APPLYING MONTE CARLO SIMULATION IN AN INDICATOR-BASED APPROACH TO EVALUATE FREIGHT TRANSPORTATION SCENARIOS

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ABSTRACT
Policymakers and decision makers are often unable to estimate the impacts and interdependencies of new transportation concepts. Methodological approaches do not include macroscopic ex-ante assessments of new technological and economic concepts. That is why a new method called the VLVI method has been developed at Otto von Guericke University and the Fraunhofer Institute for Factory Operation and Automation IFF in Magdeburg. Based on a large number of key performance indicators (KPI) that describe transportation infrastructures and their processes, the method maps various effects in and between freight transportation systems. The uncertainty of predictions is factored into the model by integrating Monte Carlo simulation. One comparative indicator with a confidence interval is calculated for every concept assessed with this method, thus specifying a concept's impact on the German transportation system.

Keywords: Monte Carlo simulation, decision support, indicator-based approach, freight transportation system

1. INTRODUCTION
An efficient freight transportation system is fundamental to a country's economic growth and prosperity (Daehre et al. 2012). Germany's location in Central Europe and German companies' substantial exports intensify this reliance (Schenk et al. 2014). According to the Logistics Performance Index (LPI), which shows the efficiency of logistics by a survey among leading logistics experts, Germany is ranked first in 2016 (Arvis et al. 2016). Regarding the infrastructure, however, Germany is only in the eighth place in the evaluation of the "infrastructure" pillar of the Global Competitiveness Index (GCI), tendency declining (Schwab and Sala-i-Martín 2016). This development was already shown by a federal and state commission established in 2012 that € 7.2 billion is lacking every year for the renewal infrastructure and deferred investments (Daehre 2012).
This makes it even more important to predict the impact of transportation policy decisions and technological innovations on the transportation system in advance (Holmgren et al. 2014). Yet expert's opinions on new concepts' impacts often diverge. For instance, the impact of the introduction of a special type of long combination vehicles (LCVs) on German roads is a topic of vigorous debate at present. Instead of 100 m³, this LCVs haul 150m³, their maximum total weight being limited to 40 tonnes (or 44 tonnes intermodal transportation), though. Advantages of LCVs are their lower axle load and their larger freight volume's reduction of daily runs (bast 2016). At the same time, consequent shifts from rail to road transportation are feared. LCVs could haul freight in the future, which has been forwarded by freight trains (Sonntag and Liedtke 2015), and thus increase the trucks' number of daily runs. The impact of the introduction of LCVs on the freight transportation system can hardly be assessed without a sound method of analysis.
Such a method should be able to incorporate as many of the long-range impacts of technological innovations in its assessment as possible. Since simulation models can depict the dynamic behavior of systems (Reggelin and Tolujew 2011, Fierek and Zak 2012, Sokolowski and Banks 2009) they are a suitable addition for the approach method, which should be developed here.

2. MODELING IN THE TRANSPORTATION SECTOR
Simulation is defined as a controlled statistical sampling technique (Fierek and Zak 2012, Hillier and Lieberman 2001), which carries out a series of experiments using a computer. Various input data is transformed into a set of output data by estimating the effect of data to the simulation model, which describes the operations of the real system (Fierek and Zak 2012). Simulation models in the transportation sector generally are algorithmic mathematical models, classifiable by their purpose and degree of detail (Reimann 2007).
Regarding the purpose a distinction is made between demand, assignment models and flow models. Demand models forecast transportation demand and are usually static, while assignment models assign generated demand data to an existing transportation network and generate line load data. Flow models are time dynamic, i.e. the system state changes dynamically with time and is calculated at certain intervals.
Simulation models can also be classified as microscopic, mesoscopic or macroscopic according to their degree of detail. Microscopic models usually incorporate not only individual units in the transportation flow with their performance and interactions among each other but also the transportation environment like traffic lights and intersections (Bungartz et al. 2009, Liebermann and Rathi 1997, Fierek and Zak 2012). Macroscopic models describe all vehicles of a transportation network or

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system as a uniform traffic flow with characteristics like volume, speed and density (Bungartz et al. 2009, Liebermann and Rathi 1997, Fierek and Zak 2012). Mesoscopic models combine microscopic and macroscopic approaches (Reggelin 2011). Since they can represent large networks with vehicles as individual elements, they are mainly used for routing and traffic control.

