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An economic cost-benefit analysis of a general speed limit on German highways

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Abstract

Uniquely amongst industrialized countries worldwide, Germany does not impose a general speed limit on highways. This is different in the Netherlands, where a limit of 130km/h is implemented. The direct border between the two countries provides an opportunity to construct a natural experiment and analyze the social impact of a general speed limit of 130 km/h for passenger cars on German highways. I quantify the social welfare impacts from travel time, accident victims, fuel consumption and emissions for two highway sections in the federal state of North Rhine-Westphalia, Germany. The results are obtained by a descriptive comparison of micro data on travel speeds and accidents, collected on the two designated cross-border highways. In the central case, I conclude that on both highways a speed limit would be beneficial from the social and private perspective. The impacts found on the two highways differ in magnitude, but the qualitative decisions are identical and sufficiently robust to their core assumptions.

Keywords: Speed Limit, Highway, Germany, Cost-Benefit Analysis, Transport Economics

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Abbreviations

A

AADT .... Average Annual Daily Traffic

B

BASt...Bundesantalt für Straßenwesen / Federal Highway Research Institute

BMVI .... Bundesministerium für Verkehr und digitale Infrastruktur / Ministry of Transportation and Digital Infrastructure

C

CBA.................................. Cost-Benefit Analysis

CO..*Carbon Monoxide*

CO_2 .... Carbon Dioxide

E

EEA .... European Environmental Agency

ESL...........................Environmental Speed Limit

G

GHG.................................. Greenhouse Gas(es)

GIS................Geographical Information System

H

HBEFA ....Handbuch Emissionsfaktoren des Straßenverkehrs / Handbook emission factors for Road Transport

HC...*Hydrocarbon*

J

JRC.........Joint Research Center of the European Commission

K

KBA......... Kraftfahrtbundesamt / Federal Motor Transport Authority

KH. .... Kaldor-Hicks

M

MAIS .... Maximum Abbreviated Injury Score

METB ....Marginal Excess Tax Burden

N

NDW .... Nationale Databank Wegverkeersgegevens / National Database of Road Traffic Data

NGO ....Non-governmental organization

NMSL .... National Maximum Speed Law

NO_X .... Nitrogen Oxides

NRW .... North Rhine-Westphalia

O

O_3.. ....*Ozone*

P

PM ....Particulate Matter

S

SCBA .... Social Cost-Benefit Analysis

StVO Straßenverkehrsordnung / Road traffic act

V

vkm .... Vehicle kilometer

VMT ....Vehicle Miles Traveled

VoR .... Value of Reliability

VoT .... Value of Time

VSL............................... Value of a Statistical Life

M

µm .... Microns

1 INTRODUCTION

Uniquely amongst industrialized countries worldwide, Germany does not impose a general speed limit on highways. This exceptional traffic policy and the resulting opportunity to legally drive at any possible speed on a public road even makes "Autobahn" – the German term for highway – a word widely known beyond the country's borders. The total highway system in Germany spans roughly 25,767 km, 70% of which remain without a speed limit today, while the other 30% are either subject to a static speed limit (≈ 21%) or a variable speed limit system (≈ 9%) (see Kollmus et al., 2017, p.4).[1] For the unrestricted parts, a speed of 130 km/h is officially recommended but not obligatory.[2] Some vehicle categories are excluded from the rule and underlie a general speed limit. For example, trucks and busses are subject to a limit of 80km/h and 100km/h respectively (see Deutscher Bundestag: §18 Abs.5 Satz 2 StVO). This leaves passenger cars as the major vehicle type that is free in the speed choice, and thus, makes this particular category the focus of this thesis.

Speed limits have always had their advocates and critics. A vast variety of stakeholders from science, politics and Non- governmental organizations (NGOs) engage in the discussion about the effects of speed limits on several factors. Arguments against or in favor of limits range from obvious aspects like the trade-off between travel speed and road safety to less salient facets, for example substitution between road types or even the loss of political support. In the course of this, different scientific disciplines are affected and the debate about the desirability of a speed limit becomes complex and often emotionally charged. The latter is especially true for Germany, where a change in policy would constrain a road users' former freedom of choice to some upper bound. This freedom of choice, however, has long been considered tradition by many Germans. Sometimes it is asserted that also the strong automotive industry is interested in retaining this freedom, which even led to comparisons with the U.S.-American incorrigibility when it comes to the citizens 'right to bear arms (see Hengstenberg, 2013).

Evidence suggests that the share of speed limit opponents in Germany remains high. In a representative survey from 2013, 62% of respondents rejected a general speed limit on highways of 120 km/h (see ZDF Politbarometer, 2013). In contrast, more current polls find that a general speed limit may achieve a thin majority, as 52% of the 2,000 interviewees in 2017 answered in favor of a general speed limit (see Deutscher

[1] The figures in the report are based on 2015 data. Length of the highways is counted as *distance kilometers*, i.e. one km of highway with two driving directions is counted as two km.
[2] However, in case of an accident, a strong exceedance of 130km/h is likely to cause partial liability.

Verkehrssicherheitsrat, 2017). Yet, there was no particular statement on the *level* of this hypothetical limit. The exact level is a crucial variable for gathering public support. Evidence from 2015 indicates that the resistance of German citizens towards an overall speed limit is negatively correlated to its level. A majority of 56% would welcome a 150 km/h limit, but this share decreases to a mere 11% when respondents are confronted with a limit of 100 km/h (see Schmidt, 2015).
Implicitly, the respondents base their assessments on weighing of individual (private) cost and benefits. Even if this may lead to an optimal decision from a personal point of view, external effects are usually not considered. This is potentially rendering the outcome of the sum of decisions unwanted from a normative welfare perspective. Looking through the eyes of a social planner, it is well conceivable that introducing a speed limit is leading from the status-quo closer towards Pareto efficiency – the state of society in which no one can be made better-off without simultaneously taking away welfare from someone else (see Elvik, 2009, p.33).
A tool for assessing policy measures in terms of economic welfare is Cost-Benefit Analysis (CBA). It aims at rationalizing the decision-making process of policy-makers by trying to consider all relevant impacts of a policy or project to society as a whole. Therefore, it is interchangeably called economic or social cost-benefit analysis (SCBA) (see Boardman et al., 2014, p. 2).
This master thesis offers a SCBA for a general static speed limit for passenger cars on German highways. Along the way, I will seek answers to the following core research questions:

- *R1.* *Which arguments should be taken into account when economically analyzing the impacts of a speed limit on highways?*
- *R2.* *How would a speed limit affect the identified impacts?*
- *R3.* *Should there – from the perspective of normative welfare theory – be a general speed limit on German highways?*

Several important factors, which are affected by a speed limit, are identified. Based on the four core impacts *opportunity cost of travel time, road safety benefits, emissions* and *fuel consumption,* I find that for the two highways analyzed a speed limit of 130 km/h would increase welfare to society. This even holds from a private perspective, which indicates that road users may be poorly informed and misperceive the trade-off between private time savings and fuel costs from speeding. The results are obtained from a descriptive comparison of key micro data collected on two designated cross-border highways between Germany and the Netherlands.

These findings and analyzing speed limit impacts in general, are important for two main reasons. First, there is a large research gap on this specific topic in Germany. To my knowledge, there exists no SCBA for a speed limit in Germany in the literature. On federal state level Scholz, Schmallowsky, & Wauer (2007) conduct a CBA for the introduction of a general speed limit in the federal state of Brandenburg. Incorporating benefits from reduced accidents and costs from additional travel time, they calculate an annual social net benefit of 5.3 mio € at a speed limit of 130 km/h. Despite this work, it is reasonable to claim that speed limit research in Germany is essentially missing. Consequently, the political debate is dominated by and based on grey literature, such as reports from automotive or environmental associations, which potentially leads to prejudiced analyses in both directions – for and against a speed limit. Second, a classic justification for speed constraints is their potential to save lives and increase road safety, both of which being of supreme political importance. The German Ministry of Transportation and Digital Infrastructure (BMVI) states in their road safety program that "every road death is one too many" (see BMVI, 2011, p.5) and set the goal to decrease road deaths by 40% until 2020. The ministry's progress report shows that by 2014 a reduction of approximately 16% has been achieved, leaving the initially set target "a very ambitious but achievable goal" (see BMVI, 2015, p.8). Still, the two strongest German parties, the Social Democratic Party of Germany (SPD) and the Christian Democratic Union of Germany with its political ally, the Christian Social Union in Bavaria (CDU/CSU) rule out general speed limits as a contributing measure. On the other hand, two of the other established parties still support a general speed limit. The green party "Bündnis 90/Die Grünen" advocates a general maximum speed of 120 km/h, thereby sharing the opinion of the left-wing party "Die Linke" on the topic.[3]

The thesis is designed as follows. Chapter 2 provides a literature overview clustered by the identified essential speed limit impacts. In chapter 3, Cost-Benefit Analysis as the analytical framework is introduced briefly. Chapter 4 defines the policy analyzed and the perspective taken when assessing the impacts. In chapter 5 the impact categories considered are presented. In chapter 6 the estimated impacts from a speed limit are quantified in magnitude using descriptive data comparison. Chapter 7 is devoted to valuing the estimated impacts in monetary terms and classify them as costs and benefits. The chapters 8, 9 and 10 present the results, provide a discussion and close the work with a conclusion.

[3] In their 2017 federal election programs, both parties explicitly promote a general speed limit of 120km/h. For download in German language available under: https://www.tagesschau.de/inland/btw17/programmvergleich/programmvergleich-verkehr-101.html (link last updated 05.08.2018).

2 LITERATURE REVIEW

The literature research for this thesis has been a complex task. Speed limits affect multiple impact categories, most of which have developed their own stream of academic literature, for example environmental studies, road safety analyses and several others. Therefore, the collected studies are clustered and reviewed by the main impact categories identified across the works. Joint studies that embrace several impacts are rare, but an outstanding article, which serves as a basis and point of orientation for this thesis, is van Benthem (2015). He conducts a wide-ranging CBA for U.S. speed limit changes on freeways in 1987 and 1996. The study analyzes the effect of speed limit changes on four main variables, namely *travel speed*, *accidents*, *air pollution* and *health*. Based on these impacts an optimal limit is approximated close to 55 mph (roughly equivalent to 88.5 km/h). [4] When comparing his selection of outcome variables with other speed limit studies, one finds that the majority of important effects discussed matches these categories. The literature review adopts this categorization and summarizes the literature divided per impact.

Travel Speed

Travel speed is included in almost all studies on speed limit impacts. Folgerø et al. (2017) investigate a 20 km/h reduction in speed limits in the urban area of Oslo, Norway. From Nov, 1st 2004 till March 2005 the municipality of Oslo imposed an environmental speed limit (ESL) of 60 km/h instead of 80 km/h on an urban national road. The policy continued until 2012 and was expanded to two other urban roads. Using a regression discontinuity design around the cut-off date (Nov, 1st) and data from three speed measurement stations, they estimate a reduction in mean travel speed of 5.8 km/h (see Folgerø et al., 2017, p.27).

Changes in 1987 and 1995 in the U.S. National Maximum Speed Law (NMSL) and their impacts in California, Washington and Oregon were analyzed by van Benthem (2015). He employs a difference in difference estimator on a large set of measurement data, finding that a 10-mph increase in speed limits translates into higher actual mean speeds of 3 to 4 mph (see van Benthem, 2015, p.49).

Gates et al. (2015) analyze expected impacts of an increase in speed limits from 55 to 65 mph on high-speed roadways proposed in Michigan in 2014. Using radar guns, they collect a sample of field speed data at 100 observation sites along Michigan non-freeway trunkline routes. Interpretation of their results should be made with care since they only have one site at which travelers were allowed to go up to 65 mph and the section has two

[4] 1 mph ≈ 1.6 km/h.

lanes in each direction separated by a raised median, which is uncommon for the Michigan trunkline system. However, they observe a difference in average speeds of passenger cars between the 55 and 65 mph sections of 5.8 mph while the share of vehicles exceeding the limit fell dramatically from 77.2% to 43.0% (see Gates et al., 2015, p. 24ff.).

Retting and Teoh (2008) investigate changes in travel speed, ten years after the repeal of the NMSL in 1995. They measure speeds at 26 sites in five different states at which previous studies had collected the same data in 1996, shortly after the states regained authority over speed limit policies. Their approach accounts for the sample selection by keeping factors such as daytime, weather and traffic flow constant during data collection. Then, conclusions about travel speed changes are drawn from a descriptive comparison. For rural interstates in two states where the speed limit remained constant, they observe an increase in mean speeds of 3-4 mph suggesting a rising speed trend over time. Conversely, a speed limit was imposed in Montana after having no numeric limit in 1996 and mean travel speeds decreased by 2 mph (see Retting and Teoh, 2008, p. 122f.).

Ashenfelter and Greenstone (2004) take advantage of the 1987 amendment of the NMSL, which allowed U.S. states to increase speed limits from 55 to 65 mph on rural interstates. In order to provide an estimate for the value of a statistical life they estimate and monetize changes in travel time and fatality risk resulting from a speed limit increase. Collecting data from speed measurement loops in 21 states for the period 1982 to 1993, they conduct a before-after study and estimate an increase of about 2.5 mph by means of difference in difference estimation.

This take of literature does undeniably not capture all studies on the topic. Anastasopoulos and Mannering (2016) as well as Mannering (2007) use survey data to study the effect of several factors including speed limits on the respondents' stated choice of speed. Extensive literature reviews were carried out by Savolainen et al. (2014), Kockelmann (2006), who broadly agree that "… a change in speed limit generally results in a less-than-equivalent change in average speed" (see Kockelmann, 2006, p. 10). Wilmot and Khanal (1999) also examine literature of speed limit effects on speed and safety, concluding that motorists often do not adhere to speed limits and choose their speed based on their personal perception of safety.

The literature provides an indication of how speed limits may affect actual travel speeds. The advantage of most previous studies is that they were able to rely on a certain change from limit x to limit y, which is different to the unique situation in Germany where no maximum speed limits constrain a driver's choice. Therefore, it remains an empirical question, to which extent and even in which direction the introduction of a limit would alter mean speeds. This question clearly depends on the relative level of a limit imposed to current average speeds.

Accidents

As seen in the previous paragraph, changes in speed limits are likely to achieve their purpose of dragging traffic speeds in a certain intended direction. Consequently, we expect travel speed to increase or decrease as a result of speed limit changes of sufficient magnitude. Moreover, there could be changes in the traffic flow. Speed limit changes might render traffic more or less homogenous. Both these factors have already been discussed in early road accident analyses, which created two streams of thought. Lave (1985) calls them "speed kills" and "variance kills". The speed-kills advocates argue that higher speeds come with more danger while the variance-kills proponents support the idea of deviations from mean speeds being the cause of accidents.[5] From common sense and the laws of physics researchers started to analyze the effect of speed on accidents. Solomon (1964) initially presented evidence that *chance of involvement* in an accident increases with deviation from mean speed ("variance kills") whereas *severity* of accidents increases with level of speed ("speed kills").

Modern studies vary considerably with respect to methods and the inclusion of one or both of the named effects as well as road types. Farmer (2016) analyzes speed limit impacts on traffic fatalities only. He employs data on traffic deaths per billion vehicle miles traveled (VMT) clustered for 41 U.S. states between 1993 and 2013. For high-speed roads which covers interstates and freeways, his poisson regression yields an estimated 8.3% (17%) increase in fatality rates when speed limits increase by 5 (10) mph (see Farmer, 2016, p. 5). The study thus presents evidence that raising a speed limit results in additional road deaths, which can plausibly be categorized as the most severe accidents.

Van Benthem (2015) not only uses data on fatal accidents but integrates all highway accidents to explore the impact of the 10 mph speed limit increase in 1987 for Washington and Oregon. He sorts the accidents by severity group and assigns them to treatment (10 mph change in limit) and non-treatment highways (no change in limit). Using a negative binomial regression specification, he presents evidence that accidents (likewise normalized by VMT) went up significantly for all categories while showing a clear ordering of larger increases for more severe accident classes. Put differently, the distribution of accidents was shifted towards more severe accidents and increased in level. For example, he estimates 13.2% and 44% surges for property damage and fatal accidents respectively. Thereby he confirms the opinions of both the "speed kills" and "variance kills" proponents, namely that higher speeds lead to additional *and* more severe accidents (see van Benthem, 2015, p. 50f.). In contrast, he does not find signs that his accident results are driven by less homogenous traffic (variance kills) since the estimated changes in travel

[5] Kockelmann (2006), p. 10f. as well as Gates et al. (2015), p. 7ff. wrap up the early studies and evolution of discussion on the two streams so I will concentrate on more recent findings.

speed (see previous section) are similar for both mean speeds as well as 85th percentile speeds. This indicates that the variance in speeds did not increase significantly due to the policy change (see van Benthem, 2015, p.49).[6]

Savolainen et al. (2014) examine effects on fatalities from speed limit policies at U.S. national level and for the state of Michigan separately. Within the countrywide analysis, they aggregate states by differences in rural interstate speed limits.[7] They report parameter estimates of a negative binomial model including random effects to account for state and time fixed effects. The coefficients imply that fatalities constantly increased with posted speed limits in the period 1999-2011. Increases in fatalities for a given change in speed limit are shown to be greater for lower levels of initial speed limits. On average, states with a maximum speed of 70 mph (75 mph) were expected to experience 31% (54%) more fatalities compared to states with a 65 mph limit (see Savolainen et al., 2014, p. 45ff.). This gives rise to the idea, that the lower the initial speed limit, the higher the effects of a given nominal change may be.

