DYNAMIC DEMAND MODELING OF FREIGHT FLEETS

Keywords: *freight transport, demand modeling, dynamic demand, fleet modeling*

Abstract (167 words):

Freight traffic and functioning logistic systems are basic prerequisites for a successful economy. The combination of behavioral changes towards online shopping and the resulting need for high delivery flexibility will lead to a growing demand of light duty vehicles (LDV). Despite already existing models which predict the size of the LDV fleet based on a given transport demand, a dynamic connection between transport demand and vehicle fleet has not yet been realized. A distribution of annual mileages from LDVs, which have a wide range, leads to the assumption that fleet operators could adapt their mileage within set limits. This dynamic mileage adaptation is expressed as a module, which can then be integrated into existing fleet models. The results show that the number of LDVs needed to satisfy the demand is less volatile compared to the use of constant annual mileage. The results can certainly be seen as one step to more realistic fleet forecasting, yet further research in the field of fleet operator behavior would be beneficial.

1 INTRODUCTION

In today's globalized world freight traffic and functioning logistics systems can be described as the essential backbone of a growing economy. The main task of these systems is to support the flow of materials within and between companies to guarantee trouble-free production and shorter downtimes. Over the course of the past few decades, global production sites and robust global logistic networks, which have a high degree of flexibility to proactively react to the necessary requirements, have become state of the art. Hence, the global production industry is characterized by its dependency on a high level logistic system with flexible fleets (Günther/Tempelmeier 2012).

Costumer behavior changes and the need for transport services, as a result of global production, will lead to an increase in transport demand for freight services. Cheap production costs in China, combined with a growing demand for cheap electronic products, have stimulated an increase in the flow of materials. In addition to this, shopping behaviors have changed in recent years. Consumers, especially those of the younger generations, primarily do their shopping online rather than frequenting shopping malls. Taking together into consideration these two effects, globalization on the one hand and changes to consumer purchasing behaviors on the other, an increase in future transport demand in parts of the sector is therefore a reasonable prediction.

The freight transport sector itself can be divided by different traffic modes. In addition to the road and rail sectors providing services on land, intercontinental material flows are mostly operated by marine and/or air transport services. The majority of freight is carried by trucks or light duty vehicles (LDV) (EUROPEAN COMMISSION 2012), due to the greater degree of flexibility provided through road traffic. In countries such as Germany, where business to customer distances are rather short, the share of road traffic increases (see *figure 1*). In combination with the behavioral changes towards online shopping and the resulting need for high delivery flexibility, the demand for road freight traffic will increase in the future.

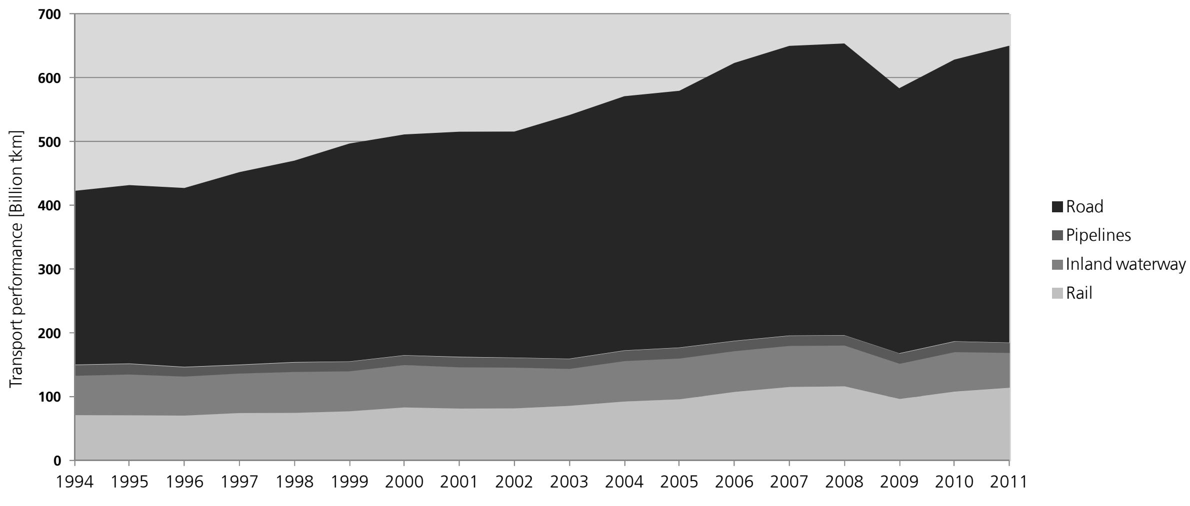

Figure 1: Development of the Transport performance by mode in Germany (DIW 2013)

Increasing transport demand leads to an increase in the number of vehicles needed for freight service. As the White Paper by the European Commission clearly states, resource efficiency and the reduction of greenhouse gas emissions is to be one of the major targets of future transport (EUROPEAN COMMISSION 2011). Therefore, the development of vehicle fleets is a field of great interest to both the public and politicians alike.