Extensive literature covers general methods pertaining to the transportation sector and traffic trends in particular. Most tools are applied microscopically and mesoscopically, while macroscopic tools are rare (Behrendt 2016).

Cost-benefit analysis (CBA) is one of most widely used methods to evaluate new transportation infrastructure projects macroscopically. It only evaluates monetizable items, non-monetizable items being treated in separate (environmental) analyzes (BMVI 2016b). That is why (Gühnemann et al. 2012) introduce the results of a CBA to a multiple-criteria decision analysis (MCDA) by involving decision makers in the development of a cost-effective investment program consistent with strategic objectives. Even (Macharis and Bernardini 2014) use MCDA in connection with a multi-actor approach for the evaluation of transportation concepts in urban and regional areas. Unfortunately, only transportation infrastructure projects are evaluated and the impact of new financing instruments (e.g. truck tolls) and technological innovations are not taken into account. This is the point of departure for a novel approach that compares new proposals and the advantages of new actions and concepts, which was developed jointly by Otto von Guericke University and the Fraunhofer Institute for Factory Operation and Automation IFF in Magdeburg, Germany.

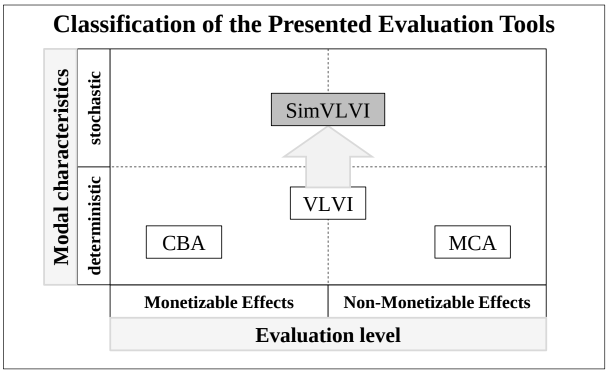

Figure 1: Classification of Tools for the Assessment of Transportation Concepts including SimVLVI

This static, deterministic model called the VLVI tool is being upgraded with simulation components in order to incorporate stochastic elements in the modeling (Figure 1).

3. VLVI METHOD: DESCRIPTION AND INTEGRATION OF RANDOM SIMULATION

The VLVI method enables ex-ante assessments of future scenarios that will affect the German transportation system's infrastructures and processes (Behrendt 2016). The model integrates key performance indicators (KPIs) in causal networks (Figure 6), which represent the relationships between the KPIs. Combined with a set of specific KPIs (based on the scenario), the method models the future impacts of political policies and technological innovations. A procedural model consisting of five procedural steps (Figure 2) is used to perform the ex-ante assessment.

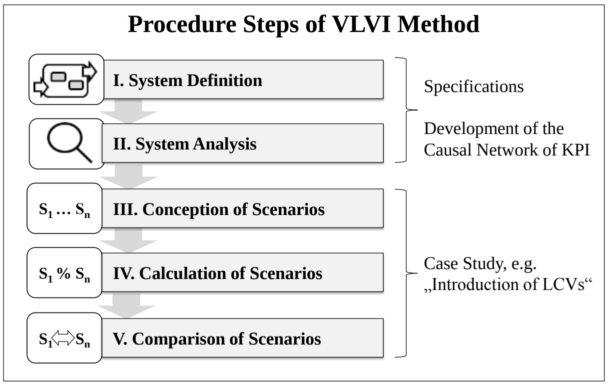

Figure 2: The Steps of the VLVI Method (Behrendt 2016, Schmidtke and Behrendt 2017)

Within the first two procedure steps a classification of KPIs is compiled and analyzed by means of a relevance analysis to determine their relevance and importance (weighting factors) towards defined objectives. For the approach presented the objectives of the German national infrastructure plan, so called "Bundesverkehrswegeplan" (BMVI 2016b) are used. An additional impact analysis identifies relationships between all relevant KPIs in order to develop causal networks of KPIs, one for each transportation mode (road, railroad and waterway). Regarding the ex-ante assessments of future scenarios and based on historical data, all KPIs are forecasted by using appropriate forecasting methods such as linear regression analysis or exponential smoothing. As a result the method analyzes influencing factors on the German transportation system by using a specific calculation schema and its comparative indicator named "VLV-indicator" (VLVI). A more detailed description and application of the VLVI method is given in Chapter 4 by the case study "Introduction of Long Combination Vehicles".