Turning towards Germany, Manner and Wünsch-Ziegler (2013) note that "… accident severities on German Autobahns have not yet been analyzed in the literature… " (see Manner and Wünsch-Ziegler, 2013, p.40). They conduct research on several aspects influencing accident severity. Based on figures from the federal state of North Rhine-Westphalia from 2009 to 2011, they categorize accidents into fatal, severe injury, minor injury and property damage only. Since there exists no obligatory speed limit in Germany, they use a single dummy variable indicating a speed limit of 100 km/h or less. Interestingly, the pseudo-elasticities of their multinomial logit model produce counterintuitive results. If a speed limit was in place, it is estimated to increase the risk of an accident in one of the categories with person damage and decrease the probability of property damage accidents. The probability of a fatal, severe or minor injury accident increases by roughly 41%, 16% and 53% respectively, while the probability of only property damage decreases by 15%. This unexpected result arguably is due to speed limits being installed at sites where more accidents occur anyway (see Manner and Wünsch-Ziegler, 2013, p. 44). An alternative specification using hourly traffic instead of daily data changes this finding and produces results consistent with expectations. In this setting, the probabilities for fatal and severe injury are reduced by 51% and 19%, whereas minor injury accident chances rise by 6% and property damage collision remain almost constant. Qualitatively, they

[6] He notes that this finding is subject to limitations, e.g. due to speed data truncation.

[7] As categories they use maximum speed limits within a state of 60-65 mph; 70 mph; 75+ mph (see Savolainen et al. (2014), p. 45).

conclude that based on their data set no clear impact of speed limits on accident severity could be found (see Manner and Wünsch-Ziegler, 2013, p. 46f.).[8]
However, the general notion that accidents and accident severity tend to move in the same direction as the change in allowed maximum speed is supported in several other studies.[9]

Air Pollution

The combustion process of any vehicle operated with fossil fuels produces polluting emissions. These greenhouse gas (GHG) emissions and air pollutants jointly constitute the third important impact category. Under EU transport legislation, there are five regulated pollutants which the European Environmental Agency (EEA) lists as follows:

1. Carbon dioxide (CO_2) – the major and well-known GHG responsible for climate change acceleration and harmful to human health.
2. Hydrocarbons (HC) – result from incomplete combustion in the engine. HCs are toxic to human health and contribute to ground level formation of ozone, which in turn harms lungs, eyes etc.
3. Carbon monoxide (CO) – highly toxic gas that is especially harmful to people with cardiovascular diseases and contributes to ground level ozone as well.
4. Particulate matter (PM) – is only partly emitted through the tailpipes but the other share stems from abrasion emissions (wear of tires, breaks, clutches, etc.). PM is highly damaging to the respiratory system and causes cardiovascular diseases.
5. Nitrogen oxides (NO_X) – constitutes a group of chemicals comprising NO and NO_2. These also form ground level ozone and contribute to the acidification and eutrophication of waters and soils.

With the exception of PM, the major share of the emissions listed above occurs from exhaust emissions (see European Environment Agency, 2016, p. 9ff.).[10] Hence, if speed limits are to influence driving speeds and conditions, which in consequence will alter fuel consumption, these emissions should be sensitive to speed limit changes. As shown in the following paragraphs, they do find attention in several studies.

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[8] The authors note that these effects may partially be driven by the presence of construction sites, which are not controlled for in the alternative specification. In addition, the estimated elasticities are not statistically significant with exception of severe injury accidents.

[9] See e.g. Elvik (2013), Pauw et al. (2014), Kockelmann (2006), Ashenfelter and Greenstone (2004).

[10] Non-exhaust PM Emissions, e.g. wear from tires, brakes, road surface etc., oftentimes are similar or higher than exhaust PM emissions (see Amato et al. (2014), p.32). Timmers and Achten (2016) even conclude that the share of exhaust PM emissions may only be 5% to 10 % of total PM emissions from road transport. It can be expected that this effect is more pronounced in urban areas than in rural (see e.g. supplementary excel file to Klein et al. (2017).

Folgerø et al. (2017) evaluate the effectiveness of an environmental speed limit in Oslo, Norway on NO_2, NO_X, and PM_{10}, $PM_{2.5}$ separately.[11] They include five years of hourly measurement data from three air-quality monitoring stations located directly at the roads in question. In their regression results, they do not find a discontinuity in any of the pollutants, indicating no effect from the measure. In some cases their estimates are even positive but insignificant (see Folgerø et al., 2017, p. 17ff.).

Different conclusions are presented in van Benthem (2015). Using a difference in difference estimator on a linear regression specification, he estimates the speed limit effects on CO, NO_2 and PM_{10} as well as ozone (O_3).[12] By varying a so-called buffer zone, the perimeter around the treatment highway in which one assumes to measure an impact in the data from the speed limit policy, he includes or drops the daily data from certain monitoring stations within or without the zone. It appears to be "reasonable to assume effects for a distance of up to 10 miles" (see van Benthem, 2015, p. 54.). For the 10-mph speed limit increase and the central case, which defines treatment stations as those, located in a vicinity of 3 miles around the highways, he finds increases of 23% for CO, 15% for NO_2 and 11% for O_3 but no effect on PM_{10}. The latter result confirmed his expectations, for which he argues that a large fraction of PM_{10} is being emitted by diesel trucks which were unaffected by the policy (see van Benthem, 2015, p. 55). Additionally, within the cost-benefit part of his work, changes in CO_2 are inferred from fuel consumption effects and valued afterwards.

Bel et al. (2015) analyze the air pollution impacts of a speed limit reduction and the introduction of a variable speed system in the Barcelona metropolitan area where maximum speed limits were reduced from 120 (100) km/h by 40 (20) km/h. They use a fixed effects quantile regression model to generalize a difference in difference model. By this means the differences in the quantiles of treatment and control speed limit zones is measured. Their controls include traffic, temperature, other general weather data and even a binary variable for Sahara dust and fire. For NO_X and PM_{10} concentrations showed no or even a slightly positive effect. They adapt the approach to data from another area with variable maximum speeds and add, that those seem to succeed in improving air quality (see Bel et al., 2015, p. 81ff.).

A different method is followed in Savolainen et al. (2014) who use traffic speed data and road types as an input to simulate emission cases for 60 and 75 mph. They present changes for different pollutants and three vehicle types, namely passenger cars, light commercial trucks and motorcycles. Maintaining the order of vehicle type as above, they find changes

[11] PM emissions are categorized by their size. PM_{10} and $PM_{2.5}$ mean, that the particulates in the air have a maximum diameter of 10 microns (μm) and 2.5 μm respectively (see Umweltbundesamt, 2009, p.4).

[12] As argued above, Ozone is not amongst the regulated pollutants but HC and NO_2 contribute to its formation and may therefore be captured indirectly.

of +20.2%, +21.5%, -2.5% for CO; +12.7%, +9.7%, -4.7 for NO_X and +12.3%, -2.5%, -13.3% for PM_{10} and $PM_{2.5}$ (see Savolainen et al., 2014, p.117). These numbers indicate that raising speed (limits) increases CO and NO_X emissions except from motorcycles but decreases PM except from passenger cars.

NO_X and PM_{10} development has also been studied in the setting of a speed management zone with stringent enforcement (automatic fining supported by camera surveillance) on highway sections in Rotterdam and Amsterdam, The Netherlands. Keuken et al. (2010) argue that not only speed reductions but also reductions in dynamics of travel speeds, (which basically means stop-and-go traffic, congestion etc.) are effective in mitigating emissions. They apply two strategies to identify the pollution impacts of the 80km/h zones with strict enforcement. The first uses regression analysis on air quality data collected on site prior to and throughout the 80km/h test periods. The second method uses traffic data to identify changes in traffic dynamics on which they apply emission factors to approximate NO_X and PM_{10} reductions. Both approaches yield similar results: NO_X decreased by 20-30% and PM_{10} was reduced by 5-20% across the two cities and approaches (see Keuken et al., 2010, p. 2525). Again in some contrast, Dijkema et al. (2008) analyze the same policy in the Netherlands and find a significant decrease of about 7% in PM_{10} but no impact on NO_X.

Amongst the studies presented above, all works discussed effects on NO_x (or NO_2 separately) and PM (PM_{10} and/or $PM_{2.5}$), some considered CO, which is stressing the importance of these factors. The literature creates the notion that impacts of speed policies on air pollution are ambiguous. Interestingly, the all so well-known carbon dioxide (CO_2) is mentioned only in the paper by van Benthem (2015) and is analytically separated from the other impacts in his study. This draws the dichotomy between *global* and *local* air pollution. Global air pollution points towards GHG emissions triggering climate change while the local pollutants focused on in the review are rather concerned with direct human health issues. The subsequent paragraph is concerned with these health issues evoked by local traffic pollution.

Health impacts from local air pollution

The chain of thought for this paragraph directly links to the previous one. It has been emphasized above that, if speed limits are to influence driving speeds and conditions, which in consequence will alter fuel consumption, the emissions mentioned above should be sensitive to speed limit changes. Now, when emissions depend on speed limits, the limit turns into an instrument to improve health for the population exposed to bad air caused by vehicles. Therefore, "[a] final input for the cost–benefit analysis is the effect of the higher speed limits, through increased pollution, on health" (see van Benthem, 2015,

p.55). He stresses that traffic emissions can lead to severe adverse health effects. Examples are increased prematurity and lower birthweights as well as infant mortality. They may put forth cardiovascular and respiratory diseases and cause premature death.[13]
Employing data from six years of birth records from California as well as geocoding techniques in order to localize mother's living distance to treatment highways, his main finding is that a 10 mph increase in maximum speeds led to 17-45 additional fetal deaths per year (or a 9,4% increase in probability for third trimester fetal death). His infant health results are insignificant and the adult health effects are not included but later inferred from pollution concentrations within the CBA (see van Benthem, 2015, p.58).
The estimation results raise awareness that speed limits may in fact decrease fetal deaths if they can amend the traffic emission correctly. Unfortunately, other studies which directly investigate the relationship of speed limits to (infant/fetal) health impacts could not be found in the literature.[14]
The broad literature on the main impact categories that has been reviewed shall provide a foundation and intuition concerning the most important aspects of speed limit analysis. Now, it is turned towards the methodological part of this thesis where CBA as the designated assessment tool is introduced briefly before going into detail with the policy analysis.

3 THE ANALYTICAL FRAMEWORK – CBA

> *"CBA is an analytical tool to be used to appraise an investment decision in order to assess the welfare change attributable to it [...]. The purpose of CBA is to facilitate a more efficient allocation of resources, demonstrating the convenience for society of a particular intervention rather than possible alternatives."*
> European Commission (2015)

The terms "investment decision" and "intervention" in the quote above may equally be replaced by "policy" or "project", which does not change the underlying premise. Assisting in finding a more efficient allocation of travel behavior is the key that turns the analysis of speed limits into an economic matter. Maximum speed policies induce impacts affecting the welfare of the citizens of a defined society. The cost- benefit analysis aims to quantify and monetize these welfare changes and compares the resulting social costs and benefits to make a recommendation in favor or against a policy. Usually, the Kaldor-

[13] See previous section on emissions and their impact. For further literature on the relationship between traffic aspects and health see van Benthem (2015), p. 55 who provides an overview of seminal works.
[14] However, studies researching traffic and fetal health in general do exist (see Footnote 13).

Hicks Criterion (KH) is applied to do so. It is a decision rule stating that a policy should be adopted only if the beneficiaries could fully compensate the "losers" of the measure and would still be better off (see Boardman et al., 2014, p.32). This is fulfilled automatically when positive social net benefits are obtained:

$$Social\ Net\ Benefits\ =\ Social\ Benefits\ -\ Social\ Cost\ >\ 0 \qquad [1]$$

This simple equation introduces the perspective of normative welfare economics, which is taken in this CBA. If [1] holds, a policy is supported and the measure under consideration is potentially Pareto improving, which means that society shifts closer towards Pareto efficiency. As a major concept in welfare economics, the Pareto optimum describes an allocation in which no one can be made better off without making at least one person worse off (see e.g. Boardman et al., 2014).

In the case of speed, a Pareto efficient solution and thus optimal welfare, would be reached if all drivers were to travel at the particular speed that maximizes net benefits (or minimizes the cost of travel) (see Elvik, 2010, p.196). However, external effects,[15] erroneous accident risk perceptions and heterogeneous speed preferences are good reasons to believe that the individual choice of driving speed is likely to be inefficient from a society´s point of view. These "market imperfections" have often justified a policy intervention by means of limiting driving speeds (see Elvik, 2010, p.197).

It can make sense for the CBA to disentangle the external effects from the behavior change attributable to the policy impacts.[16] However, the primary goal is to figure out the *social* costs (benefits) which are defined as the sum of private and external costs (benefits) (see Brenck et al., 2016, p.402). Thus, it holds that:

$$Social\ cost\ =\ private\ cost\ +\ external\ cost \qquad [2]$$

To measure these social costs and benefits Boardman et al. (2014) have established an analytical framework consisting of a stepwise procedure to structure the CBA process. I adopt their stages for the workflow in this thesis. TABLE 3–1 lists the consecutive steps and maps them with the chapters and research questions in this thesis. Thus, the table represents the framework of the subsequent analysis.

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[15] External Effects of automotive use and adequate internalization strategies have been laid out extensively in Brenck et al. (2016), Parry et al. (2007). An introduction to external effects in the context of CBA can be found in Mishan and Quah (2007) and is generally covered by any introductory (micro-) economic textbook.

[16] I will classify the calculated results in this thesis as private or external in Chapter 8.1.

TABLE 3–1: MAJOR STEPS IN THE CBA			
No	Description of Task	Corresponding Chapter	Research Question
1.	Specify the set of alternative projects.	4	R1
2.	Decide whose benefits and costs count (Standing).	4	
3.	Identify and catalogue the impact categories.	2 & 5	
4.	Predict the impacts quantitatively.	6	R2
5.	Monetize all impacts.	7	R3
6.	Compute the value of each alternative.	8	
7.	Perform sensitivity analysis.	8	
8.	Make a recommendation.	9	

Source: Own table based on Boardman et al. (2014), p. 6, aligned with the structure of this work.

With this short wrap up on the purpose of CBA and its underlying welfare economic perspective in mind, the next chapter dives right into the analysis of a general speed limit policy for passenger cars on German highways.

4 SUBJECT AND STANDING

Kicking off the exploration, one has to define how the specific policy under consideration – the subject of analysis – is designed. What does the project look like and which alternatives are there?

It is advantageous to begin with the counterfactual to characterize the policy's setting. The counterfactual can be understood as the baseline option to compare the analysis results to, which is the project or policy that would be displaced when deciding in favor of the project under evaluation (see Boardman et al., 2014, p. 7). In this CBA, the status-quo shall serve this purpose.

Today, any vehicle is allowed to use the German highway system, provided its engine is capable of accelerating to at least 60 km/h. These roads, known as "Autobahn", are limited access roads with a minimum of two lanes per direction and are equipped with a median construction facility to divide the directions.[17] On these roads, there exists a speed recommendation of 130 km/h but no mandatory speed limit per se. There *do* nevertheless exist speed limits for certain reasons. Essentially, these reasons are, when highway sections in have proven to be accident-prone the past or if residents shall be protected from

[17] As an illustration APPENDIX 1 shows a real-world location plan as well as the cross section for a highway section in North Rhine-Westphalia, which was obtained from the state's highway administration during the data collection process.

noise. The latest official figures on the share of highways without a limit stems from a 2015 survey across states conducted by the Bundesanstalt für Straßenwesen (BASt); the federal highway research institute. It suggests that 70.4% of German highways remain without any speed restriction (see Kollmus et al., 2017, p. 4). The authors note that they can only present aggregated figures relative to the total highway system. This is because "due to the political weight of the discussion about a general speed limit on federal highways, the states linked the provision of data [on the sections with/without limits] to the condition that it is […] not being handed over to third parties" (see Kollmus et al., 2017, p.2). The remaining 29.6% of the overall 25,767 highway kilometer [18] are subject to either a static (≈ 21%) or a variable speed limit system[19] (≈ 9%) (see Kollmus et al., 2017, p.4). Additionally, sections may be restricted temporarily when construction works are in place.

For the roughly 70% of unrestricted highways, §18 of the German road traffic act (Straßenverkehrsordnung; StVO) imposes a couple of exceptions, which in effect leave just three vehicle categories untouched when it comes to the free choice of speed. The vehicle types that can freely choose their speeds on the respective sections are light duty vehicles (≤ 3.5 t), passenger cars and motorcycles without a trailer. Over the past years, passenger cars consistently accounted for more than 85% of the daily traffic on highways (see BMVI, 2017, p.109). Accordingly, the analysis will focus on this vehicle category.

The hypothetical policy considered at the core of this research is the introduction of a **general, static** and **permanent speed limit for passenger cars** on highways in Germany. Taking the outlined status quo as a reference, which is assumed to continue alternatively to the project, this means:

1. **General**: the limit applies to any highway user and any vehicle category if the highway section is not yet regulated differently. As long as the speed limit is set to a level above 100 km/h, which is very likely to be a reasonable constraint when comparing with maximum speed laws in Europe, this effectively targets only the vehicle categories named above.[20]

[18] Measured as distance km, meaning that a one km highway section with two travel directions is being counted as two distance km.

[19] Variable or dynamic speed limit systems allow for adaptation of limits to current traffic and weather conditions, usually by means of flexible LED- traffic signs. This adaptation to the current situations means that the posted speed limit is constantly updated based on traffic and weather information such that there exists repercussions in both directions between speed limits and traffic situation. This imposes challenges to the statistical analysis of such speed limit measures.