Most models that are used to predict transport performance and fleet development assume an inelastic connection between transport demand and the size of the fleet (e.g. ASTRA; Schade 2004). Initially, this assumption seems to be plausible. Taking a closer look at past statistics, as shown in *figure 2*, fleet development is not directly related to changes in transport performance. In particular times of crises, such as within 2009 and 2010, the rate of change could differ by a large margin (DIW 2013, KBA 2012).

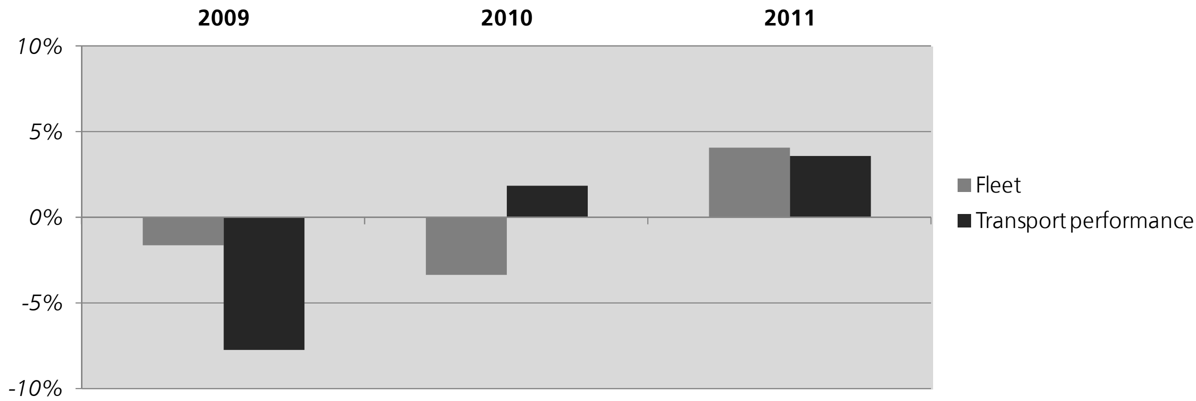

Figure 2: changes in fleet (traction units) and transport performance (DIW 2013, KBA 2012)

As a first step to dynamic fleet modeling, this paper tries to expand upon existing models that focus on an inelastic connection between transport demand and fleet development, by integrating a dynamic adaptation of the annual mileage driven by the vehicles. Therefore, the base assumption is that the freight carrier attempts to match the transport demand by optimizing the use of the already existing fleet.

To be able to achieve a realistic modeling concept, the freight carrier market has to be analyzed in order to assess and describe the behavior of freight carriers. The next step is the integration and design of a module that will allow for the dynamic adaptation process of the annual mileage. Finally, the results of this simulation would be compared within a scenario analysis to assess the model quality and to compare the results with the general expectations.

2 FREIGHT CARRIER MARKET AND FLEET OPERATOR BEHAVIOR

The considered freight carrier market in Germany includes a wide set of different vehicle types and sizes (Blumensaat et al. 2007, Appel et al. 2008). The following paragraph deals with the light duty vehicles (LDV) which will be of high importance for the future freight sector.

In order to assess freight carrier behavior, information about the yearly use of LDVs is needed. Combining information about the annual mileage with the wide range of usage conveys the heterogeneity and diversity of the fleet.

Therefore, an average value of the annual mileage could not be used to describe the characteristics of the whole fleet. A first step to a closer understanding of the fleet composition was the creation of a sample of used LDV sales with a sample size of 3,000 (TruckScout24 2012). By using the first registration date of the LDVs in combination with the current mileage in kilometers, it is possible to calculate the average annual mileage. The result, as shown through a statistical distribution, can be seen below in *figure 3*.