Since the VLVI method does not factor in concepts' uncertainties regarding the mentioned case study, a static, stochastic model was developed to create SimVLVI.

3.1. Stochastic Modeling

The inclusion of randomness is the underlying idea of stochastic modeling. One of the basic approaches, Monte Carlo simulation (Nahrstedt 2015) employs random number generators to generate data from specific stochastic distributions. Every computation generates a different output based on the random input. The output is utilized to simulate sampling of an infinite base population. The required sample size is definable by methods of inductive statistics (Chapter 4.4) and is a function of the confidence level preferred. Statistical inference is employed to estimate the sample statistics and transfer them to the base population. This delivers a random model describing the system's uncertainty with a corresponding confidence interval.

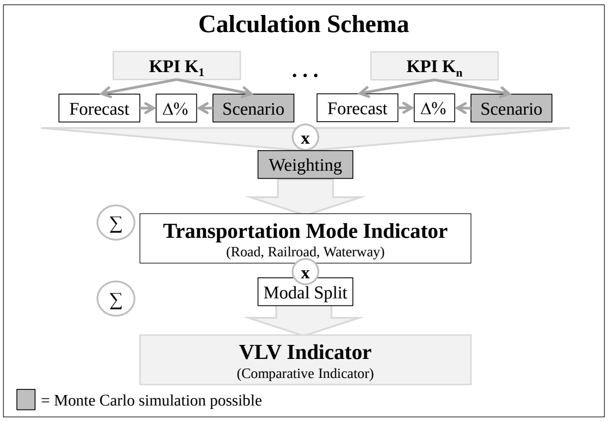

Figure 3: Basic Calculation Schema of the VLVI Method

The core of the VLVI method is its calculation schema (Figure 3). Weighted KPIs (weighting results from relevance analysis) changed by the scenario are aggregated in indicators that specify the scenario's impact on transportation modes. Multiplying the totaled indicators by their modal split yields a comparative indicator referred to as the VLVI. It specifies the pros and cons of changes to a system in a weighted percentage.
Various stochastic simulations (shaded in Figure 3) can be applied in the method to vary the scenario values or to employ variable rather than static weighting. The following examines variable scenario values of the impact of LCVs on the German transportation system. The analysis of the case study follows the five steps of the VLVI method.

3.2. Validation

For the validation of the VLVI method an ex-post analysis has been realized. The introduction of an electronic truck toll system in 2005 provides a suitable scenario. Since 2005 trucks heavier than 12 tonnes have to pay toll (a distance dependent charge) for using German highways (VIFG 2015). This method should enhance the financing situation of infrastructure by shifting to a user financing principle (Doll and Schade 2005). Two scenarios for the analysis year 2005 were developed:

1. In 2005 a revenue of € 2.8 billion per year was expected due to the new truck toll, which should be reinvested in the German road infrastructure by 40% (Doll and Schade 2005). These expected revenues raise the KPI "gross fixed assets" as well as the KPI "net fixed assets" and set appropriate scenario values for the forecast year 2015. The VLVI method calculated a positive effect for 2015, which could not be seen in reality. Taking into account the simultaneous decrease of tax financing (general budget for transportation infrastructure) in the following years this discrepancy is explainable (Bernecker and Fichert 2013).
2. The real data, KPIs measured in "Transportation in Figures" which is published each fall by the Federal Ministry of Transport (BMVI 2016a), was set as scenario values. As a result a loss of economic substance for the German transportation system was calculated, which is congruent to the results of the federal and state commission work (Daehre 2012) and confirms the representation accuracy of the VLVI method.