[20] APPENDIX 2 lists speed limits in several European countries. It can be seen that with the exception of Norway all countries in the list have a speed limit on motorways above 100 km/h.

2. **Static**: the highway sections without a speed restriction would either be prepared with commonly used metal traffic signs, or no signs would be set up at all. They are not variable in a sense that they depend on the current traffic situations.
3. **Permanent**: the speed limits are implemented and in force permanently and the regulation is not intended to be amended at a certain point in time.

Due to the hypothetical nature of the policy, this work embodies an *ex ante* CBA. Innately, such an analysis is subject to uncertainty, as it is inevitable to estimate and value the expected effects of the policy under reasonable assumptions.
One of the first necessary assumptions is to determine whose benefits and costs should count in the socio-economic evaluation (see Boardman et al., 2014, p.7). The decision for or against a speed limit is clearly one to be taken by the federal government of Germany, which in turn, can plausibly be viewed as a social planner. Their primary concern is often with the people of their respective jurisdictions. However, in this case standing shall be given to every highway user irrespective of his or her nationality. This is because some of the effects, for example, CO_2 emissions classify as global impacts. An ethical argument is also, that giving standing to domestic people only would imply that a foreigner who dies on German highways is not included in the welfare considerations. Hence, the study will quantify and monetize the impacts that occur to all individuals using the German highway system.[21]

5 Identifying Costs and Benefits

Now that the project has been defined and the group with standing in the CBA is determined, it is turned towards the identification of the *impact* categories. Boardman et al. (2014) state that impacts can be both outputs from a project as well as inputs to it, and may contribute to either the cost, benefits or to both sides of the calculation. They note that an impact needs to exert a cause-and-effect relationship of a projects' outcome on the utility of humans with standing. If impacts only affect the welfare of people without standing in the CBA, they are not to be counted. As a last remark they advise the analyst to recall that impacts may be a benefit for a (sub-) group of the population with standing but can simultaneously constitute a cost for another (see Boardman et al., 2014, p.8ff).[22]

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[21] Figures by Lensing (2010) suggest that about 90% of daily vehicle kilometers on German highways are driven by domestic vehicles anyway. Thus, giving standing to all road users is not far away from the domestic perspective.
[22] Applied to the present case a conceivable example for this phenomenon is that a speed limit restricts the choice of speed, which may cause welfare losses to the group of people enjoying a fast ride on a highway. Conversely, more conservative drivers could gain a social benefit from feeling safer on the highway if there are no (or at least less) cars traveling at extreme speeds.

Cataloguing impacts is a critical task as the selection will alter the outcome of the analysis. In some cases, the selection may have the potential to decide about whether a project has positive or negative net benefits – it can turn a “do” into a “don’t do” decision and vice versa.
The list of imaginable impacts from a speed limit change is long. The literature review in section 2 already provides an identification of broad impact categories. Since they are based on a wide-ranging foundation of academic works, these categories provide are a good starting point. Below the four pillars are recalled:

(1) Travel speed
(2) Accidents
(3) Air Pollution
(4) Health from air pollution

These impacts do not necessarily represent direct benefits or costs and include more than a single cost or benefit to society. For example, reduced travel speed itself is mostly not regarded as a direct cost but increased travel time from driving slower will usually be.
From these categories, one can drill down the most relevant quantifiable items for the present CBA, which are listed in TABLE 5–1.
Travel time and fuel consumption directly link to travel speed and are chosen as the core benefit or cost item that is being affected by this impact category. They classify as purely private since they fully accrue to the individual driver. Accidents are split into fatalities, severe injuries and light injuries, where it is the number of people harmed, that shall contribute partly to private, partly to social costs or benefits. Finally, the category air pollution is viewed in two dimensions to quantify, namely global and local emissions, as has been examined in the literature review. Both will be treated as external cost.
It is noteworthy, that the list does not contain changes in health impacts from pollutant emissions. Since I use an estimate of the social cost of emissions in the valuation section, I do not estimate the impacts on health from pollution directly. To avoid double counting, this impact is implicitly incorporated in the social cost of emission changes.
The items listed are intuitively plausible and match with the majority of aspects listed by (see Elvik, 2001, p.15) who discusses items that are generally considered in CBA for road investment projects in Norway. Thus, by basing the study on impact categories and their corresponding subcategories gathered from well-known literature, the selection of the cost or benefit items appears well defendable.

Table 5–1: Overview of quantifiable cost and benefit categories			
Impact categories	**Quantifiable Benefit/ Cost Items**	**Description**	**Classification**
Travel Speed	Travel Time	Change in time needed to travel a certain distance.	Private
	Fuel Consumption	Change in fuel when traveling at altered speed.	Private
Accidents	Fatalities	Change in fatalities from highway accidents.	Private / External
	Severe injuries	Change in severe injuries from highway accidents.	Private / External
	Light injuries	Change in light injuries from highway accidents.	Private / External
Air Pollution	Local air pollution	Change in emissions of local pollutants.	External
	Global air pollution	Change in emissions of global pollutant CO_2.	External

Note: The table lists the core impact categories as identified within the literature review and assigns relevant quantifiable items for the CBA. The Items are classified as private or external
Source: Own table.

The reader may potentially think of other impacts that could be of social interest. Of course, a CBA can impossibly capture all conceivable effects of a policy measure but should aim at operationalizing those with the highest expected effect or relevance. However, I discuss other benefits/cost categories in the sensitivity analysis to see how they would alter the decision.

6 Predicting Impacts

The previous section provided an answer towards the first research question (R1) of this thesis. A review of previous highway research was used to assemble a normative collection of the most relevant factors to be included in speed limit studies (Table 5–1). This chapter deals with R2, elaborating on the question, how a speed limit would change the identified benefit and cost items. In section 6.1 the study design and key backgrounds of the analysis are presented, whereas the remaining sections of this chapter estimate the direction and magnitude of change for each impact.

6.1 Study Design, Strategy and Data

6.1.1 Study Design

Given that any speed limit on highways in Germany is due to certain reasons, such as higher danger of an accident, analyses within the country may be criticized to suffer from selection issues. The mere presence of a speed limit is already caused by certain characteristics of the road section in question. In this sense, an incomparability of limited and unlimited sections within the country arises. Thus, it has to be expected that speed limits are endogenous when estimating their impact on the key variables such as travel speed.

In order to overcome this challenge, the empirical approach used in this thesis takes advantage of the fact that Germany is located in continental Europe. The country is surrounded by neighboring countries, all of which have implemented a general speed limit on high-speed roads. The idea is to identify German highway sections that do not underlie a speed limit but cross a federal border from where on they are subject to the respective limit of the neighboring country. In this way, a natural experiment can be constructed. This is an advantageous approach as the possibility of field experiments, i.e. randomly varying speed limits on a certain highway section, is basically not feasible. In this case, natural experiments are a suitable tool to target the research problem. One can think of the study design as a spatial before-after case study. The approach makes use of what will be called the "intra-highway" differentials – changes of a given variable between the domestic (Germany) and foreign (Netherlands) part of a particular cross-border highway. Thus, the identifying assumption is that *the impact variables observed in Germany would converge to the same values measured on the foreign part of the same highway, if Germany was to adopt the same speed limit policy as in the foreign country.*

To my knowledge, this method is fairly new and has not yet been used in the literature. The work therefore also adds to the transport research literature inasmuch as the identification strategy can potentially serve other research endeavors.

From a methodological point of view, the differences will be estimated using a descriptive comparison of the wide-ranging data collected (see 6.1.4). Initially, a regression design was planned, however, generating a reasonable set of control variables to obtain valid results was unfeasible within the scope of this thesis.

In theory, to operationalize the idea, one would want to find a long highway section, divided in the middle by a federal border. Ideally, the German part would be free of any speed limits while the foreign counterpart would be consequently restricted by the general speed limit of the neighboring country. Unfortunately, such a stylized highway does not exist in reality. Several steps and a lot of effort of this work were put into the mere identification of justifiable roads for the analysis.

Identification of highways

First, I composed a list of all neighboring countries of Germany. I eliminated those, which were either expected not to have comparable highway standards to Germany or those, where data collection and availability was expected to be cumbersome due to language barriers or differing standards (e.g. Czech Republic and Poland). Second, I assembled a list of all highways passing a border to the remaining countries as well as the corresponding federal states and the highway administrations in charge. Third, I conducted a mail-survey among the states highway administrations to clarify the availability of actual driving speed data as well as information about installed speed limits on the roads in question. This was necessary, because previous research efforts revealed that there exists no institution in Germany, which centrally collects these data.[23]

As a fourth step, it was necessary to reduce the number of highways for which data was available to a subset of roads with a high share of unlimited sections in the border region. After clarifying the availability of similar data within the foreign countries, a couple of highways remained, mostly leading from Germany into the Netherlands.[24]

As a final step towards the identification of suitable highways for the analysis, I controlled the comparability of the domestic and foreign part of the highways with respect to construction details and basic road geometry. Using publicly available online applications and geographical information systems (GIS), I constructed elevations profiles, a measure of curvature and checked for the number of lanes.

Finally, I identified two highways, which stand the list of requirements and are suitable for the analysis. Both lead from the state of North Rhine-Westphalia (NRW) to the Netherlands. On Dutch highways, the general speed limit currently is 130km/h. It was raised from 120 km/h by Melanie Schultz van Haegen, the former Minister of Infrastructure and the Environment, in September 2012. On June 26th 2012, she informed the House of Representatives in a chamber letter about the results of her previously conducted road experiments and presented the final picture of changes in the highway net (see Ministerie van Infrastructuur en Milieu, 2012). These experiments were concerned with potential issues such as NO_2 concentrations and traffic safety. The results broadly supported the feasibility of higher speed limits on 48% of the Dutch highway net. Under the motto "From A to better" she ran a cross-media communications campaign to inform the public about the policy amendment and revised the old traffic signs on affected roads (see Ministerie van

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[23] See APPENDIX 4

[24] Initially, another highway to Austria was considered. Its inclusion in the analysis would have been a good check for robustness. Unfortunately, data on the German part turned out to be insufficient. However, the Austrian highway institute ASFINAG quickly provided data on driving speeds and traffic intensities and may be a good partner for future research efforts.

Infrastructuur en Milieu, 2012).[25] The speed limit of 130 km/h currently valid in the Netherlands is an interesting scenario to compare the German situation with. As the recommended speed in Germany is the exact same level, it provides an opportunity to analyze *which impacts are to be expected if this regulation was a binding limit rather than a mere recommendation*.

6.1.2 The analyzed highways

The core characteristics of the two highways analyzed in this work are summarized in Table 6–1. The first highway is the road number A61 in Germany which I label "H_{1G}", denoting the German part of Highway 1.[26] Its Dutch extension is highway number 73 in the Netherlands (labeled H_{1N} accordingly).[27] The second highway is the A3 (H_{2G}) for the German part and its number changes to A12 (H_{2N}) in the Netherlands.
I was able to define the road segments, such that they ensure a comparable length for both, the domestic (totaling 144 km over both German sections) and foreign (147 km) parts. The overall length of the selected sections adds up to roughly 290 km (or 580 direction-km). Except for the Dutch H_{2N}, all roads consistently have four lanes. The H_{2N} has a few segments on which there are six lanes, which is not problematic since all relevant sections with a posted speed limit of 130 km/h have four lanes. North Rhine-Westphalia and the Netherlands are also well suitable for the analysis because the land in the region is essentially flat. To support this fact, I present descriptive statistics on the slope of all highways in APPENDIX 5. I constructed the elevation statistics using official geo-information web applications.[28] The highway sections were cut into pieces of 1000m, for each of which I calculate the slope.[29] The average absolute slopes vary between 0.23% - 0.45% (see TABLE 6–1 and APPENDIX 5). This means that across all 1000m pieces per highway, the height differential was on average 2.3 to 4.5m. Put simply, this is essentially flat. The data underpins the statement of a road planner from the highway administration in NRW, who stated that slopes > |1,5%| are not to be expected in the area. One exception to this is the maximum incline of roughly 2% observed on H_{2G}. However, this is still a low value and a rare exception (see Boxplot in APPENDIX 5), which could also be caused by minor inaccuracy of the constructed elevation profile.

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[25] APPENDIX 3 shows the map with the resulting speed limits after the amendment, which was attached as additional material in the chamber letter by the minister. I indicate the highways covered in the present work.
[26] The labeling is not intended to provide a ranking in any sense.
[27] In fact, a short segment, which connects the A73 and the A61 in the border region of the Netherlands, belongs to highway number 74 but I do not include data on this segment.
[28] These applications are Geoportal NRW and Actueel Hoogte Bestand Nederland.
[29] Thus, for a 100 km stretch of highway, an equal number of individual slopes would be calculated. Then the descriptive statistics over these values are presented.

In the absence of noticeable mountains, roads do not need to be adapted to maneuver through difficult terrain but can be built relatively straight. Intentionally, highways are not constructed as a straight line to prevent fatiguing travelers. However, the curves on the chosen sections are moderate. As a basic measure of geometry, I calculated the ratio of the highway length to the linear distance of its start and ending point. The values range from 1.07 to 1.2, which describes that the highways are 7%-20% longer than the linear connection would have been. From TABLE 6–1 it comes out that the foreign highways are slightly more "curvy" than their German counterparts. However, given the moderate differences, it seems reasonable to assume this not to invalidate the general comparability of the sections.

To get a better impression of the highways selected, I visualize them in a map, highlighting their location and major cities around (FIGURE 6-1). It already shows the speed measurement stations used in the analysis, which will be explained in detail in section 6.1.4.

TABLE 6–1: THE ANALYZED HIGHWAYS

	Highway 1		**Highway 2**	
Label	H_{1G}	H_{1N}	H_{2G}	H_{2N}
Country	Germany	Netherlands	Germany	Netherlands
Highway Number	A61	A73	A3	A12
Highway km*	0 – 79	39 – 109	0 – 65	149 – 72
Length of section**	158 km	140 km	130 km	154 km
% of no (domestic) or general speed limit (foreign)	71%	82%	95%	15.04% (day) 58.19% (night)
Ratio of Road length to linear distance	1,09	1,15	1,07	1,2
Lanes per direction	4	4	4	4 (partly 6)
Slope Statistics:				
Average	0.44%	0.25%	0,42%	0,23%
Std.Dev.	(0.32%)	(0.24%)	(0.58%)	(0.22%)
Min/Max	0.01% / 1.45%	0.00% / 0.90%	0.01% / 2.08%	0.00% / 1.00%

Note: The table provides an overview of the key facts of the highways analyzed in the thesis.
* In each column, the first number indicates the point at the border and the second marks the end of the relevant section within the country. ** Measured as distance km, i.e. counting the highway length for both directions.
Source: Own table and calculations. Data on speed limits according to 6.1.3. Ratio of road length as well as no. of lanes obtained from analysis within GIS application. Slope statistics obtained from elevation profiles constructed using official public geographic web applications: Geoportal NRW and Actueel Hoogte Bestand Nederland.

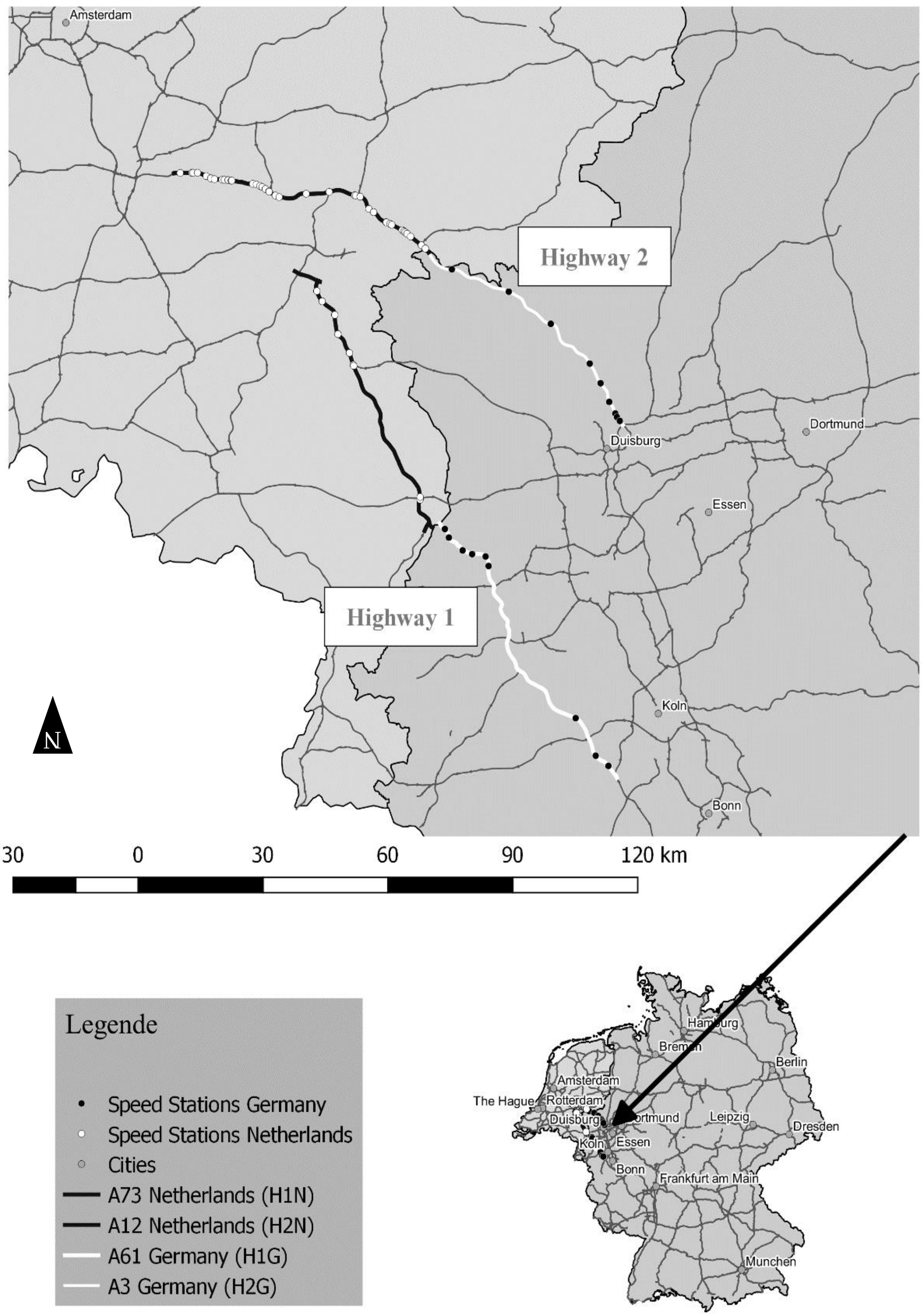

Figure 6-1: Selected Highway sections between Germany and the Netherlands including speed stations and major cities.