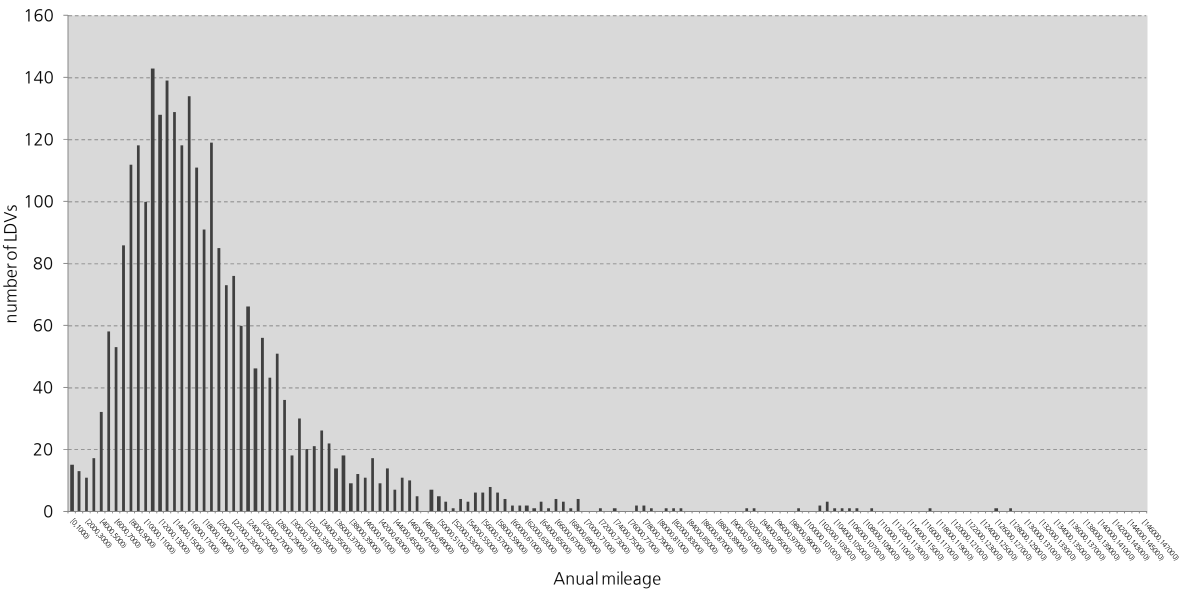

Figure 3: Distribution of annual mileages within the sample of the LDV fleet (TruckScout24 2012)

What is remarkable is the fact that the annual mileage differs considerably within the sample. On the one hand, there is a significant number of LDVs driving less than 10,000 km per year yet on the other hand, there are vehicles which have an annual mileage of more than 50,000 km. Lower annual mileages can be explained by craftsmen or small enterprises driving only short distances each day (mostly from the company to the construction site and back). High annual mileages can be explained through the market of express services doing longer distances on a daily basis. LDVs that are driving between 12,000 km and 20,000 km a year (DHL 2012) are typically the parcel delivery services operated by UPS, DHL, etc. Taking these factors into consideration, the variety of usage as well as the different mileages, makes it considerably more difficult to generalize the fleet. Nevertheless, a certain generalization is needed for the modeling process with the conflict being between the claims of a realistic model and a model that is easy to handle.

The generalization needed for the modeling process is given by the statistical description of the annual mileage distribution. *Figure 4* shows the carried out box plot with the key figures of the distribution.

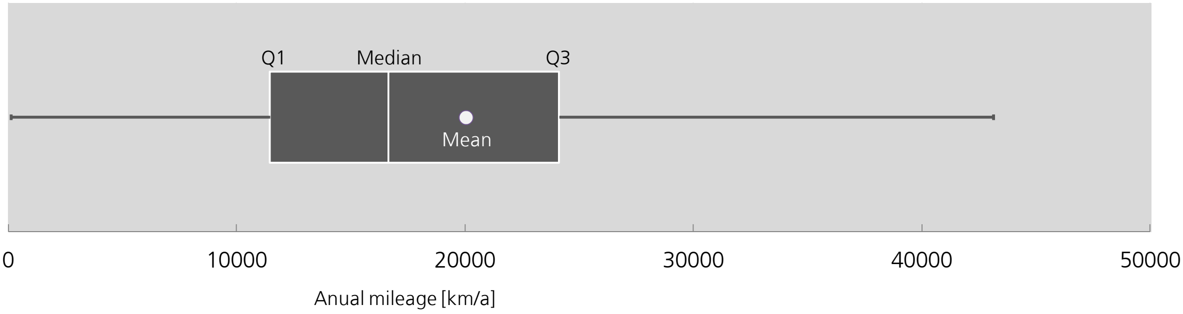

Figure 4: Box plot of the annual mileage distribution

The median that divides the distribution into two equal parts of 50% lies at 16,646 km, which is just below the mean with 20,024 km. The first quartile at 11,429 km and the third quartile at 24,108 km limit the box plot. As the distribution appears to be skewed to the right, the median could be a better description of the average.

