regulatory framework and provide basic recommendations based on the model results.

Different than the previous modeling approaches, the model developed in this research is designed as a hybrid decision model, and makes use of the simulation and optimizations techniques simultaneously. By providing one of the first hybrid models that analyze the automotive industry, it makes a significant methodological contribution to the literature. In addition to the methodological contribution, the presented research also makes a remarkable contribution to the literature as content. While previous studies focus on the U.S. car market and CAFE, this study focuses on the German car market and the European regulatory framework considering Regulation (EC) No 443/2009 together with the other policy instruments - super-credits, electric vehicle purchase incentives, and energy tax. Further, the study extends previous studies by providing an analysis of the industry for a wider range of alternative transport technologies, namely diesel, gasoline, LPG-CNG, hybrid, electric, hydrogen and biofuel.

The research presented in this paper can be extended in several ways by considering the perspectives of the entities in the developed model. When the government's and policy makers' perspective is considered, it is possible to continue the scenario analysis by running the model under different levels and combinations of the given policy instruments. When the car manufacturers' perspective becomes the main focus, in addition to tracking the overall sales of electric vehicles, it is possible to split the electric vehicle sales into segments such as mini, compact, sports, etc. and provide more detailed results. Besides, an optimization submodel maximizing the profits of car manufacturers can be embedded into the simulation model instead of an optimization submodel minimizing the costs of car manufacturers. However, this may require some market data such as the demand/price elasticity of electric vehicles. In addition to them, since the developed model provides a system approach, the car manufacturers are considered as a whole and analyzed at the industry level in the model. As an extension, in the future, the car manufacturers can be analyzed at the firm level, and the emissions trading option can be integrated into the model. Finally, when the emphasis is given to the energy providers and consumers, it would be interesting to analyze the impacts of investing in charging stations and smart grid applications, and the consumer characteristics (urban vs. rural, or individual vs. corporate) to the market diffusion of electric vehicles.

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