Source: Own illustration. Shapefiles for map creation were collected from Nationale Databank Wegverkeersgegevens" (NDW), www.geoportal.de and www.geofabrik.de. Speed station locations are coded based on location coordinates provided by the respective speed station operator. Germany (dark grey filling) and the Netherlands (light grey filling).

Another aspect when comparing two highway sections is the traffic demand on the analyzed roads. If one highway was significantly more used than the other, intra-highway differences between domestic and foreign sections may be driven by traffic intensity. To account for this, average annual daily traffic (AADT) is a central variable employed in traffic models. It is calculated as the annual average of vehicles passing a given highway measurement point each day for a given year (see Leduc, 2008, p.9). Based on the collected data for this thesis (see 6.1.4) I estimate the AADT for the German and Dutch part of both highways.[30] Over the years 2015-2017 the average vehicles per day on H_{2G} (H_{1G}) were 48,535 (41,301) compared to 47,708 (47,099) on the Dutch H_{2N} (H_{1N}). This is a desirable estimate, since all highways (with a slight deviation on H_{1G}) are close to the German average daily traffic, which was at 48,800 in 2014 (see BMVI, 2017, p.106). These figures reassure that I do not analyze highways with an unusual traffic density.
Moreover, the estimates show that the country differences in daily traffic are not of much concern. For Highway 2 the absolute difference in AADT is merely 827 vehicles. On Highway 1 the same difference amounts to a larger but still not critical 5799 vehicles per day.[31] For the sake of the argument made, namely, that traffic density is in a comparable range on each of the two roads, the latter figure is not perfect but acceptable.
Having obtained these numbers it is also possible to provide an estimate of the annual vehicle kilometers traveled per section. This can be easily computed by

$$vkm_{Hc} = AADT_{Hc} \cdot 365 \cdot l_{Hc} \qquad [3]$$

Where *vkm= estimate of annual vehicle kilometers per year*
Hc= Highway section in country c
AADT = Average annual daily traffic
l= length of highway

(see Scholz, Schmallowsky, & Wauer, 2007, p17).

The *vkm* describe a statistical estimate of the total vehicle kilometers driven on average per year for a given highway. Thereby the estimate constitutes an important information as some input factors (e.g. accidents) need to be scaled by some measure of highway

[30] See APPENDIX 6 for calculations.
[31] The figure may appear large at first. However, a regular four-lane highway with no speed limit in Germany has a capacity of around 3400 vehicles/h (see Scholz, T., Schmallowsky, A., & Wauer, T (2007), p. 20) and many highways reach daily traffic of more than 100,000 vehicles. 5799 vehicles/day translate into 241 vehicles/h, which does not affect traffic flow very significantly.

usage to maintain comparability. TABLE 6–2 comprises the estimates for the vkm per section. As the inputs to the calculation are the specific length of a road segment and the measure of AADT, which have been shown to be relatively similar across the highways, also the vehicle kilometers traveled lay in a narrow bandwidth. The estimates will for example be used in the valuation of accidents and provide a final important estimate for describing the highways. The next section finalizes the picture and looks at the overview of speed limits in more detail.

TABLE 6–2: ESTIMATES OF MEAN ANNUAL VEHICLE KILOMETERS TRAVELED PER HIGHWAY SECTION.

	Unit	**H_{1G}**	**H_{1N}**	**H_{2G}**	**H_{2N}**
AADT	Vehicles/ day	41,301	47,099	48,535	47,708
Annual Average Traffic	Vehicles/ year	15,074,865	17,191,135	17,715,275	17,413,420
Length of Highway	km	79	70	65	77
Annual vehicle km traveled (vkm)	Vehicles* km/ year	1,190,914,335	1,203,379,450	1,151,492,875	1,340,833,340

Source: Own Table and calculations. The underlying speed data is described in section 6.1.4. Highway length was measured in GIS application (identically to values in TABLE 6–1).

6.1.3 Speed Limits on the analyzed highways

To evaluate the impact of speed limit differences, it is indispensable to get a good idea of the distribution of speed limits on the highways in question. Speed limits are subject to constant changes in several dimensions. Amongst other scenarios, they can be differentiated by time of the day, vehicle classes or driving direction; they are installed when construction works are going on or when the road surface is damaged. Accounting for all potential issues is a tedious exercise even for a single highway and country. As a realistic approximation and consistent with the project approach, I concentrate on the *permanent* speed limits posted on the sections.[32]

For North Rhine-Westphalia, I received an overview of the posted speed limits by highway km for 2016 and 2017. The information was provided by the Ministry of Transport of the federal state of North Rhine-Westphalia („Ministerium für Verkehr des Landes Nordrhein-Westfalen“). Fortunately, the relevant highway sections did not change over the years. The speed limits for the Dutch highways were obtained from a GIS-shapefile

[32] As personal correspondence with the highway authorities of NRW revealed, an overview of short-term speed limits (e.g. for construction sites) is neither existing nor practicable to maintain. Often, several authorities are responsible for operating and maintaining certain sections of the same highway and consolidated information is not available.

that is published in the open data portal of the national database of road traffic data “Nationale Databank Wegverkeersgegevens” (NDW).[33] As this data expresses the current state, I compared it to the map available from the 2012 chamber letter mentioned in 6.1.1, which sketches the same picture. Thus, based on the consonance of 2012 and current speed limits, I assume that permanent speed limits between the amendment of the national maximum speeds in Sep 2012 and the time of writing this thesis did not experience relevant changes.

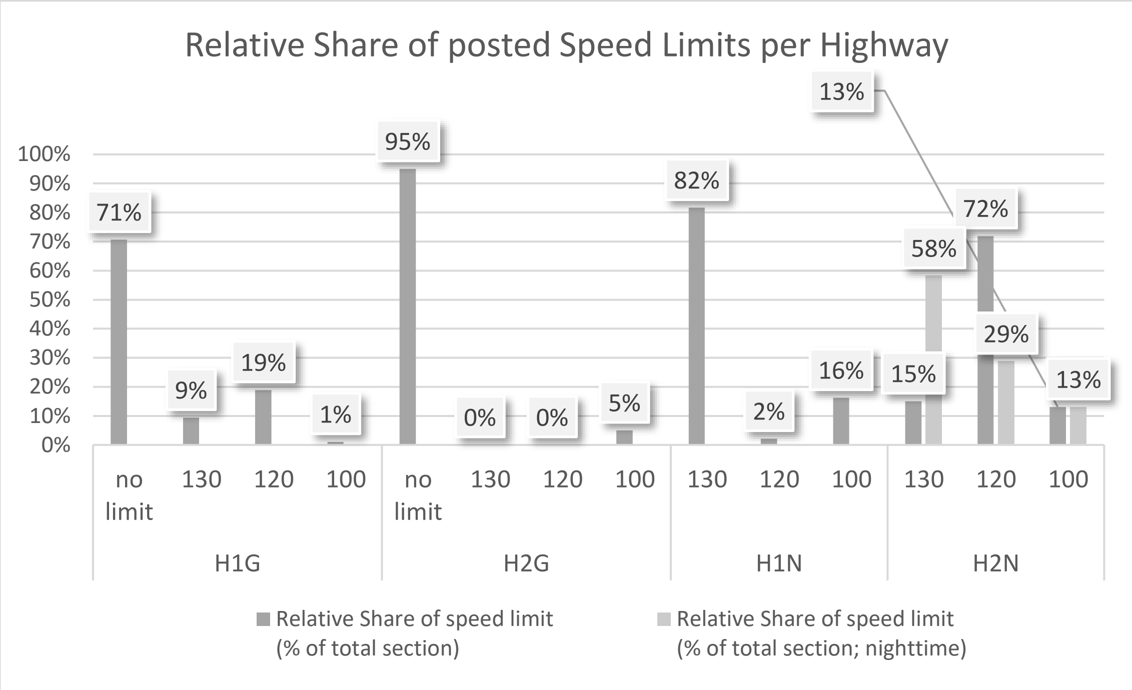

Figure 6-2: Distribution of posted speed limits on the analyzed highways (km/h). Source: Own calculations and illustration based on data from „Nationale Databank Wegverkeersgegevens" (Netherlands) and the Ministry of Transport of the federal state of North Rhine-Westphalia (Germany).

FIGURE 6-2 depicts the distribution of speed limits on the selected roads. The largest parts of the German highways have no posted speed limit (71%/ 95% on H_{1G}/H_{2G}). In the Netherlands, H_{1N} is subject to the general speed limit of 130 km/h over 82% of the defined road. Only H_{2N} is somewhat more variable. During the day (6 am to 7 pm) the highest share is limited to 120 km/h (72%) which falls to 29% in the remaining hours of the day due to time differentiation. Hence, at night, on 58% of the highway vehicles are allowed to travel at 130 km/h. I deal with this exception by only including data from these stations and time periods, where there was a 130 km/h limit posted. The description of the data and its sources follows in the next section.

[33] The current version is retrievable under http://opendata.ndw.nu/ (Link last checked 12.08.2018).

6.1.4 Data

Collecting and assembling data was a major task of this thesis. The aim was to collect data on travel speeds and accidents specifically pinned down to the selected highway parts for both countries. This section explains what data is used for the analysis and where it is obtained from. The overview is structured by category. In the impact estimation parts hereafter, the details on the descriptive statistics are laid out (section 6.2 - 6.4).

Travel speed data

The data on travel speeds was collected from inductive loops placed under the road surface. These loops count the number of vehicles passing the station, categorize them by size and summarize the results for selectable time intervals. Some of these stations also measure travel speeds of the individual vehicles in each category and provide mean speeds at the same level of aggregation. For the analysis, I use hourly data on speeds and vehicles for passenger cars in the years 2015-2017. In Germany, the data was provided by the state's highway administration, called "Straßen NRW". For the Netherlands, the data stems from the NDW Database. Since the publicly available online version only provides highly aggregated figures, the NDW equipped me with a user account to their remotely accessible detailed database.

The included stations had to fulfill several requirements to ensure suitable and comparable data.

1. Data is available for the full time span in both countries.
2. Stations are located on the main carriageway (no side arms, acceleration lanes, etc.)
3. The station is an induction loop and not any other type of speed measurement instrument (e.g. infrared measurement sites).
4. The induction loop measures traffic speeds *and* intensities. Not only one of these components.
5. The stations have a vehicle classification available, which allows for comparison. The German data differentiates passenger cars and trucks. In the Netherlands the stations differ in their categorizations. I could only use stations with a certain three-type classification in order to observe a category for passenger cars that is comparable to the German data. The Dutch category chosen is defined as all vehicles under a length of 5.6m, which effectively corresponds to passenger cars.[34] significantly

[34] One has to abstract from motorcycles which may fall into this category as well. However, their share on highways is so low, that this abstraction is not expected to bias the data.

6. The station provides the arithmetic means of travel speeds. Especially in the Netherlands, several stations transmit harmonic means of the hourly data, which would lead to incomparability to the German figures as they use arithmetic averages.

These requirements considerably reduced the number of available stations leaving me with 91 suitable speed measurement stations. These are distributed across the highway as seen in TABLE 6–3.

TABLE 6–3: NUMBER OF SPEED MEASUREMENT STATIONS AND SPEED AND VEHICLE INTENSITY OBSERVATIONS BY HIGHWAY (2015-2017).

	H_{1G}	H_{2G}	H_{1N}	H_{2N}
Number of speed stations	12	18	14	47
Total number of hourly observations	532,317	904,108	683,826	1,262,448

Source: own table based on collected speed data as described above.

In Germany, these stations measure both lanes per direction, while in the Netherlands there exist different stations, some of which measure only one lane while others include two lanes per direction. All stations provide the driving direction, the date, hour, and the count of all vehicles passing a certain station. Finally, I assigned the corresponding speed limit to each station based on my information of posted permanent limits.

Accident Data

There are two margins one can adjust to obtain a reasonable number of accident observations. The first is the road length, which is fixed in my study. The second is the time horizon included. Thus, for the accident data I opt for a longer period, namely 2005 to 2016.

For the state of North Rhine-Westphalia, I collected accident data from the state's road administration.[35] The organization provided the accidents tailored to the precise road segments as defined in my request and limited to accidents on the main-carriageway only. This is necessary since (consistent with the speed data) accidents in the side arms etc. are disturbing when analyzing the speed limits on the main road. The data draws on police records taken on-site of a particular accident and contains detailed information for every

[35] Originally, I obtained data for all years, the highway administration was able to provide at the time of my request, namely 2003 to 2017. After aligning the data with the Netherlands, I dropped the years 2003, 2004 and 2017 since they are not available for the foreign highway parts.

recorded accident on the highway sections. A single accident entry contains a large number of variables that can be used for further analysis (e.g. road condition, driver characteristics etc.). Each accident is classified into severity categories: deadly accident, accident with at least one severe injury, accident with at least one light injury, and two categories for accidents with property damage only (one separated if drugs/alcohol were involved). I ignore the latter because in 2008 the ministry of the interior initially obliged police officers to record light property damage accidents, which leads to underreporting in the previous periods.[36] However, the property damage only accidents will be elaborated on in the sensitivity analysis.

TABLE 6–4: DEFINITIONS OF ACCIDENT SEVERITY CATEGORIES IN GERMANY AND THE NETHERLANDS.

	Germany	Netherlands
Road fatality	Road death, which occurs within 30 days of a road crash.	Death resulting from a road crash within 30 days of the crash.
Seriously injured	Any person immediately taken to hospital after a road crash for inpatient treatment of at least 24 hours.	Person admitted to hospital for an injury with a Maximum Abbreviated Injury Score of two or more (MAIS2+).
Slightly injured	Any other person injured in a road crash.	Other injuries, not admitted or admitted to hospital with a maximum Abbreviated Injury Scale score of one (MAIS1).

Source: own table based on ITF (2017).

For the foreign counterparts I started with a large data set called “Accidents and Network” which is provided by the “Ministerie van Verkeer en Waterstaat Rijkswaterstaat”.[37] Consistent with the German data, the accident information stems from police records taken on-site of a particular accident.[38] In the Netherlands, each accident is linked to the digital road network (national roads database file). The files list all accidents recorded in a given year and are intended explicitly to provide a basis for policy evaluation and other research. Because the data processing changed in 2004, I ignore earlier data. Thus, my data set covers the years 2005 to 2016.

[36] This was already found by Manner and Wünsch-Ziegler (2013) and I could verify this information during my personal correspondence with state officials.
[37] The data is available under https://www.rijkswaterstaat.nl/apps/geoservices/geodata/dmc/bron/ (last checked: 12.08.2018).
[38] This fact also implies that accidents that are not registered by the police do not enter the statistic. This gives rise to potential issues of different rates of unknown cases in the two countries, which I can´t observe. However, for the severe categories such as fatal and severe accidents these figures are expected to be marginal.

Rijkwaterstaat provides the raw data sets on an annual basis. Each data set consists of several separate files structured by the core data on the accidents itself, their respective involvements and the current road network in each year. A large shapefile for use in geographical information systems is provided within each year. Because I only analyze *parts* of the two highways, it was necessary to determine the identical highway sections as used for the speed data. Unfortunately, due to changes in the network, the section IDs are not stable over time. Therefore, I use each year´s shapefiles to reduce the road network information to the same relevant sections. After excluding all sections that are not the main carriageway I extracted the year-specific highway section IDs. This allows me to link the accident files (stored in separate spreadsheets) to the identified section IDs. With this procedure, it was possible to assemble the accidents, which have taken place on the exact defined roads in a given year.

After assembling the section-specific accidents for both countries, I aligned the included variables whenever possible. Important for the study here is the alignment of the severity category variable. The definitions for the accidents with person damage are shown in TABLE 6–4. The Netherlands defines its classification based on the maximum abbreviated injury score (MAIS) which was developed by the American Association for the Advancement of Automotive Medicine in the USA. The AIS classifies injuries on a scale from 0 (no injury) to 6 (currently untreatable).[39] A direct translation of the German accident statistics to the AIS score applied in the Dutch definitions is not available (see Baum et al., 2011, p. 14). However, it is clear that the fatal crashes are subject to the same definition. The two injury categories are more cumbersome to align, but there is information allowing to infer from.