Based on these values, generalized modeling with the aim of incorporating dynamic mileage variations can be done. This leads to the question of whether or not the freight carriers could vary the driven kilometers. All freight carries act in an economic and practical framework which allows for only slight dynamic adaptations to changing conditions.

The reasons for this on the one hand, are the strict limitations of working time which allow only a small increase of vehicle use in respect to the daily working time. On the other hand, the framework of the daily logistic business restricts the vehicle use due to determined loading time slots, customer needs, and given logistic networks with specific transport distances (Bretzke/Barkawi 2012). Rising transport costs (Wittenbrink 2009, p.33; Fiedler 2007, p.74), as well as pressure for efficiency within the freight transport sector, leads to the assumption that the vehicle use is already optimized today (Göpfert 2012). Hence, the possibility to adapt the vehicle usage to changing transport demand seems to be limited within certain borders.

Taking into account the annual mileage distribution and incorporating into a modeling concept the knowledge regarding fleet operator behavior, the major question that arises is how a possible adaptation process could be mathematically described. It appears that the possibility to adapt the mileage declines the more the current mileage deviates from the median. At the moment, there is little evidence for the development of the capability for adaptation, and thus, assumptions have to be made.

For further information regarding the adaptation function, please refer to the following section which examines the model in greater detail.

3 METHODOLOGY AND MODEL DESCRIPTION

This part of the paper is going to show how the dynamic mileage adaptation was realized in a system dynamics model. As the module can be seen as an extention of the already existing fleet model, both parts are described below with a focus on the dynamic adaptation part.

Using system dynamics as a modeling framework enables the simulation of feedback loops to create a model which is both realistic and possible. Furthermore, the system dynamic modeling is not based on the equilibrium theory of the classic economic approach. Hence, there are hardly any limits in the modeling process, which can also be seen as one of the challenges. One of the main reasons why the system dynamics approach was used in this model is on the one hand the easily creatable connection to already existing modules of the ASTRA (SCHADE 2004) model and on the other hand the possible enlargement to create a more realistic model. This can be optimized and expanded as soon as there is more information about the annual mileage distribution.

The following paragraph gives a short overview of the whole model as well as a detailed description of the two modules including the use of the system dynamics methodology. The two modules and their interactions, as realized in the model, are illustrated in *figure 5*.

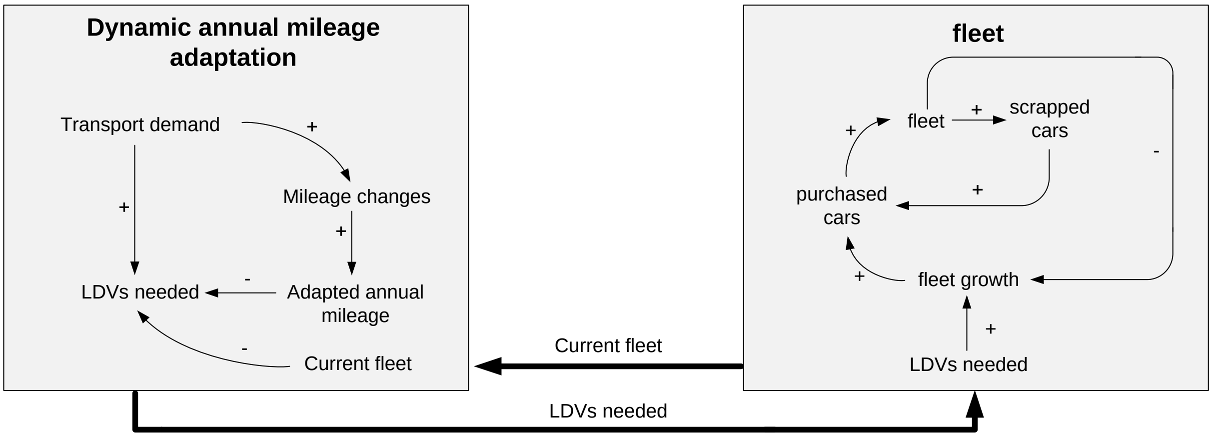

Figure 5: Model structure, interaction of the two modules

The fleet module calculates the fleet growth based on the LDVs needed compared to the current fleet. The current fleet itself influences on the number of needed LDVs by multiplying with the adapted annual mileage to get the current transport offer. Without the annual mileage adaptation the number of needed LDVs to satisfy the transport demand is calculated based on a constant average annual mileage. Therefore, there is a direct correlation between this variable and the changes to transport demand.