4. CASE-STUDY: INTRODUCTION OF LONG COMBINATION VEHICLES IN GERMANY

In many European countries new truck concepts are debated or put already into practice. In Sweden for example, trucks with a length extended to 25.25m are common, while trucks on roads in Germany were limited to 18.75m (Figure 4). In 2012 a field trail with long combination vehicles (LCV) started investigating the use of vehicles and its combinations with a length of up to 25.25m in Germany. This field trail was initially limited to a period of five years and was accompanied by a comprehensive program of scientific tests from the Federal Highway Research Institute (bast 2016). Since 2017 LCV are allowed to use German roads while the maximum total weight is still limited to 40 tonnes (or 44 tonnes in combined transport). Heavier vehicle combinations of up to 60 tonnes reveal safety concerns because bridges and cash barriers are constructed for lower maximum total weights, expensive expansion measures would be necessary. Therefore only the introduction of LCV as shown in Figure 4 are taken into account for the following case-study. LCV have the characteristic of higher volume increased from 100 m³ to 150 m³, which offers the possibility of decreasing the total number of trucks on roads, while transporting the same volume of cargo. Additional axes are needed in comparison to conventional trucks and decreases the average axes load of LCVs.

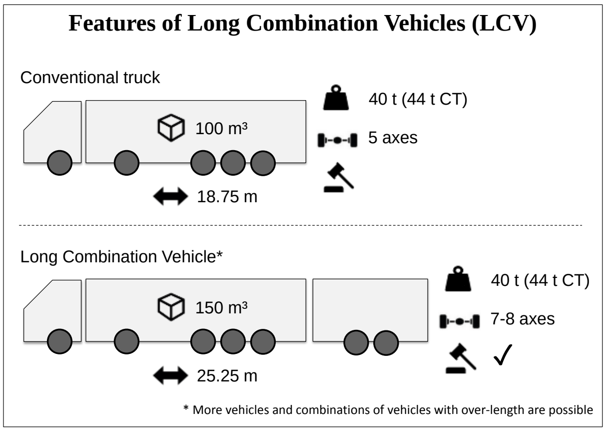

Figure 4: Features of Long Combination Vehicles (LCV) (bast 2016; VDA 2006)

4.1. System Definition

The model created when the system is being defined (Behrendt 2016) has to be able to represent the desired development of the transportation system. In the case presented here, the German national infrastructure plan (BMVI 2016b) is the source of the development aims. Its goals are both quantitative, e.g. "reducing shipping costs", and qualitative, e.g. "modernizing and maintaining transportation infrastructure". As a whole the following development aims are considered:

1. Modernizing and maintaining transportation infrastructure
2. Reducing shipping costs
3. Improving traffic flow
4. Increasing reliability of transports
5. Reducing emissions
6. Improving connection of intermodal hubs

These development aims underlying the analysis are contingent on the object of analysis.
To describe the system a morphological box (Figure 5) is used. It is divided into the categories of system, process and object, which are analyzed in subcategories. This division facilitates a structured approach when categorizing concepts (Illés et al 2007; Zsifkovits 2013; Schenk et al. 2010). The morphological box presented here is suitable for classifying most scenarios but can be expanded if necessary.

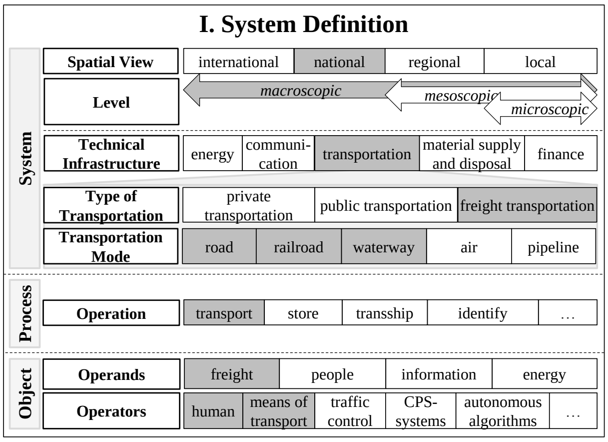

Figure 5: Morphological Box of Freight Transportation (Behrendt 2016; Illés et al. 2007; Zsifkovits 2013; Schenk et al. 2010)

The system definition for the introduction of LCVs is shaded in Figure 5. A macroscopic view has been selected to describe changes in the national transportation system. Since the share of freight transported by air or pipeline is insignificant compared to other transportation modes, this analysis only examines the transportation modes of road, railroad and waterway. The effects to the system will be assessed for the year 2025, a long-term period, which represents a good basis in order to indicate realistic developments.