For an injury to be classified as "severe" in the German statistic, it is linked to the condition that the person is hospitalized for at least 24 hours. Now in ITF (2017) the authors use extrapolated data from the Hannover and Dresden area where they are able to come up with some estimates of serious injuries in 2015 including a MAIS score. They note that "in 2015, 15 442 or 22.8% of all hospitalized road crash casualties [in Germany] had a MAIS of 3 or above" (see ITF, 2017, p.193). This implies that the remaining share of *hospitalized* casualties has had a MAIS below this value. Since the MAIS 1 is classified as "minor" injuries and the lower category 0 applies to unhurt persons, it can reasonably be concluded that only MAIS scores of 2 ("moderate") or above contribute to the category of severe accidents in Germany as well. At a minimum, potential differences in the definitions can be expected to be inconsequential for the analysis.

Finally, it may be noted that the Netherlands data has one category for property damage accidents, which applies if an accident simply did not have any person hurt. On the other

[39] Definitions used here come from Haasper et al. (2010)

hand, in Germany there were three categories for property damage only accidents (serious property damage, light property damage, property damage and alcohol/drugs involved). I merged these categories to generate consistency with the Dutch data.

6.2 Impact of a general speed limit on travel speed

The central question to be answered in this section is: *How would travel speed change if there was a speed limit introduced on German highways?* It has become common practice to review three main performance measures, namely mean speeds, 85th percentile speeds and measures of speed variance.[40]

For the present case study, one may expect that all three measures are lower in the Netherlands, since a speed limit introduces a constraint on drivers speed choice. Furthermore, the reduction in 85th percentile speeds may be more pronounced than the decrease in mean due to less excessive top speeds, which would underline a more homogenous traffic flow. From these theoretical thoughts, I derive the following hypothesis to analyze empirically in this section:

1. ***A speed limit on German highways reduces average travel speeds.***
2. ***A speed limit on German highways homogenizes the traffic flow and reduces top speeds.***

I use the dataset introduced above to evaluate differences between the Dutch and German highways and compare the results of the two highways to each other to check for robustness of the results. For the highway $H_{2G,}$ I restrict the data set to only these stations where a speed limit of 130 km/h was posted in order not to bias the analysis by the inclusion of differing stations.

In TABLE 6–5 the speed observations are summarized by highway. For the years 2015-2017 and over all stations per road, mean speeds and standard deviations are lower on the Dutch highways. In addition, the top speeds are more pronounced in Germany.

TABLE 6–5: SUMMARY OF HOURLY MEAN SPEED BY HIGHWAY DURING THE YEARS 2015-2017.

		Obs	**Mean**	**Std. Dev.**	**Min**	**Max**
Highway 1	H_{1g}	518,724	121.388	13.804	1	232
	A_{1n}	603,233	118.514	11.076	2	189
Highway 2	H_{2g}	904,108	123.735	16.827	1	250
	H_{2n}	486,972	116.018	14.848	3	188
Overall		2,513,037	120.502	14.904	1	250

Source**:** own table based on speed data as described in section 6.1.4.

[40] See e.g. Savolainen et al. (2014), Kockelmann (2006) Gates et al. (2015).

FIGURE 6-3 shows a box plot graph of the assembled speed data by highway. The median values are in a similar range over the highways but slightly higher for Germany when compared with the Dutch roads. The interquartile range and adjacent values are quite symmetrically arranged around the median value for each highway, implying little skewness in the distribution.[41] Yet, the graph shows lower variability on the Dutch highways. Several outliers are displayed on each highway for both lower and higher speeds than usual.

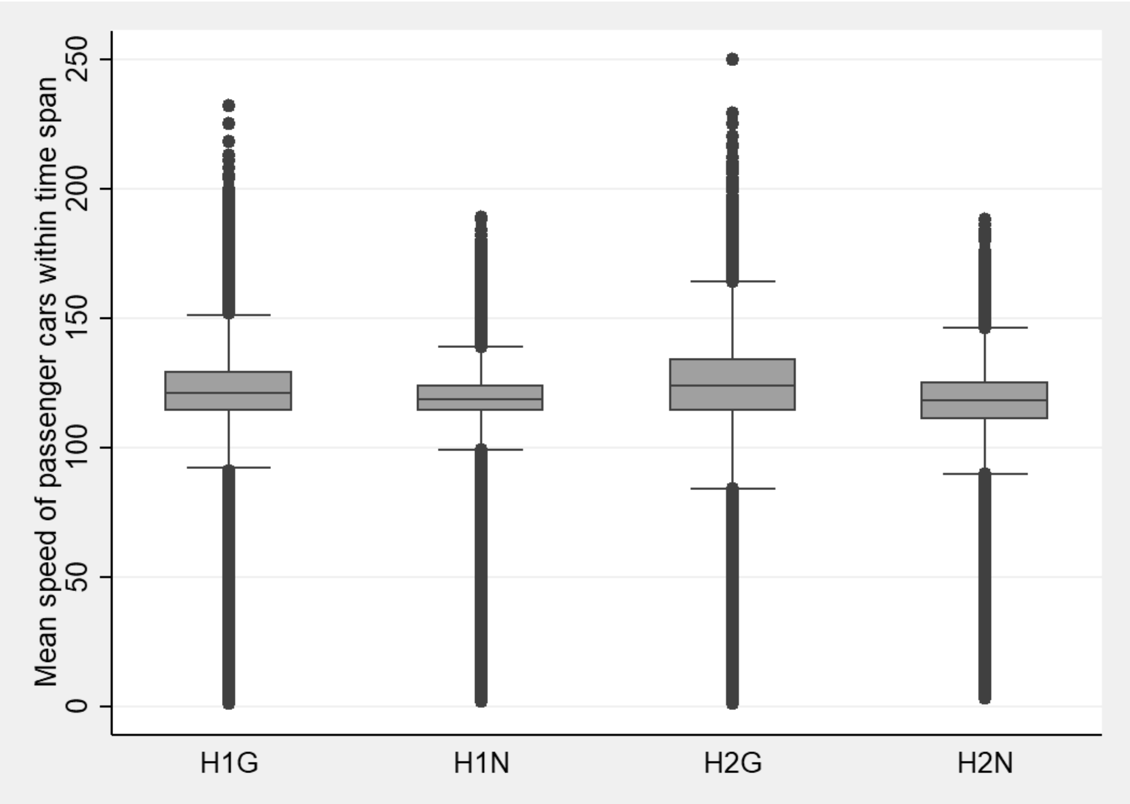

Figure 6-3: Boxplot graph of observed hourly mean speed by highway, 2015-2017. Source: own figure based on speed data as described in 6.1.4.

These can be explained by traffic intensities which cause mean speeds to be lower, if traffic is high and lead travelers to speed up, when facing an empty road. The graph also reveals that the German data contains several observations of hourly mean speeds above 200 km/h, while the maximum hourly averages measured on the Dutch roads did not exceed 189 km/h. This is in line with expected behavior, since higher speeds can be driven legally in Germany. APPENDIX 9 puts together the mean speeds and traffic intensities for

[41] APPENDIX 8 plots the distributions per highway, which support a symmetric distribution around the mean for each highway.

hours in which the speed was measured above 200 km/h and shows that top speeds are observed only when traffic is very low in the corresponding time span.[42]

The intuitive phenomenon that speed decreases as traffic density increases and approaches zero at the maximal traffic density is called speed-density relationship.[43] Often traffic engineers are interested in calibrating models and estimating functions for this relationship, which is not within scope of this work. However, I calculate the correlations of mean speed and number of vehicles in a given hour for each of the highways, which range from -0.37 to -0.52, thus showing a medium strong negative relationship.[44] Despite these figures being plain correlations, one may hardly argue that the direction of causality is such that there are more cars on the highway because people drive slower. With a high degree of certainty, reality is vice versa.

TABLE 6–6 comprises descriptive statistics of the speed data and reveals further insights into the truly driven speeds by highway and year. Panel 1 tabulates mean speeds and 85th percentile speeds for the years 2015-2017. The data is averaged over all stations on a particular highway for a given year and the standard deviation and number of observations is reported. For H_{2N} I restrict the stations to those, which are located in a section with the general limit of 130 km/h (restricted set of stations).

Firstly, it can be noted, that yearly mean speeds do not reach the Dutch general speed limit of 130 km/h on any of the domestic or foreign highways. Due to the high aggregation level, this should not be surprising. The 85th percentile in Germany is always above 130 km/h, which indicates that around 15% of hourly observations exceed this threshold. In the Netherlands, the 85th percentile speed is in no case higher than roughly 126.5 km/h. In addition, there are no visible time trends in the annual data. For a time period of three consecutive years it seems reasonable to assume no structural changes in motorization, improvement of vehicle safety or altered vehicle composition on the roads which one would need to take care about in the analysis.

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42 The data included eight outliers on H_{1G} with an average speed of more than 200 km/h where traffic intensities ranged between 94 and more than 400 vehicles per hour. After investigating the observations more closely, I decided to eliminate them due to a high chance of misreported data.

43 See Greenshields Bruce D. (1935).

44 See APPENDIX 10 for scatter plots of the relation between mean speed and count of vehicles per hour as well as a table of the correlations by highway.

TABLE 6–6: SUMMARY STATISTICS OF COLLECTED SPEED DATA.

Panel 1: mean speeds and 85th percentile speeds by highway for the years 2015-2017 (km/h).

		2015		**2016**		**2017**	
		Mean speed	85th percentile speed	Mean speed	85th percentile speed	Mean speed	85th percentile speed
Highway 1	H_{1G}	121.777	131.208	122.099	131.641	120.299	130.560
		(13.380)	(10.989)	(13.848)	(11.718)	(14.113)	(10.444)
		175,560	179,640	169,509	175,012	173,655	177,643
	H_{1N}	118.851	125.943	118.563	126.326	118.121	126.466
		(9.372)	(3.876)	(11.465)	(5.236)	(12.202)	(5.612)
		201,684	213,530	203,601	207,768	197,948	200,856
Highway 2	H_{2G}	124.409	137.466	123.310	135.792	123.476	136.703
		(16.685)	(11.260)	(16.758)	(12.735)	(17.023)	(12.014)
		305,802	311,020	304,906	311,742	293,400	294,630
	H_{2N}	115.319	122.757	115.950	124.085	116.749	125.754
		(13.906)	(6.882)	(15.081)	(8.380)	(15.445)	(9.296)
		159,025	196,524	160,874	189,358	167,073	200,468

Panel 2: differences in mean speeds and 85th percentile speeds as well as their respective standard deviations (km/h).

H_{2G}-H_{2N}	9.090	14.709	7.359	11.707	6.727	10.949
	2.779	4.378	1.676	4.356	1.579	2.717
H_{1G}-H_{1N}	2.926	5.265	3.537	5.315	2.178	4.094
	4.008	7.114	2.383	6.482	1.911	4.832

Note: Panel 1 reports mean speeds and 85th percentile speed by year and highway. Standard deviations written in brackets, the third line for each highway is the number of observations. Mean speeds are yearly averages over hourly observations while I have daily values per station for the 85th percentile which is then averaged per year and highway. Only stations located where the general speed limit of 130 km/h is posted are included. Panel 2 calculates differences between the German and the Dutch value for mean speeds and 85th percentile as well as their corresponding standard errors.
Source: own table based on data as described in 6.1.4.

Throughout all years and for both highways, the mean travel speeds and the 85^{th} percentile speeds are higher on the German highways relative to the Dutch parts. The differences are calculated in Panel 2, where I subtract the Dutch from the German figures. All values are positive and indicate the difference for a given year. For example, in 2016 the cars measured at the stations along the highway H_{1G} were about 3.5 km/h faster than at the stations along the H_{1N}. The standard deviation amongst observations for the same highway and year was about 2.3 km/h higher in Germany. When exploring the standard deviation of the variables it becomes salient that observations vary substantially less on the Dutch highway sections. This would strengthen the hypothesis, that traffic flow on the speed constrained highway sections is more homogenous. Accordingly, 85^{th} percentile speeds decrease stronger in each year than mean speeds, which additionally supports the presumed reduction of top speeds and alignment of the speed distribution when speed limits are present.

It is of major interest to compare the differences between the two highways analyzed to see how robust the calculated speed declines between Germany and the Netherlands are. TABLE 6–6 gives a first indication, that the intra-highway differences in mean speeds and 85^{th} percentiles are structurally more pronounced for Highway 2 than for Highway 1. For example, in 2015 on Highway 2 mean speeds have been 9.1 km/h lower in the Netherlands compared to the German part of the highway, while this difference was only about 2.9 km/h on Highway 1. For illustrational purposes, I include the calculations where I do not restrict the stations of H_{2N} in APPENDIX 7.[45] With the restricted set of stations on Highway 2, the differences between the two highways plausibly decrease, but the general notion of a higher "intra-highway" speed differential on the section remains.

Two effects account for this imbalance. On the one hand, mean speeds on H_{1G} were structurally 2-3 km/h higher than on the H_{2G}. Second, mean speeds on H_{2N} were structurally 1-2 km/h above those on the H_{1N}. Jointly, these effects go in the same direction. A plausible explanation for this can be found in the more uniformly distributed speed limits along Highway 1 (see Figure 6-2). This creates a better traffic flow, which is evident in the lower standard deviations along the H_{1N} despite higher travel speeds. For the German highways, this reversed relation between speeds and standard deviation cannot be found, but the differences in the distribution of speed limits are significantly smaller.

[45] APPENDIX 7 duplicates the descriptive statistics and annual differences as calculated in TABLE 6–6 but includes *all* available stations on H_{2N}.

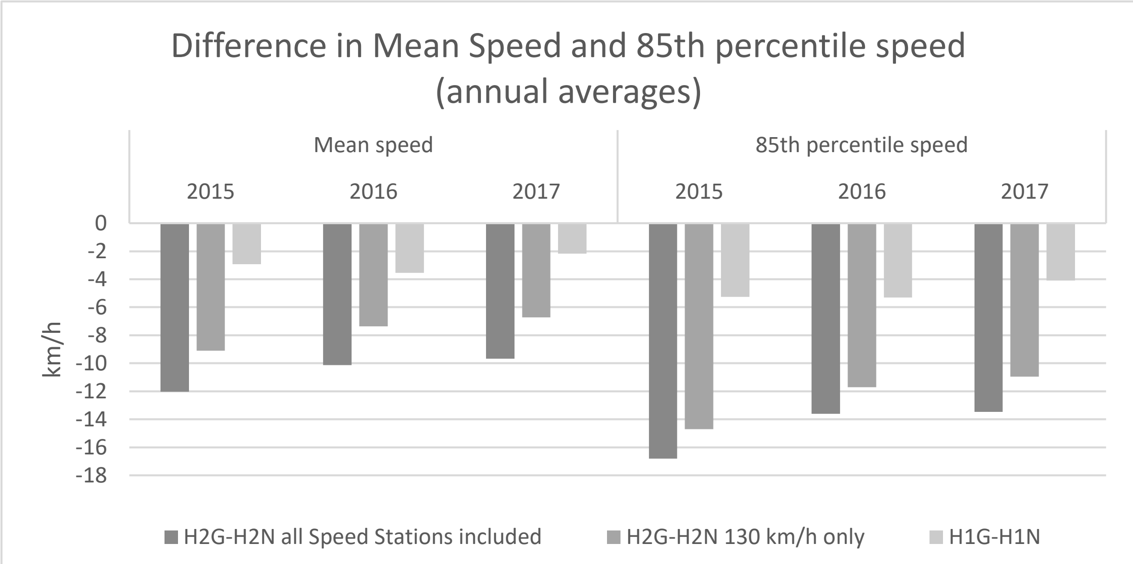

Figure 6-4: Difference in mean speed and 85th percentile speed (annual averages).Source: own figure.

The graph in Figure 6-4 shows differences in mean speed and 85th percentile for the analysis years. On Highway 2, I report the differences in annual averages for all Stations as well as the restricted set of only those observations where a speed limit of 130 km/h was posted, which is of better comparability to Highway 1. Clearly, the restriction of the H_{2N} data leads to a lower difference in speeds caused by the effects named above. When concentrating on the restricted data, the highest differences are observed in 2015, where mean speeds (85th percentile speeds) were 9.1 km/h (14.7 km/h) lower on the Dutch Highway 2 section compared to the German counterpart. In contrast, the lowest effects over a year are present in 2017 on the Highway 1 with a reduction of 2.2 km/h (4.1 km/h) in mean speeds (85th percentile speeds). Again, the graph nicely illustrates a certain convergence in the distribution of travel speeds within a given highway, as the reductions in 85th percentiles are consistently larger than the corresponding changes in means.
Turning towards the intra-highway changes in standard deviations (FIGURE 6-5) the picture is similar. However, now the largest reductions are detected on Highway 1. For example, in 2015, the observations of average speeds on the Dutch side disperse considerably less around its mean than on the German share. This materializes into a 4 km/h reduction in standard deviation. At its minimum, the reduction in standard deviation of mean speed is calculated at 1.6 km/h (restricted data set for Highway 2 in 2017). The right-hand side proves that the observed decline in standard deviation around the 85th percentile speed is larger. This shows that the variance differential between the two countries becomes larger for higher speeds, which is additionally pointing towards a smoother traffic flow in the Netherlands.