The fleet module

The fleet module is the core aspect of the whole model. The structure displayed in *figure 6* shows the functionality of the module. The number of LDVs is represented by a stock variable which is increased by new purchased LDVs and reduced by the number of LDVs that are not in circulation any longer. Besides the calculation of the total number of LDVs currently in use, the age distribution of the fleet can be illustrated by one-year age cohorts. Thus, fleet composition according to emission standards can be easily identified. The number of new LDVs needed to satisfy the transport demand and the derived fleet growth determine the number of purchased LDVs. Fleet growth is determined via the comparison of the existing fleet with the need for LDVs, a value that is based on transport demand.

In case of a shrinking transport demand and thus a negative difference between LDVs needed and the existing fleet, only a certain percentage of the scrapped vehicles will be replaced.

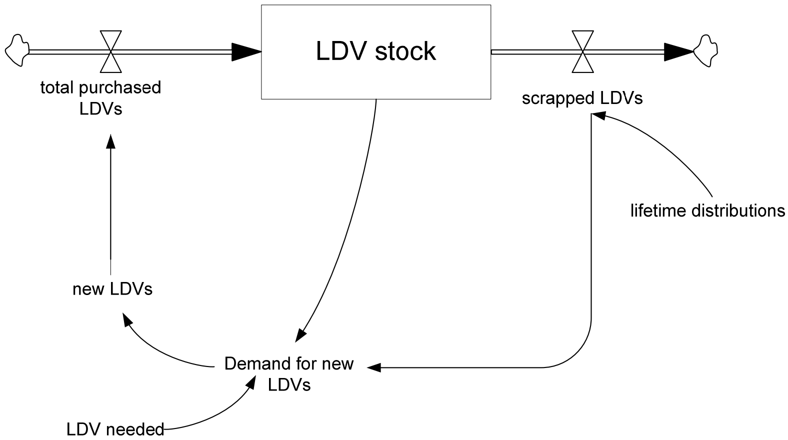

Figure 6: The fleet module

At the moment, the number of the needed LDVs is calculated based on the transport demand divided by a constant annual mileage, which leads to a very volatile fleet growth. As a first step, the fleet module was extended and coupled with the following dynamic mileage adaptation module.

The dynamic mileage adaptation

In order to reflect the dynamic behavior of fleet operators described in section 2, a dynamic annual mileage used in the fleet module seems to be more realistic. The dynamic mileage adaptation (see *figure 7*) can be seen as a first step towards a dynamic connection between fleet growth, i.e. transport offer, and transport demand.

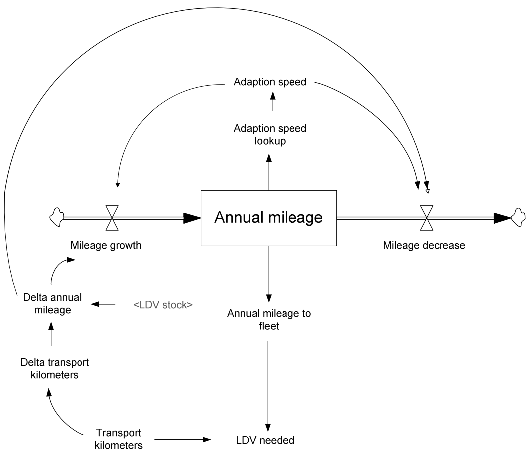

Figure 7: dynamic mileage adaptation

Based on the transport demand, the yearly delta transport demand can be calculated. This indicator influences on the delta annual mileage which will be needed to satisfy the transport demand with the current fleet. Depending on the value of the delta annual mileage, the current mileage will increase or decrease in order to adapt the present fleet on the changing circumstances. The dynamic of the adaptation is specified in the variable *adaptation speed lookup* which is determined by the chosen scenario (see section 3). After that, the annual mileage changes can be calculated. These calculations are based on the behavior change of the freight carrier and the resulting number of needed LDVs.