4.2. System Analysis

Each of the transportation modes (road, railroad and waterway) has to be examined separately to develop the appropriate causal networks of KPIs. Potential KPIs are subjected to a relevance analysis to determine their relevance for the defined objectives (Chapter 4.1). This leads to an assessment of the KPI's influence on the respective development aims, whereby a distinction is made between "positive influence", "negative influence" and "not clearly assessable".
The KPIs are weighted against each other in a subsequent impact analysis using Vester's scale (Illés et al 2007) for pairwise comparison: A quantifier of "1" denotes a weak relationship, "3" an intense relationship. This analysis makes it possible to classify KPIs into a causal network (Figure 6) with the direction of influence running from top to bottom. For instance, "transport volume" affects the "percentage of empty run kilometers", which is simultaneously a function of the "average distance carried".
Causal networks are rendered similarly for the transportation modes but the outcomes differ in part. Weighting may differ and other KPIs may be employed, e.g. "rate of electrification" (in a railroad causal network) or "quality of port infrastructure indicator" (in a waterway causal network).

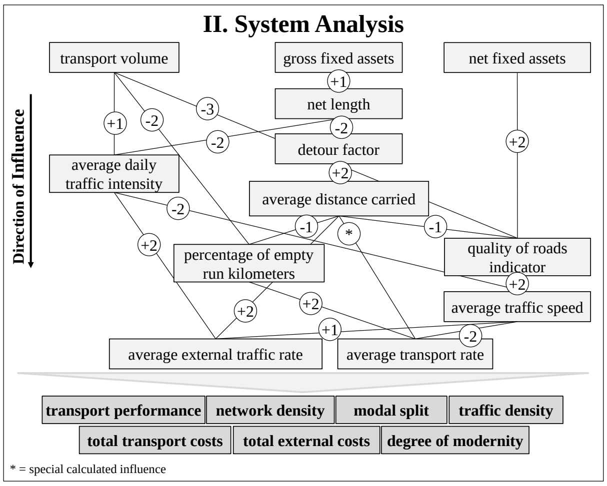

Figure 6: Road Transportation Causal Network

All KPIs are forecast based on their historical data by using such methods as linear regression analysis or exponential smoothing. An annual value can thus be forecast for every KPI, which ought to appear without changing the system. As is evident in the calculation schema (Figure 3), this forecast value is compared with the KPI value that could be generated by the scenario.
In general the first two procedure steps, system definition and system analysis, form a basis for the following case studies. After defining and analyzing the causal networks once the procedure steps three to five can be repeated for each exemplary application, as long as the same view and objectives are regarded.

4.3. Conception of Scenarios

In general, two different approaches can be used for the conception of scenarios. On the one hand, an environmental analysis can be carried out collating external opportunities and risks derived from political, economic, social, technological, environmental and legal conditions ("PESTEL", Johnson et al. 2011). As in the case presented, a future scenario can be also defined due to vigorous debates at present (field trail for LCVs, bast 2016) on the other hand.
A future scenario describes the changes in the transportation system caused by political policies or technological innovations in a certain year. The scenario has to be calculable in order to simulate its impact. By surveying literature and interviewing experts, the impacts are quantified so that a scenario can be described by a set of changed KPIs. The scenario value of a KPI not set by experts is calculated by weighted change (Figure 3) of the higher level KPIs (Figure 6).
Since experts often disagree or are uncertain about future developments, the literature occasionally only delivers an interval rather than any exact value for the scenario values of KPIs. For instance, (bast 2016) does not expect the introduction of LCVs to cause a shift of freight between the transportation modes of road and rail; whereas (Sonntag and Liedtke 2015) estimate that 7.6% of the volume transported will shift from railroad to the road. An interval [0; 0.076] can be set to include both views in the approach.
Scenarios with at least one of these intervals are referred to as trend scenarios. A deterministic method such as the (original) VLVI method necessitates using one best and one worst case scenario to approximate trend scenarios. This is no longer necessary in SimVLVI. Using Monte Carlo simulation to vary input, a trend scenario can be mapped directly. While the interval boundary can be extracted from the source, statistical distributions are often lacking even if the interval originates from a single source. Then it must be defined to compute the VLV indicator. Since the distribution of the random numbers can heavily influence the results, the statistical distributions that fit the situation best have to be chosen. Because rectangular and beta distribution are both definable in a closed interval, they are particularly suitable for implementing trend scenarios. The following are helpful guidelines whenever sources do not contain any information for a distribution:

- Rectangular distribution fits best when the interval comes from a single source.
- Beta distribution fits best when the interval is a combination of two values from two different sources. It can be adjusted according to the sources' credibility: If both are equally credible, the parameter should be set as a=b=0.5 (Figure 7, left), thus weighting both source values highly. If one source is more credible, the parameters may, for instance, be altered as a=3.5 and b=1 (Figure 7, right), so one value is weighted higher.