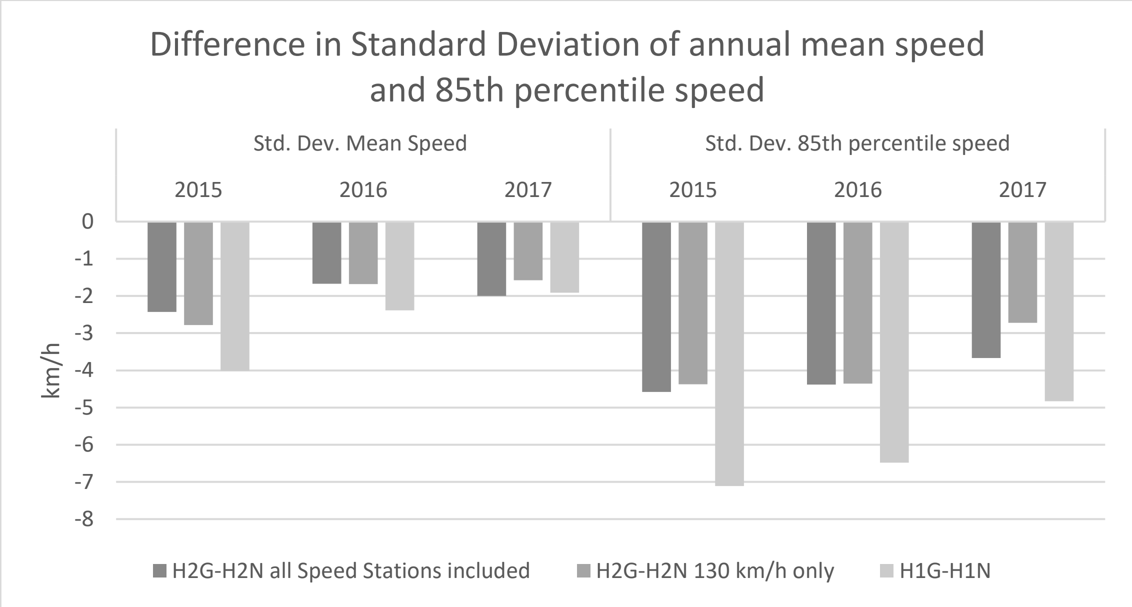

Figure 6-5: Difference in standard deviation of annual mean speed and 85th percentile speed. Source: own figure based on speed data as described in 6.1.4.

Similar effects on the two highways would have been desirable; however, on a highway-specific level, the data for both highways shows the theoretically anticipated effects. To confirm this, I run a two-sample t-test from samples with unequal variances for each of the two highways on both the restricted and the unrestricted dataset. The null hypothesis of no differences in means is clearly rejected the at the 99% confidence level.[46]

As the major interest in this analysis is the expected impact of a hypothetical limit of 130 km/h, I stick with the restricted data. TABLE 6–7 composes the minimum and maximum of the observed annual differences in mean speed and standard deviation. These values shall serve as a plausible range of the impact on travel speed. More specifically, I define their average per highway as the central case scenario.

TABLE 6–7: MINIMUM, AVERAGE AND MAXIMUM ANNUAL CHANGES IN MEAN SPEEDS AND STANDARD DEVIATION OF MEAN SPEEDS BY HIGHWAY (KM/H).

	Mean speed			**Standard deviation**		
	Min	Average	Max	Min	Average	Max
H_{1N} - H_{1G}	-2.17816	-2.880320	-3.53651	-1.911015	-2.767387	-4.0079706
H_{2N} - H_{2G}	-6.72654	-7.725240	-9.08972	-1.578562	-2.011114	-2.778523

Source: own table and calculations based on speed data as described in 6.1.4.

[46] The tests assume normality of the sample so I plot the distribution of mean speeds by highway together with the respective normal distribution in APPENDIX 8. The plots show little deviation from the normal distribution so the assumption seems not problematic.

Based on the observed data, the central case for the impact on travel speed is an expected reduction in mean speed of passenger cars by -2.88 km/h / -7.76 km/h on Highway 1/ Highway 2 respectively. Likewise, the expected reduction in standard deviation of mean speeds is -2.77km/h / -2.01 km/h.
The study design and selection of the highway sections tries to ensure a high comparability on each of the highways. Still, I do not isolate the causal effect of the speed limit, and thus cannot claim with certainty, that the full effect calculated is causally attributable to the posted speed limit. However, it was shown that both hypothesis stated at the beginning of this section are supported by the descriptive data analysis. Mean speeds and speed variances are clearly reduced on the Dutch highways indicating a slower and more homogenous traffic flow. This finding may also have impacts on the traffic safety, where it is turned to in the next section.

6.3 Impact of a general speed limit on accidents

The central question dealt with in this section is**:** *How would traffic safety be affected by a general speed limit on German highways?* In the analysis of travel speeds it was found that both, speed and speed variance decrease on the speed-limited highways. This gives rise to analyze, whether the theories introduced in the literature review are reflected in the data. Therefore, this section assesses if a speed limit would increase traffic safety and sets up the following hypotheses.

1. *Accidents would be less in number ("Variance kills" theory is reflected).*
2. *Accidents would be of reduced severity ("Speed kills" theory is reflected).*

Along the lines of testing these hypotheses, it is the aim to provide an estimate of the expected difference in fatalities as well as severely and lightly injured individuals. Thus, I will mostly use the absolute differences between the two highway parts for comparison. As my data set covers a long period of 12 years (2005-2016), it is necessary to deal with the amendment of the Dutch maximum speed policy in 2012. To do so, I distinguish two phases for the comparison (see TABLE 6–8).

TABLE 6–8: TWO PHASES FOR ACCIDENT ANALYSIS.

		National Maximum Speed Policy on highways	
Phase	Period	Germany	Netherlands
1	12/2016 – 10/2012	No binding limit	130 km/h
2	09/2012 – 01/2005	No binding limit	120 km/h

Source: own table.

For a 12-year period, it was not feasible to retrace all speed limit changes that might have occurred on the two highways. Fortunately, police records include the posted speed limit at the site of the accident in both countries. Therefore, I evaluate accidents only, when they occur at sites with a posted speed limit of 130 km/h (120 km/h) in Phase 1 (Phase 2) and compare them to those with no posted speed limit in Germany. I include the second phase because the general speed limit of 120 km/h provides some variance for the analysis and may therefore turn out to be a check for robustness of the effects. This means that comparison shall be conducted between no limit in Germany and the particular general speed limit per period, which jointly will be called the "speed limits of interest" in the following.

Extracting and comparing the individual accidents based on the posted speed limit, requires that the absolute road length that is subject to the speed limit of interest, is equal for the domestic and foreign part compared. Highway 1 very well meets this condition. Based on the figures in TABLE 6–1, the total length of unlimited segments on H_{1G} is 112.1 km, which is almost equivalent to 114.8 road kilometers limited by 130 km/h on H_{1N}.[47] Additionally, I showed that one could realistically assume speed limits to follow the distribution illustrated in FIGURE 6-2 at least for Phase 1.

From Ministerie van Infrastructuur en Milieu (2012) it is known, that the same road segments along H_{1N} that are limited by 130 km/h today, used to be subject to 120 km/h under the preceding maximum speed policy. I will need to assume this to be true for Phase 2 in general. This is a relatively strong assumption, but I present results for both phases separately.

Highway 2 has more variation in speed limits and does not fulfil the prerequisite described above. A comparison and derivation of effects based on the selected approach would thus be questionable, which forces me to narrow down my analysis to Highway 1 only.

For the years 2005 to 2016 my data file contains a total of 6,153 police-recorded accidents on Highway 1. 2,916 of these occurred on the German part while the remaining 3,237 accumulate from the Dutch section. These initial figures are relatively balanced and in fact, there were more accidents documented on H_{1N} than on H_{1G}. After dropping all accidents at sites with a speed limit different from those in TABLE 6–8, I still observe 3,413 accidents. In TABLE 6–9 I set out the accident counts by highway and severity category.

As noted, I will concentrate on person-damage accidents (category 1-3) due to the peculiarities in the German data collection process. Additionally, from the public perspective,

[47] H_{1G}: Total length of 158 km * 71% with no limit = 112.1 km. H_{1N}: Total length of 140 km * 82% of limit 130 km/h = 114.8 km.

these are of highest interest.[48] However, the table shall give an idea of the significant share of property-damage only accidents. In the Netherlands, this category amounted to 89% of all accidents listed. In Germany, this number is only 68%, but represents a lower bound since this category was rarely reported in the years prior to 2008.[49]

TABLE 6–9: ACCIDENTS BY HIGHWAY AND SEVERITY CLASS, 2005-2016.

	Fatal (1)	Severe injury (2)	Light injury (3)	Property damage (4)	Total
H_{1G}	12	190	407	1291	1900
H_{1N}	16	86	65	1346	1513

Source: own table based on accident data described in section 6.1.4.

Now, the remaining analysis focuses on the category 1-3 accidents. When the speed limits of interest account for 71% (H1G) and 82% (H_{1N}) of the total road length, one would expect their section's share of total accidents to match these proportions if they are uniformly distributed along the highway. FIGURE 6-6 does this comparison.

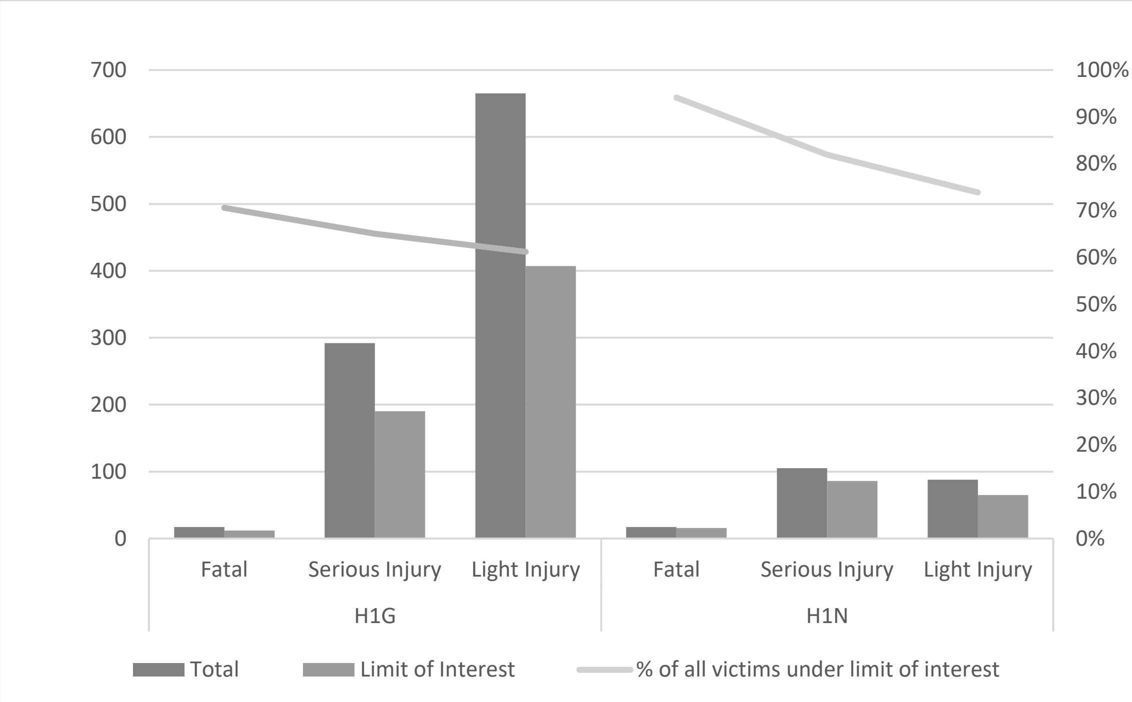

Figure 6-6: Total accidents with person damage and the corresponding share on sections with speed limit of interest, 2005-2016. Source: own figure based on accident data as described in 6.1.4.

[48] Person damage crashes may not necessarily constitute the highest economic value due to the high share of property damage crashes. However, I assert that most people agree to the idea, that for moral reasons one would rather omit property damage accidents than fatalities within a SCBA irrespective of their absolute economic cost to society.
[49] See the significant surge of category 4 accidents reported in APPENDIX 12.

Over the categories 1-3, 63% (H_{1G}) and 80% (H_{1N}) of total accidents are attributable to these sections, which is roughly confirming the expected proportion.[50] The graph provides first evidence for Hypothesis 1 as the accident counts are clearly greater on the German part. This is illustrated by the bars projected on the primary axis. While for fatal accidents, the counts are in a similar range, the accident figures of the other two categories on H_{1G} certainly go beyond those on H_{1N}. Moreover, the grey line in the chart depicts the share of total crashes that are included in the analysis for each severity category. This is interesting because there is a clear trend that with severity, also the share of accidents increases. As the speed limits of interest are the highest possible within the countries, this indicates that the higher the severity category, the more of these accidents in the category fall into sections where higher speeds are allowed. This holds within both countries and provides a first argument in favor of Hypothesis 2, namely that accidents may be of reduced severity when speed limits restrict the traveled speeds.

In contrast, *between* the countries, the level is constantly higher on the Dutch part. This is represented by the grey line, which is consistently above the level of its German equivalent. Since the potentially allowed speed is higher on the German side, one would expect a higher accident share in each category, which speaks against Hypothesis 2. This may partly be due to the larger total number of crashes, which does not apply to fatal accidents as they are quite similarly frequented.

To dig deeper into the data, I disentangle accidents into the two periods defined and compute their annual sums. Additionally, the actually harmed individuals need to be considered. TABLE 6–10 comprises the absolute annual *differences* in accidents and victims by severity class. In bold, I report the mean country difference for each time phase.[51] Since the phases are of different length and the year 2012 is split up between the two, I normalize the absolute difference in accidents and victims by the number of month in the respective phase and scale up this monthly average in order to obtain annual mean values.[52] Since accidents designate an economic cost, positive figures indicate an increase in accident cost for Germany, while negative values imply a reduction. The table is composed from the domestic perspective as it provides estimates of differences for Germany if they had the same policy as in the Netherlands.

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[50] Percentage share of the sum of accidents over all three categories. Germany: 609/974; Netherlands: 167/210.

[51] See APPENDIX 13 for the absolute counts per year and highway, which serves as a basis for the calculations here.

[52] This corresponds to: $\Delta A_{pj} = \left(\frac{\left(A_{pj}^{H1N} - A_{pj}^{H1G}\right)}{m_p}\right) \cdot 12$, where A_{pj}^{H1N} is the total number of accidents of category j in phase p on the German highway and m_p is the number of month in phase $p \in \{1,2\}$. Calculation of the mean difference in victims per phase was done accordingly.

TABLE 6–10: ANNUAL DIFFERENCE IN TRAFFIC ACCIDENTS AND VICTIMS BY PHASE AND SEVERITY CATEGORY, 2005-2016.								
	Fatal		**Serious Injury**		**Light Injury**		**Total**	
	Acc.	Pers.	Acc.	Pers.	Acc.	Pers.	Acc.	Pers.
H_{1N}-H_{1G}								
Phase 1	**0.00**	**0.00**	**-11.29**	**-12.24**	**-30.12**	**-52.24**	**-41.41**	**-64.47**
2016	-1.00	-1.00	-4.00	-6.00	-33.00	-63.00	-38.00	-70.00
2015	2.00	2.00	-5.00	-4.00	-34.00	-47.00	-37.00	-49.00
2014	0.00	0.00	-17.00	-17.00	-30.00	-56.00	-47.00	-73.00
2013	-1.00	-1.00	-18.00	-21.00	-27.00	-50.00	-46.00	-72.00
Q4 2012	0.00	0.00	-4.00	-4.00	-4.00	-6.00	-8.00	-10.00
Phase 2	**0.52**	**0.90**	**-7.23**	**-8.26**	**-27.61**	**-46.71**	**-34.32**	**-54.06**
Q1-3 2012	0.00	0.00	-8.00	-12.00	-21.00	-41.00	-29.00	-53.00
2011	-1.00	-1.00	-17.00	-18.00	-28.00	-38.00	-46.00	-57.00
2010	-1.00	-1.00	-18.00	-20.00	-33.00	-53.00	-52.00	-74.00
2009	-1.00	-1.00	3.00	4.00	-18.00	-36.00	-16.00	-33.00
2008	-1.00	2.00	-6.00	-7.00	-25.00	-55.00	-32.00	-60.00
2007	2.00	2.00	-11.00	-20.00	-29.00	-37.00	-38.00	-55.00
2006	0.00	0.00	0.00	-1.00	-36.00	-57.00	-36.00	-58.00
2005	6.00	6.00	1.00	10.00	-24.00	-45.00	-17.00	-29.00

Note: The table reports the annual differences in accidents and persons per year within each phase. The phase totals are the average annual difference within the phase. To calculate these, I take the difference in accidents and persons for each category, normalize it with the number of months in the particular phase and multiply by 12 month. The differences are such that I subtract the Dutch from the German values. Consequently, positive (negative) values imply an increase (decrease) in accidents or victims from the German perspective.
Source: Own table based on accident data as described in section 6.1.4.

The last two columns show the total difference of accidents and victims over all categories. It becomes evident that the data provides broad support for Hypothesis 1. When summarized over all categories, both the number of crashes and the number of victims are larger on the German road part. This is true for every year and shows that it is reasonable to expect accident counts and victims to decline, when Dutch highway regulations would apply in Germany. In fact, the differences in severe and light injury accidents are quite large. For example, in 2014 there were 47 fewer accidents and a total of 73 fewer victims registered on H_{1N}. The major share of accidents are light vehicle accidents (30 crashes) which caused 56 light injured persons. [53] This is a common pattern throughout

[53] Not all victims stem from the crashes of the same severity class. It needs only one injury of a certain severity to attribute the accident to this respective category. For example, light injured people can evolve from every accident category whereas traffic deaths can naturally be a result only of fatal accidents.

the years because intuitively (and luckily) with increasing severity, accidents tend to occur less frequently. Merely for the fatal accidents (and two annual exceptions in severe accidents) a higher number in crashes and victims is observed on H_{1N} in some years. Remarkable in this category is the year 2005, where the German highway section remained free of casualties while the Dutch highway section experienced six fatal crashes. This year constitutes an outlier in the data. However, this renders the accident analysis slightly more conservative, as potential benefits are reduced by keeping the data point. Also, the annual case numbers are so low in the category, that this is likely caused by sample size and does not reflect a structural relation between the countries.