The major challenge of this module is represented by the adaptation speed, which influences the adaptation rate significantly. As already mentioned, the distribution of the annual mileage differs considerably. As a realistic starting point, the median of this distribution is regarded as the best fitting value. The major question is how the freight carriers could change the annual mileage in order to adapt different developments of transport demand. The baseline idea was that the capability to adapt declines as the distance to the median increases. One first assumption was that due to framework restrictions, an adaptation is only possible between the first and third quartile. Taking into account that the restrictions for most freight carriers could be the limiting factor, it seems to be more likely that fleet operator would lower their mileage only down to the average value between median and first quartile. Below this threshold value freight service could be unprofitable, thus the adaptation rate will drop to zero and the annual mileage will not change anymore.

$$A(x) = \begin{cases} 0 & \text{if, } p(x) < (q_1 + m)/2 \\ 0.00038 * x - 5.38 & \text{if, } (q_1 + m)/2 \leq p(x) < m \\ 1 & \text{if, } p(x) = m \\ -0.00027 * x + 1.45 & \text{if, } m < p(x) \leq (q_3 + m)/2 \\ 0 & \text{if, } p(x) > (q_3 + m)/2 \end{cases}$$

where

$A(x)$ = adaptation speed function
$p(x)$ = mileage distribution
q_n = n- Quartile
m = median

Equation 1: Adaptation speed function

The mean value of this distribution was used as the upper limit to take respect to the fact, that there will be a few freight carriers which are able to vary the annual mileage up to relatively high values. *Equation 1* shows the complete adaptation rate function as a discontinuous defined function which drops to zero below and above the defined limits. As a curve form a linear relationship was chosen, knowing well, that other relationships could also be possible.

To summarize: A given transport demand in the form of vehicle kilometres as a major input will be used to calculate the needed annual mileage in order to satisfy this demand by the current fleet. The annual mileage realized in the model as a stock variable is able to vary within set limits. The flexibility of the adaptation process is stronger, the closer the needed mileage is to the median. In case the transport demand is not matched by the adaptation process, the number of needed vehicles will change. This value will then be used as an input to the actual fleet module.

4 ANALYSIS AND RESULTS

The developed module described above offers the possibility to simulate different scenarios in regards to the adaptation process. Besides the limited adaptation process discussed in detail in section 3, two other scenarios are considered. The results of the following scenarios will be analyzed concerning their influence on LDV fleet growth.

Scenario 1: constant mileage
Scenario 1 is based on the general assumption that the demand for LDVs can be calculated by dividing transport demand (vehicle - km) by a constant annual mileage. This scenario does not allow any dynamic mileage variation. The connection between transport demand and transport offer is completely inelastic.

Scenario 2: dynamic adaptation
The second scenario allows a dynamic adaptation of the annual mileage taking into account the fact that freight carriers change their behavior. Within this scenario the dynamic adaptation process is unlimited hence the freight carriers are able to change their annual mileage from zero to infinite.

Scenario 3: limited adaptation
The base for scenario 3 is the limited adaptation process of the annual mileage discussed into detail in this paper. Constraint variations of the freight carriers lead to a limited adaptation of the annual mileage within certain borders.

The results for the development of the annual mileage, as detailed in *figure 8*, show how the three scenarios differ. A complete dynamic adaptation of the annual mileage (scenario 1) leads to very volatile changes of the values in order to match the transport demand. The limited dynamic adaptation (scenario 3) as described in section 3 follows the development of the transport demand only within certain limits (between 2020 and 2021). Above those limits, the framework restrictions lower the capability of adaptation to zero.

Another important aspect is the difference in adaptation speed, which can be seen in the early development (2003 till 2004). According to less dynamic adaptation due to higher variations from the median, the changes of the annual mileage remain on a lower level than in scenario 2.