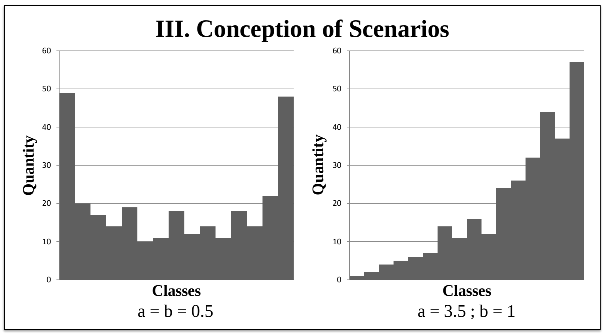

Figure 7: Histograms of Beta Distributions with a Sample Size of 300

4.4. Calculation of Scenarios

Inland vessels usually transport heavy cargo such as turbine parts or bulk cargo like coal or gravel. Since it is unlikely that LCVs used to haul bulk cargo (bast 2016), which would impact inland shipping, a shift between inland shipping and LCV is not considered here.
(bast 2016) expects LCVs to take over 2.6-6.9% of conventional trucks' kilometrage, which accords to all point-to-point transportation of more than 25 km and over 70% of the truck's volume utilized (bast 2016). A rectangular distribution in [0.026; 0.069] has been chosen for the simulation (Table 1). All other impacts of

LCVs are a function of this percentage share of kilometrage. The “average distance carried” of 240 km for LCVs ascertained by (bast 2016), is significantly higher than the distance of 165.4 km forecast for conventional trucks. The scenario’s value of “average distance carried” is a function of both values yielded by percentage calculation. The same applies to “average daily traffic intensity”, which drops as the number of LCVs increases: One shipment with an LCV can replace 1.545 shipments with a conventional truck (bast 2016). Not only is the axle load lower (bast 2016) but there is also significantly less stress on the road infrastructure, thus leading to improvement at no additional cost. The impact of the “quality of roads indicator” is therefore assumed to be positive in the model. The impacts described are employed as scenario values in the model (Table 1).

Table 1: Simulation Scenario Values for the Introduction of LCVs

IV. Calculation of Scenarios

KPI	Source value	References	Simulation
Railroad			
Transport Volume	-7.6%	Sonntag and Liedtke 2015	Beta Distribution with a=b=0.5 for [0; 0.076]
	0.0%	bast 2016	
Road			
LCVs Percentage	*2.6 – 6.9%*	*bast 2016*	*Rectangle Distribution for [0.026; 0.069]*
Transport Volume	Transferred tonnage	Sonntag and Liedtke 2015	Transferred Tonnage depending of the Railroad Transport Volume
	0.0%	bast 2016	
Average Distance carried	240km	bast 2016	Depending of the LCV Percentage
Average daily Traffic Intensity	1 LCV ≈ 1.545 trucks	bast 2016	Depending of the LCV Percentage
Quality of Roads indicator	Lesser road pressure	bast 2016	Equally distributed Value [0.01; 0.023] depending of the LCV Percentage
Waterway			
No changes			

The minimum required sample size is a function of the confidence level and the tolerable error. Both variables have to be defined so that they are significant enough for the analysis. They were defined for the LCV scenario as follows:

- confidence level = 95%
- tolerable error = 3%

These variables are used to calculate the minimum required sample size with Formula 1 (Waldmann 2016, Rössler and Ungerer 2008). A pilot survey of a sample size of n = 30 (Mossig 2012, Bahrenberg et. al 2010) ascertains that the VLV indicator varies by 7.5%.

$$n \geq z_{1-\frac{\alpha}{2}}^{2} * \frac{s_0^2}{\varepsilon^2} \tag{1}$$

- n = sample size
- $z_{1-\frac{\alpha}{2}}^{2}$ = quantile of the standard deviation distribution for the confidence level $1-\frac{\alpha}{2}$
- s_0 = standard deviation of the pilot survey
- ε^2 = tolerable error

Formula 1 calculates a minimum required sample size of n = 320.