TABLE 6–10 shows that a structural decline in accidents is observable, where the Dutch regulations apply. While I cannot explicitly name the variance in speeds as a central cause for this observation, the previous section showed that speed variances are indeed consistently larger on the German sections compared to their Dutch counterparts. What is evident from TABLE 6–10 is that Hypothesis 1, namely that *accident counts* are expected to decline when a speed limit would be implemented, is well supported.

With respect to Hypothesis 2, the analysis offers mixed results. The total accident figures aggregated over the years 2005 to 2016 (FIGURE 6-6) indicate that more severe crashes tend to happen more frequently in those areas *within* the particular highway part, where the highest travel speeds are allowed. If Hypothesis 2 is to hold, a comparison *between* the countries should reveal a shifted distribution of the accidents towards less severe crashes in the Netherlands. To see this I present the relative frequencies of accidents for each category in the pie charts below. The data is restricted to Phase 1 because during this phase category 4 accidents have been collected consistently and can be summarized over the years included. It is salient, that the share of the accident categories with person damage (1-3) is clearly larger on H_{1G} (~ 23%) than on H_{1N} (~ 6%). Again, on a highly aggregated level, this speaks in favor of Hypothesis 2.

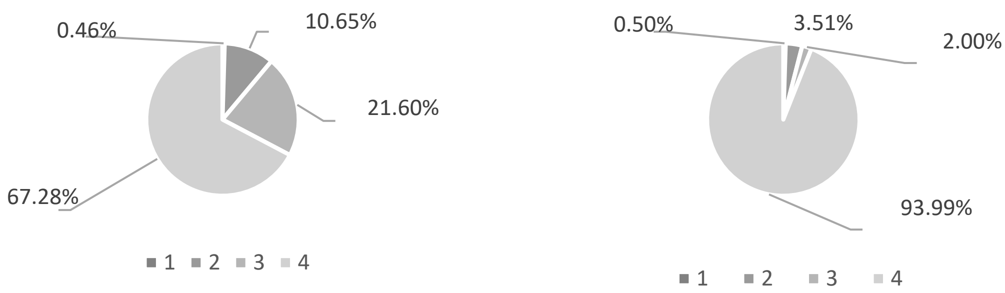

Figure 6-7: Relative accident frequencies by severity category in Phase 1 on H_{1G} and H_{1N}.

Note: The graph on the left hand side displays relative accident frequencies by severity category in Phase 1 on H_{1G}. H_{1N} is illustrated similarly on the right hand side.
Source: Own figure based on accident data as described in section 6.1.4

However, the desired and politically intended effect of a speed limit is that its implementation would materialize in relative declines of accidents. For the present case this means that the accident statistics on H_{1G} should converge to the figures observed on H_{1N} when adopting the Dutch regulations. Consequently, the relative accident reductions *within* each severity category should be most pronounced for the fatal accidents and then gradually diminishing in magnitude of change for lower severity classes. I calculated the relative declines corresponding to TABLE 6–10 but they neither showed the expected nor other interesting patterns.[54]

I cannot make a statement about the robustness of this effect, since I analyze Highway 1 only. Thus, the absence of the expected effects may be explained by the relatively small sample size of the case. The conclusion remains that there are mixed results for Hypothesis 2. The tendency of higher speeds resulting in more severe accidents can be cited from previous studies,[55] but my setting does not fully mirror this finding. If there was a general speed limit on the German highway part, one could claim the distribution of *all* accidents to converge towards to the distribution found in the Netherlands, meaning that the relative frequencies per severity category converge. In contrast, the actually observed differences within each category did not yield the desired effects, leaving the argument subject to doubt.

The overall hypothesis predicted an increase in traffic safety as a direct result of the introduction of a speed limit. This hypothesis is principally confirmed by the data. More research on the German case would be needed to make valid causal explanation but I give an idea of reasonable values. As stated above, the focus in the subsequent monetization within the CBA is the change in persons harmed. I want to rely on the observed data and stay consistent with the analysis of travel speeds in the previous section. Thus, the central case here needs to be the evaluation of the impacts of a speed limit of 130 km/h, which corresponds to Phase 1 in the present accident analysis. I therefore define their annual average changes as the expected effects of a 130 km/h speed limit on German highways using formula [4].

$$\Delta\, Victims_j = \frac{\sum_{i=2012}^{2016}\left(\frac{v_{ijN}}{vkm_N} - \frac{v_{ijG}}{vkm_G}\right)\cdot\frac{m_i}{12}}{I} \quad \forall\, j \in \{1,2,3\} \qquad [4]$$

Where *v= victims*
j= severity category (1 – fatal, 2 – severe injury, 3 – light injury)
I= number of years in Period 1

[54] Since they were of little information, I do not present the calculations. Nevertheless, the relative differences can easily be calculated from the total values presented in APPENDIX 13.
[55] See Chapter 2.

i= specific year in period 1
G/N= German/ Dutch highway
vkm= estimate of annual vehicle kilometers per year (TABLE 6–2)
m= Number of month in year i included in Period 1 (e.g. 2012: m = 3)

These weighted average changes need to be normalized by annual vehicle kilometers traveled in order to maintain comparability when applying them in the valuation.[56] The calculation leads to the central case accident differentials per vehicle mile. TABLE 6–11 composes the expected changes per million vehicle kilometers.[57] As I subtract the German from the Dutch figures, negative values imply an estimated reduction of victims per vehicle km on German highways under a 130km/h speed limit. For example, in this central case scenario based on data from Highway 1, I calculate an expected annual decrease of 0.0366 light injured persons per million vehicle kilometers.

TABLE 6–11: EXPECTED CHANGE IN ANNUAL TRAFFIC VICTIMS BY SEVERITY CATEGORY PER MILLION VEHICLE KILOMETERS.

	Fatal Victims	Serious Injury Victims	Light Injury Victims
Central case Change in number of victims	-0.00000521873	-0.00827941907	-0.03655438992

Source: own table and calculations based on accident and vehicle kilometers data as described in section 6.1.4

6.4 Impact of a general speed limit on fuel consumption and emissions

When assessing transport projects, an analysis of the environmental impacts is essential. Largely, these impacts are dependent on the changes in fuel consumption attributable to the same project. Additionally, fuel is one of the two major components of operating costs of driving a vehicle. The other is depreciation, which is rather fixed and insensitive to small changes in speed (see Kockelmann, 2006 p. 29). This section therefore deals with the assessment of expected fuel economy effects as well as the environmental aspects. The latter was classified into global and local emissions in the literature review, where it was found that the impact of speed limits cannot always be predicted with certainty.[58] What the reviewed studies have in common is that they rely on collected measurement data for the emissions analyzed. Within the scope of this thesis, it was not feasible to collect similar data myself. Therefore, the approach employed here will be to infer changes in emissions as well as fuel consumption from the comprehensive speed data set.

[56] The weighting in the calculations is simply due to the fact, that only the fourth quarter of 2012 falls into Period 1.
[57] Applying [4] on the total accident victims as tabulated in APPENDIX 13 one can reproduce the calculations.
[58] See chapter 2.

The relationship between fuel consumption and (mean) speed is typically U-shaped.[59] For the speed ranges driven on highways (i.e. typically above 80km/h) the function typically has a positive slope, which leads to the expectation that increases in speed lead to higher fuel consumption, while decreases are associated with fuel economies. With respect to global CO_2 emissions, the relationship to speed in this case is clearly positive as it is the main product from fuel combustion (see European Environment Agency, 2016, p.9). Because a liter of fuel combusted always releases a stable amount of carbon dioxide, there exists no viable technology which can reduce this emission component per liter of diesel or gasoline (see Parry et al., 2007, p. 376).[60] For the analysis, this fact allows to infer the changes in CO_2 emissions from estimated changes in fuel consumption.
In some contrast, regulations have been successful in decreasing local emissions over the past decades. Meanwhile the tailpipe emissions, which are of concern here, normally vary more with vehicle kilometers than the mean travel speed (see Parry et al., 2007, p.375). However, the emission level can still be expected to be dependent on driving speed characteristics (see Korzhenevych et al., 2014, p 8).
To approximate the impact of traffic speed on fuel consumption and emissions one cannot simply infer from the difference in mean speed since the effects are unlikely to be linear.[61] Therefore, I will work with the *distribution* of speeds as observed in the data and compare the domestic with the foreign. This represents the expected situation if the German highways were subject to the same 130 km/h limit. Hence, the hypothesis set up for this section is:

1. *A speed limit on German highways leads to improved fuel economy and reduces local and global emissions due to its decreasing and homogenizing impact on the distribution of travel speeds.*

The speed analysis already indicated that a speed limit leads to a decrease in mean speeds and the distribution of travel speeds is expected to contract to a smaller range. To emphasize this, I analyze the deciles of the speed distribution as observed in the dataset. TABLE 6–12 provides the upper bounds (UB) as well as the respective mean speeds for each decile by highway section.

[59] See e.g. Mellios et al. (2011), p. 80 for the case of CO_2.
[60] For example, the British government publishes conversion factors for organizations obliged to report their UK- operations emissions. According to their 2016 figures one can translate a liter of conventional gasoline (diesel) into 2.3 kg (2.6 kg) of carbon dioxide. See: Department for Business, Energy & Industrial Strategy (2016).
[61] See e.g. Mellios et al. (2011).

TABLE 6–12: MEANS AND UPPER BOUNDS OF THE SPEED DISTRIBUTION DECILES BY HIGHWAY SECTION.				
Decile	**H_{1G}**		**H_{1N}**	
	Mean	UB	Mean	UB
1	95.444	108.000	99.313	109.626
2	109.713	112.000	111.334	112.818
3	113.039	115.000	114.047	115.175
4	116.523	119.000	116.119	116.990
5	119.514	121.000	117.768	118.532
6	121.995	124.000	119.326	120.149
7	124.944	127.000	121.143	122.300
8	128.801	132.000	124.017	125.985
9	134.321	138.000	127.959	129.918
10	144.336	232.000	134.117	189.000
Overall mean	121.388		118.514	
Decile	**H_{2G}**		**H_{2N}**	
	Mean	UB	Mean	UB
1	92.986	104.000	84.577	103.465
2	107.202	111.000	106.849	109.148
3	113.092	116.000	110.834	112.444
4	117.579	120.000	113.901	115.279
5	121.511	124.000	116.630	118.000
6	125.000	127.000	119.438	120.910
7	128.403	131.000	122.333	123.681
8	133.763	138.000	124.935	126.166
9	140.909	145.000	127.491	128.997
10	151.598	250.000	133.182	188.000
Overall mean	123.735		116.018	

Source: own table and calculations based speed data as described in section 6.1.4

In the lowest and highest decile, the comparison of mean to upper bound speed shows a very wide range. I decided to increase the granularity of the analysis and calculate all percentile values. This also improves the precision of the monetization in chapter 7.

The comparison between the countries is illustrated in FIGURE 6-8 where I calculate the relative in- or decrease of mean speeds for each percentile as percentage changes from the German value.[62] Accordingly, a negative value indicates an expected decrease in speed in a given percentile of travel speeds, if there was a 130 km/h speed limit in Germany. What can be noted is that the effects for the lowest 30% of observed speeds are ambiguous. In absolute terms, the 3rd decile is found around 115 km/h up to which the effects on the highways show little clear effects. On Highway 1, the first percentile shows a decrease in mean speeds of roughly 4%. After that, mean speeds are in most cases higher

[62] The totals of the speed percentiles are shown in APPENDIX 14.

on H_{1N} compared with H_{1G}. This effect declines with higher speeds, fluctuates around zero and turns negative at the 27th percentile.

On Highway 2, I observe high negative differences for the lowest percentiles. These may again be explained by periods of heavy congestion or unobserved factors in the analyzed period (2015-2017) such as construction sites, which – as mentioned – were not possible to account for. Again, as in the assessment of travel speeds above, the change on Highway 2 is systematically more pronounced. However, the general effects are in line with previously stated expectations. The lower speeds are ambiguous and sometimes even higher in the Netherlands, which may be due to homogenized traffic flow. The higher the mean speeds become, the larger the negative percentage change which is reflecting the natural fact, that higher speeds are targeted more profoundly by a speed limit policy. At the same time, this shows the alignment in the distribution of travel speeds.

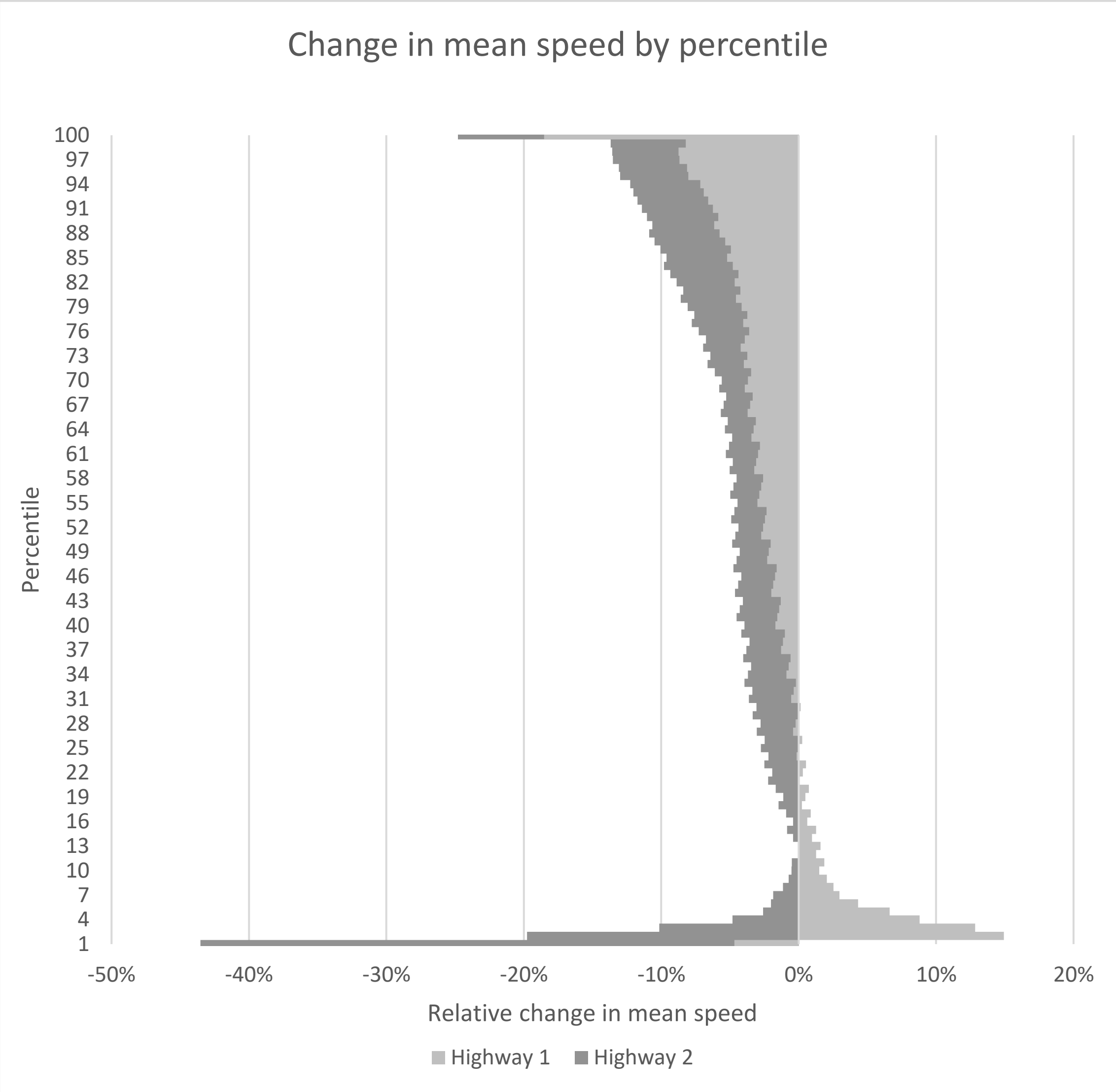

Figure 6-8: Comparison of relative differences in mean speeds within percentiles. Source: own figure and calculations.

The next step is to introduce emission factors applicable to the estimated changes in the speed distribution. To do so, I follow the official methodological guideline complementing the “Bundesverkehrswegeplan 2030”, which is the German traffic forecast and planning conducted and published by the BMVI. It recommends to make use of the “Handbuch Emissionsfaktoren des Straßenverkehrs” (HBEFA) (see BMVI, 2016b, p.142). This “Handbook of Emission Factors for Road Transport“ is created and maintained under the authority of the environmental agencies of several European countries – including Germany. It is also supported by the Joint Research Center of the European Commission (JRC).[63] The comprehensive database provides emission factors for different vehicle categories and a variety of emissions – including the EU- regulated air pollutants of interest – as well as fuel consumption. In the freely available online version of the handbook, it is not possible to obtain values contingent on travel speed. However, the UBA, which is the institution in charge for Germany kindly provided the desired speed-dependent emission factors.

TABLE 6–13: SPEED DEPENDENT EMISSION FACTORS
FOR AN AVERAGE DIESEL AND GASOLINE PASSENGER CAR.