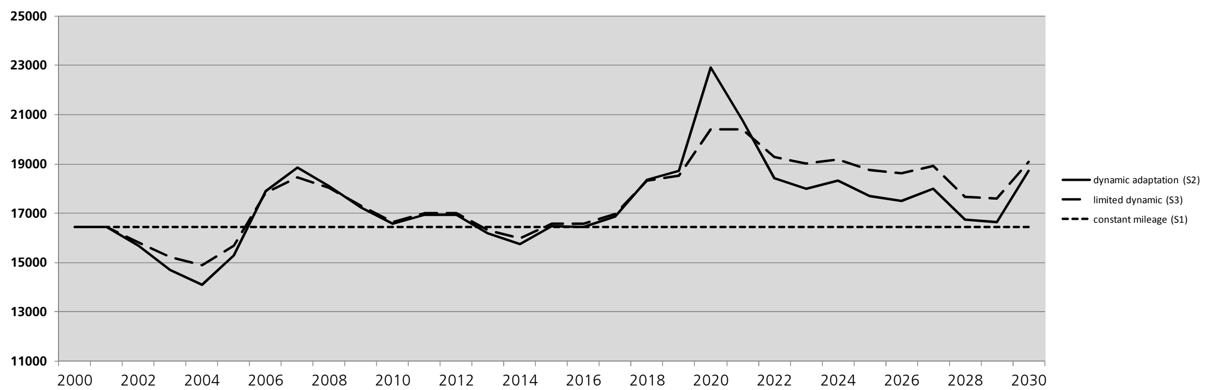

Figure 8: development of the annual mileage

The first scenario with its non-dynamic development of the annual mileage leads to constant values remaining on the same level during the whole observation period. As a whole, the

dynamic adaptation of the annual mileage, depending on the degree of limitation, allows for a variable adjustment of the fleet usage to the transport demand.
The second part of the results is formed by the implication of the mileage adaptation on the actual number of LDVs needed to satisfy the transport demand. The completely inelastic connection between transport demand and the number of LDVs needed explains the shape of the curve of scenario 1 (see *figure 9*), which is as volatile as the transport demand itself.

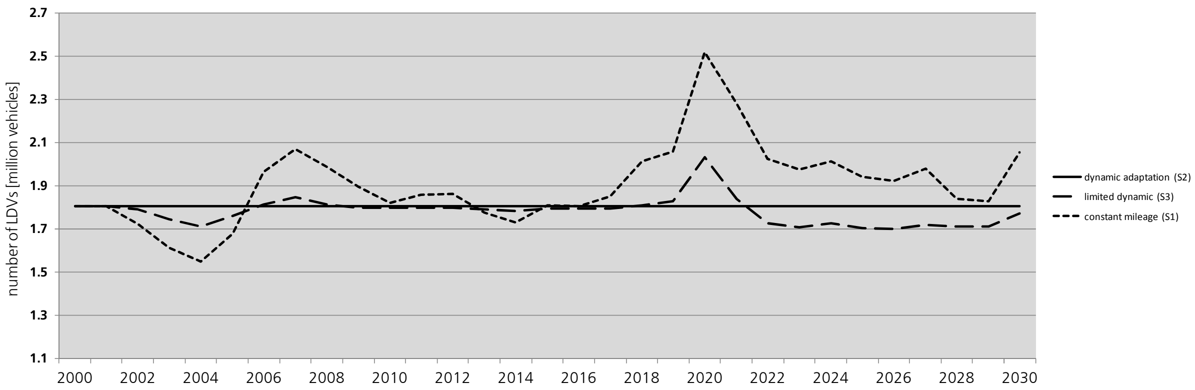

Figure 9: development of the number of needed LDV

With the complete dynamic adaptation from scenario 2, the number of needed LDVs remains stable on the same level as the mileage varies according to the transport demand. Thus, the fleet size will remain the same as the operators could adapt the mileage to satisfy different levels of transport demand. The delayed and only partly dynamic mileage adaptation of scenario 3 leads to a curve basically oriented on the results of scenario 2. The lower adaptation speed induces a less volatile number of LDVs needed. Another effect is that in case of increasing annual mileage, the lower adaptation speed implies that the mileage will remain on a high level. Therefore, the number of LDVs needed drops below the value of scenario 2.

The modelling results of this first step to dynamic annual mileage variation show that, depending on the degree of dynamic adaptation, the results differ quite a lot. The most realistic approach, the limited adaptation (scenario 3) leads to results which are significantly less volatile than the ones with constant mileage (scenario 1). Nevertheless, there is a need for improvement concerning the description of the adaptation speed. A more detailed model, taking different types of usage into account, could lead to results closer to reality. Moreover, detailed research on the field of mileage adaptation is needed.

5 CONCLUSION

The main objective of this paper is the system based analysis of a dynamic annual mileage adaptation of light duty vehicles (LDV). The theoretical basis for this is a distribution of annual mileages from used LDVs as well as the current system based fleet models. The major aim is to improve existing fleet models which include only inelastic connections between demand and offer.

Both simulation and analysis are based on a model using the system dynamics software VENSIM as a foundation/basis. The main advantages of this approach are the dynamic and mostly unlimited possibilities to model coherencies which do not rely on equilibrium processes like most economic models. Dynamic adaptation processes and feedback loops can be combined easily.