4.5. Comparison of Scenarios

The VLV indicator is calculated 320 times as described in Chapter 4.4 to generate the required sample size. The fit of the data to the normal distribution is checked by various tests, thus the arithmetic mean and the standard deviation of the transportation mode indicators and the VLV-indicator can be assessed. Formula 2 delivers the proper confidence interval for the data (Waldmann and Helm 2016, Rössler and Ungerer 2008). This is the way sample uncertainties are usually expressed in statistics.

$$\bar{x} - z_{1-\frac{\alpha}{2}} * \frac{s}{\sqrt{n}} \leq \mu \leq \bar{x} + z_{1-\frac{\alpha}{2}} * \frac{s}{\sqrt{n}} \tag{2}$$

- $\bar{x}$ = mean of the sample
- s = standard deviation of the sample
- μ = mean of the base population

The outcome is presented on the right side of Figure 8. The impact of LCVs can also be estimated with the deterministic VLVI method (Figure 8, left). Then, the trend scenario has to be split into sub-scenarios defined by varying the input parameters. This treatment is necessary in any kind of deterministic method. It gives decision makers many different outcomes for sub-scenarios of a single decision, which they have to use as the basis of decisions without any information on the probability of the sub-scenarios’ occurrence. A model based on the Monte Carlo method, on the other hand, solely delivers information on the impact of a decision-making option.

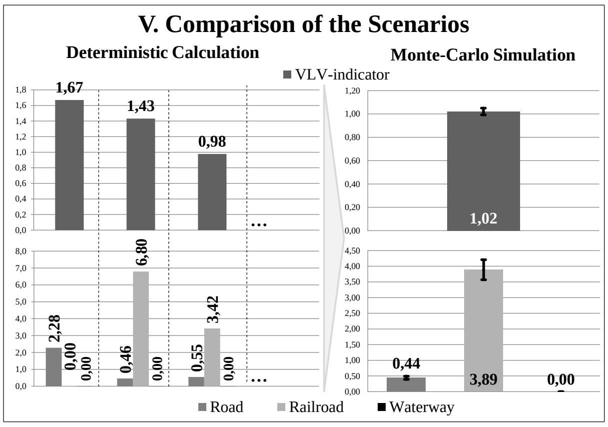

Figure 8: Comparison of the Results of deterministic VLVI and SimVLVI

Based on these sources and the aforementioned constraints, the introduction of LCVs can be expected to improve the freight transportation system by 1.02±0.03%. The rail freight transportation system, operating virtually to capacity, will transport up to 7.6%

less. The greatest improvement of 3.89±0.32% can thus be expected there.
The road transportation system will not deteriorate as feared. The additional load from shifted rail freight will not offset the positive impact of LCVs, e.g. lower axle load and higher volume of freight. It may even contribute to a slight improvement of 0.44±0.05%. Moreover, the lower cost of haulage using LCVs rather than conventional trucks can benefit shippers.
Since the influence of transportation modes on the entire system is a function of its modal split, the relatively strong improvement of the rail transportation system has only slight influence on the complete system.

5. CONCLUSION AND OUTLOOK

The macroscopic SimVLVI demand model assesses new transportation concepts in advance. This enables political policymakers and industry decision makers to assess their options using a statistically grounded number that factors in ever impact, which is important according to the literature. The various views of experts and the literature can be aggregated and an objective basis for an assessment can be established. The Monte Carlo simulation implemented facilitates risk analysis of concepts without decreasing the VLV indicator's interpretability. The widest variety of options can thus be compared easily, even if they are as different as a financing instrument and an innovative transportation system.
In addition to trend scenarios, Monte Carlo simulation can also be employed to vary the weighting defined in impact and relevance analyses. Even if there is consensus on the approximate assessment of the correlations between the KPIs, a precise definition may require compromise. Applying the Monte Carlo method to the weighting in the VLVI model could reproduce this uncertainty like the uncertainties in trend scenarios. This would make an even more exact assessment of the concept possible.

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