A sound statistical basis for the modeling activity is given by a distribution of annual mileages. This distribution is founded on a sample (n = 3,000) of used LDV sales. The results of the performed statistical analysis showed that the values vary within a wide range. Based on these results the question arose whether or not an adaptation of the annual mileage seems to be possible despite the framework restrictions of freight carriers. As a first step, a variation between the average of median and first quartile as well as the mean value are considered. The adaptation speed was introduced to describe the possibility of the freight carrier to react dynamically. Within the mentioned borders the adaptation speed drops linear from the factor one around the median down to zero.

The evidence obtained in the first part is transferred to a system dynamics model. Besides the already existing fleet model used in ASTRA, a new module is added and described in detail. This module contains a dynamic variation of the annual mileage, which includes the adaptation speed delineated above. A given transport demand defines the annual mileage needed to satisfy the demand with the current fleet. Based on this calculation, the freight carriers try to adapt their annual mileage. Due to the adaptation speed, which differs depending on the current mileage, changes in transport demand can only be partially compensated. The new amount of needed LDVs, which is not inelastically coupled to transport demand anymore, leads to fleet growth or decline in the fleet module.

The simulation results of the three scenarios show that the differences between inelastic coupled fleets and dynamic mileage adaptation are significant. While the fully dynamic adaptation of scenario 2 leads to a constant number of needed LDVs, the inelastic coupling with constant mileage in scenario 1 induces very volatile values for the demand of new LDVs. The limited adaptation of scenario 3 seems to project the freight operators behavior in the best way.

The described approach is closely related to the given sample of used LDVs. In order to improve the theoretical data base for the model, a bigger sample divided into different user groups (parcel services, craftsmen currier services ...) could lead to more realistic results. Another opportunity for improvement could be seen in detailed research on the field of the adaptation speed, which influences the behavior significantly.

Nevertheless, this model constitutes a major step towards realistic fleet modeling, including the opportunity to assess the effects of volatile economic framework conditions (e.g. crisis). The dynamic connection between transport demand and vehicle fleet allows on the one hand better fleet forecast and on the other hand more specific statements to future development of transport emissions.

6 REFERENCES

Appel W, Brähler H, Dahlhaus U, Esch T, Kopp S, Rhein B (2008): "Nutzfahrzeugtechnik", 5th edition, Vieweg+Teubner Verlag / GWV Fachverlage GmbH, Wiesbaden.

Blumensaat K, Paehr G (2007): "Dieselmotoren für leichte Nutzfahrzeuge", in: Mollenhauer H, Tschöke K (2007): "Handbuch Dieselmotoren", 3rd edition, Springer Verlag, Berlin, p. 578 – 585.

Bretzke W.-R., Barkawi, K. (2012): "Nachhaltige Logistik", Springer Vieweg, Berlin.

DHL (2012): http://www.dpfleet.de/fzv/fzbieterservlet?WCI=BFZ, last access: 11-13-2012

DIW (2013): "Verkehr in Zahlen", DVV Media Group, Hamburg.

European Commission (2011): "WHITE PAPER- Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system", Brussels.

European Commission (2012): "EU transport in figures - statistical pocketbook", Brussels.

Fiedler J (2007): "Fahrzeugkostenrechnung und Kalkulation", in: Lohre, D. (ed.) (2007): "Praxis des Controllings in Speditionen", Frankfurt p. 71-84.

Günther H.-O., Tempelmeier H.(2012): Produktion und Logistik, Springer Verlag, Heidelberg.

Göpfert I. (2012): "Logistik der Zukunft - Logistics for the future", Springer Gabler, Wiesbaden.

KBA - Kraftfahrtbundesamt (2012): Bestand an Lastkraftwagen in den Jahren 2003 bis 2012 nach zulässiger Gesamtmasse, http://www.kba.de/cln_033/nn_268962/DE/Statistik/Fahrzeuge/Bestand/Groessenklassen/b__groessenklassen__lkw__zeitreihe.html, last access: 12-18-2012

Schade W (2004): "Strategic Sustainability Analysis: concept and application for the assessment of the European Transport Policy", Dissertation thesis, Nomos Verlag, Baden-Baden.

TruckScout24 (2012): http://www.truckscout24.de/search/ger/home.asp?language=ger, last access: 11-13-2012

Wittenbrink P (2011): "Transportkostenmanagement im Straßengüterverkehr: Grundlagen - Optimierungspotentiale - Green Logistics". Springer Gabler, Wiesbaden.