	Speed in km/h						
Diesel	**80**	**90**	**100**	**110**	**120**	**130**	**>130**
FC	40.1570	39.7314	40.6430	44.7432	47.6392	50.8867	56.7559
CO	0.0175	0.0126	0.0100	0.0125	0.0092	0.0072	0.0075
HC	0.0073	0.0069	0.0065	0.0057	0.0053	0.0057	0.0065
NOx	0.4936	0.5646	0.5930	0.6714	0.8468	1.1338	1.4845
PM	0.0068	0.0064	0.0069	0.0073	0.0083	0.0097	0.0104
Gasoline							
FC	46.7305	46.5712	48.6153	55.3889	63.1100	69.5586	75.3210
CO	0.3106	0.2926	0.4021	0.6135	1.0270	1.9508	3.9251
HC	0.0115	0.0119	0.0136	0.0150	0.0180	0.0250	0.0414
NOx	0.0524	0.0575	0.0578	0.0691	0.0830	0.1177	0.1302
PM	0.0012	0.0012	0.0016	0.0024	0.0041	0.0060	0.0078

Note: The table provides speed-dependent emission factors for an average German 2015 (gasoline / diesel) passenger car. For the fuel consumption, the following densities are used: 742 g/l for gasoline, and 832 g/l for diesel. All emissions are tailpipe-only. This applies especially to PM which implies that PM can be understood as $PM_{2.5}$ since all particulate from internal combustion is smaller than 2.5 μm. NO_x is expressed in NO_2 equivalents since emitted NO quickly oxidizes into NO_2.
Source: data provided by UBA. The definitions stem from the HBEFA website (see Footnote 63).

TABLE 6–13 presents the emission factors in gram per vehicle kilometer for an average German diesel and gasoline passenger car for the year 2015. The average vehicle is determined by a number of characteristics of the German vehicle fleet of the respective

[63] See HBEFA accessible under www.hbefa.net (link last updated 17.08.2018).

year.[64] Included are fuel consumption (FC), and the key local emissions as regulated within the EU (CO, HC, NO_x, PM). HBEFA measures tailpipe emissions only, which is the focus of my analysis.

The next problem to solve is to perpetuate the discrete emission factors, such that the calculated percentile speeds in the current and expected case can be plugged into some speed-emission function. To do so, I fit a second order polynomial trend for each of the emission factors and differentiate by fuel type using the defined speed observations.[65] Thus, by plugging the speeds per country and highway into the speed-emission functions, I can calculate the expected fuel consumption and emission effects per vehicle kilometer on a percentile basis. The estimation of CO_2 changes is then directly converted from fuel consumption changes.[66]

These differences by highway and fuel type in gram/vkm constitute the central case effects for each emission (fuel) factor. As these are comprehensive tables and the scaling is of little intuitive accessibility I provide them in the APPENDIX 16. However, the figures are used in the subsequent monetization chapter, where I describe the monetization process and present higher aggregated figures. Generally, sticking with the percentile changes accounts for the different impact of a speed limit on shares of traffic. Also, the numbers illustrated in FIGURE 6-8 resemble the plausible phenomenon that speed limits target the higher speeds more and thus have a higher impact. In this context, when calculating changes in emissions from speed differentials, it is favorable to work with relative changes in speed since this takes into account that the higher initial levels of traffic speeds on a given highway are, the more noticeable effects are likely to be reached.

This chapter first provided the necessary backgrounds to understand the analysis approach. Afterwards the central case scenario of expected impacts from a 130 km/h speed limit on German highways were defined systematically. Jointly, the preceding sections have answered the second research question of this work. At the end of each impacts' subsection the expected magnitude and direction of change has been presented. The subsequent chapter turns towards the monetary valuation of these impacts, which is no straightforward task as the categories constitute non-market impacts.

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[64] These characteristics include for example vehicle mass, engine power an others. See e.g. Mellios et al. (2011).

[65] This excludes the last column of TABLE 6–13, because it represents a mean value for higher speeds and is therefore not directly attributable to a certain km/h level.

[66] Following HBEFA, the conversion factor to be used here is 3.135 gram (3.179 gram) per gram of gasoline (diesel) combusted. With the mean density of 742 g/l for gasoline, and 832 g/l for diesel, this is equivalent to 2,326kg CO_2/ l Gasoline and 2,645 kg CO_2/ l Diesel, which is also consistent with the values in Footnote 60.

7 VALUING COSTS AND BENEFITS

This part aims at putting a price tag at the core benefit and cost categories. It follows, that the focus here is to provide an answer to the third and last research question, namely if – from a social perspective – a speed limit policy as described would be desirable.
Therefore, I calculate the *social net benefits*, which are estimated to occur *annually on the sections investigated.* These arise from the following impacts:

1. Opportunity cost of travel time
2. Fatal, severe and light injured individuals from traffic accidents
3. Fuel economy
4. Local and global air pollution

Valuation of these impacts requires attributing prices to each item. With the exception of fuel consumption, for which one can make use of the gasoline or diesel price, all of these impacts are non-market goods.[67] This requires shadow pricing of these impacts. A shadow price – or equivalently "accounting price" – can be both a corrected price of a market-determined value (e.g. when the analyst is convinced, that market values are too heavily distorted by market failures) or a price for goods, where no market exists at all (see Mishan and Quah, 2007, p.61f.). Obtaining defendable valuations for non-market goods often requires comprehensive research. Fortunately, this is a common issue in transport projects, which allows the use of readily available studies and guidelines.
In the central case valuation I rely on available figures from the "Bundesverkehrswegeplan 2030" (see BMVI, 2016a). This is advantageous for three reasons. First, it provides values explicitly tailored to local German circumstances. Second, it supports the defensibility of the prices used, as they are taken from official government documents. Third, its methodological complementing material provides inputs or recommended sources for each of the impacts, allowing for a consistent valuation over all considered impacts. Moreover, the report ensures a consistent price level, which allows for direct comparability of the impacts. In line with the report I use real 2012 Euro in the analysis (see BMVI, 2016b, p. 95). The figures suggested by the federal ministry are collected from the methodological handbook which complements the report. It serves as the main source for the required accounting prices in the central case scenario, composed in TABLE 7–1.

[67] Admittedly, also emissions are traded on markets sometimes, for example when considering emission certificates for corporations. Still, they are not typical market goods nor are the emissions from private transport priced directly.

TABLE 7–1: ACCOUNTING PRICES AND CORE VALUATION PARAMETERS FOR THE IMPACT VALUATION.

Item	Accounting price/ quantity	Unit	Source
Travel Time Opportunity cost			
Business travel	27.48	€/h	Own calculation based on BMVI 2016b
Non-Business travel	9.71	€/h	Own calculation based on BMVI 2016b
Avrg. Passengers/ vehicle*			
Business travel	1.1	Passengers/Car	BMVI 2016b
Leisure travel	2	Passengers/Car	BMVI 2016b
Share of Trips by Travel Purpose**			
Business Travel	15.5	% of total person-km traveled	Own calculations based on BVU et al., (2010).
Non-Business Travel	84.5	% of total person-km traveled	Own calculations based on BVU et al., (2010).
Social cost of accident impacts			
Value of a statistical life (VSL)	2.480.996	€/ victim	BMVI 2016b
Severe injury	287.635	€/ victim	BMVI 2016b
Light injury	18.020	€/ victim	BMVI 2016b
Social cost of Emissions			
CO_2	86.5	€/t	Own calculation based on UBA, (2014)/ BMVI 2016b
CO	62	€/t	BMVI 2016b
NO_X	15400	€/t	BMVI 2016b
HC	1700	€/t	BMVI 2016b
PM (exhaust only)	122800	€/t	BMVI 2016b
Fuel cost			
Gasoline / Diesel	0.71	€/l	BMVI 2016b
Share of passenger cars by fuel type			
Gasoline / Diesel	66.5 / 32.8	% of total vehicles registered in Germany	Federal Motor Transport Authority / (Kraftfahrtbundesamt) KBA
Annual vehicle kilometers traveled			
H_{1G}	1,190,914,335	Km/ year	Own data & calculation from 6.1
H_{2G}	1,151,492,875	Km/ year	Own data & calculation from 6.1

Note: All prices given in 2012 Euro.
*Values are taken from Table 43 in source as cited. They assume a travel distance of more than 50 km.
** The source cited defines a current state value for 2010 as well as a forecast for 2030 for the number of person kilometers traveled by trip purpose (private, shopping, work, apprenticeship etc.) in Germany. For each trip type, I interpolate the figures linearly and classify the distinct purposes as either business or non-business travel. For this classification is follow BMVI 2016b, p. 96.
Source: as given in the last column of the table.

Social opportunity cost of travel time

Here and in the following I will abstract from potential changes in traffic demand. This means a speed limit policy would not induce or divert any traffic. The core parameter to calculate this welfare cost component is the value of time (VoT). If a citizens' travel time increases due to lower speeds, the opportunity costs of the trip rise due to the increase in time forgone which could have been used in other utility-adding ways. Examples are more leisure or additional paid working hours. There is vast academic literature on the VoT and "the preferred source from where to obtain value(s) of time at country level should be official national data, based on local research" (see European Commission, 2015, p.90). The BMVI reports time values by distance based on a mix of revealed and stated preferences methods (see BMVI, 2016b, p.97ff).[68] The value of time increases with trip distance in the study, which is reasonable since for longer rides it becomes more valuable to save a certain amount of time. I distinguish two travel types, namely business and non-business. For both, the distance of H_{1G} (79 km) is used and calculated from the figures provided in BMVI (2016b) by linear interpolation.

Based on the estimate of vehicle km traveled and the respective share by trip type I calculate the difference in hours needed to complete the distance. Therefore, I apply the central case speed result from chapter 6 to the mean speeds observed on H_{1G} and H_{2G}. This time differential can then be priced with the respective value of time for business and non-business travel. Under this procedure, the expected social time opportunity cost for the two sections per year are:

TABLE 7–2: ANNUAL SOCIAL COST FROM TRAVEL TIME.

	Business	Non-Business
H_{1G}	- 1,118,723.82 €	- 3,911,181.97 €
H_{2G}	- 2,906,001.81 €	- 10,159,703.13 €

Source: own table and calculations.

Clearly, the larger fraction of time opportunity cost on both highways is attributable to non-business travel. Despite the higher hourly opportunity cost for business trips, the high share of privately driven vehicle kilometers and the fact that the occupancy rate of business travel is lower, leads to these results. In line with expectations, the larger speed difference on Highway 2 results in higher opportunity cost. In fact, the social cost is 2.6 times larger compared with Highway 1. The figures explicitly carry a minus sign, as they constitute cost incurred to social welfare.

Fatal, severe and light injured individuals from traffic accidents

In chapter 6 I derived an estimate of injuries and deaths, which would statistically be saved per vehicle kilometer when adopting the Dutch speed limit policy. BMVI (2016b)

[68] These methods are commonly applied for shadow pricing in CBA. In this particular case, respondents were confronted with different travel options that varied in dimensions of price and time (revealed preference method) and also asked about their actual travel behavior (stated preference method). The study was commissioned by the BMVI (see TNS Infratest /IVT /ETH Zürich 2015).

defines two economic cost components for valuing person damage based on estimates from Bundesanstalt für Straßenwesen (2010). Firstly, the *resource cost* reflect lost production and economic cost of an accident. Secondly, the risk-value component is a measure of the WTP of reducing the own risk of dying or being hurt in an accident. It serves as "a proxy to estimate pain, grief and suffering caused by traffic accidents in monetary values" (see Korzhenevych et al., 2014, p.19). The social cost for a fatality is a special shadow price, since it reflects the value of a statistical life (VSL). By nature, putting a price tag on a person's life is subject to much debate, which resulted in enormous attention in CBA literature.[69]

TABLE 7–3: SOCIAL COST OF FATALITIES, SEVERE AND LIGHT INJURIES.

Cost category	Fatality (VSL)	Severe injury	Light injury
Resource cost	1.161.892	116.151	4.829
Risk-Value-Component	1.319.104	171.484	13.191
Total social cost	2.480.996	287.635	18.020

Source: own table based on BMVI 2016b.

I apply these prices and the kilometers traveled to calculate the expected social benefit from improvements in traffic safety in the central case scenario. Even though the analysis could only be done based on the Highway 1 data, I also apply the estimated changes for Highway 2 but scale them by the respective vkm. This is a conservative choice as the speed differentials on Highway 2 were considerably higher. Consequently, this may lead to an underestimation of the true benefits for Highway 2. The resulting annual social benefits are shown in TABLE 7–4.

TABLE 7–4: ANNUAL SOCIAL BENEFITS FROM TRAFFIC SAFETY.

	Fatalities	Serious Injuries	Light Injuries
H_{1G}	15,419.53 €	2,836,103.78 €	784,467.31 €
H_{2G}	14,909.11 €	2,742,223.52 €	758,499.99 €

Source: own table and calculations.

A first notable peculiarity is the low benefit from fatal accidents. However, the fact, that in the period observed there was no difference in the number fatalities between H_{1G} and H_{1N} leads to very small changes caused only by different vehicle kilometers traveled on the sections. Thus, even though the VSL is the highest price attributable to any accident outcome, in this case study the social benefits from the most severe accident category are

[69] See e.g. Yang et al. (2016), Viscusi and Aldy (2003) as well as any CBA Textbook or public institution guidelines on conducting CBA, which are cited in this work.

low. Again, due to the plain sample size, this effect can be quite sensitive. The serious injuries contribute most to welfare gains followed by the less severe injuries. Whereas the number of light injuries per vkm is expected to decrease the most. This effect is simply driven by the higher social cost of a serious injury accident. As I observe changes on Highway 1 only, the effects just vary slightly between the two sections due to differences in total vkm. Again, the H_{2G} estimates presented here can be viewed as a lower bound estimate as explained above.

Fuel economy, local and global emissions

For calculating the private and social cost of fuel and emissions, I use the emission factors provided by HBEFA (TABLE 6–13). Based on the central case scenario, which provided the change in emissions in gram per vehicle kilometer, I calculate the expected savings within each percentile. This implies that 1% of vehicle kilometers driven per highway accrue to the individual speed percentile and requires accounting for the share of these kilometers attributable to diesel and gasoline vehicles.[70] Thereby I can sum up the percentile changes for each individual emission factor and calculate the change in tons (liter in the case of fuel) for each highway.[71] Then I can multiply the total expected emission or fuel consumption changes with the particular emission price as stated in TABLE 7–1. The social cost of local emission factors are directly provided in BMVI (2016b), while the figures for CO_2 within the guide stem from UBA (2014). I use the primary source, which presents CO_2 prices for 2010 and 2030. To derive a consistent valuation, I interpolate their figures linearly to obtain a 2012 value. Due to the short time period interpolated this should be an acceptable approach.

For fuel prices I can again rely on BMVI (2016b). Using the same price for both, gasoline and diesel may appear unusual from prices known at gas stations. Indeed, the figures stem from mean prices observed at gas stations in 2012 but the price composition is modified. The authors of the study do not find it plausible that cost components like transport and processing differ between the fuel types such that the price differences observed appear to be primarily driven by the margin. As this does not reflect economic resource cost properly, they correct the values to the presented accounting prices.

The highway specific changes in tons per emission factor and the corresponding annual benefits are shown in TABLE 7–5. Expectedly, improved fuel economy and the narrowly linked CO_2 emissions yield the largest social benefits, as they are quite sensitive to speed

[70] This implicitly assumes that there is no difference in the distribution of diesel and gasoline vehicles within each percentile, i.e. that we do not have structural differences that a particular vehicle category drives faster or slower. In addition, it implies that the cars observed on the highway are representative for the German vehicle fleet.

[71] For fuel consumption the ton-value is converted into liters applying the fuel densities according to HBEFA: 742 g/l for gasoline, and 832 g/l for diesel. (see Footnote 66)

changes. NO_x reductions also constitute a significant share of social benefits, which is driven primarily by its high social cost per ton. The figures for the diesel engine reflect the typical composition of local pollutants from exhaust gas, where NO_X has the largest share and is followed by PM. The HC/CO emissions are minimal (see Reşitoğlu et al., 2015, p.17). The PM reductions are very low across fuel types, which is not surprising when kept in mind, that I estimate tailpipe emissions only and the largest fraction of PM is induced from abrasion (see European Environment Agency, 2016, p.10). Therefore, actual PM reductions are plausibly expected above the level reported here.

I present the total social benefits graphically in FIGURE 7-1 where I summarize the results of both fuel categories per highway. Across fuel types the annual social benefits are estimated with 5,820,894 € on H_{1G} and about twice as much on H_{2G} with a total value of 11,602,126 €. About 63% of these benefits accrue to fuel economy. The remaining share is split quite equally between global CO_2 emissions (18%) and the joint local emissions (18%). These ratios are stable over both highways, which is logical as the same speed-emission functions are applied and the speed distribution changes are similar in structure.

TABLE 7–5: ANNUAL SOCIAL BENEFITS FROM FUEL ECONOMY AND EMISSION REDUCTIONS									
			Fuel Consumption	**Global Emissions**			**Local Emissions**		
	Fuel type		FC	CO2	CO	HC	NOx	PM
H1G	Gasoline	Change in tons	-3,186.920	-9,990.995	-313.130	-2.044	-12.779	-0.910
		Social cost	-3,049,479.09 €	-864,221.11 €	-19,414.07 €	-3,474.25 €	-196,804.03 €	-111,782.13 €
	Diesel	Change in tons	-750.011	-2,384.284	0.018	-0.041	-44.618	-0.344
		Social cost	-640,033.07 €	-206,240.53 €	1.11 €	-69.92 €	-687,121.03 €	-42,255.88 €
		Total Social Cost	**-3,689,512.16 €**	**-1,070,461.64 €**	**-19,412.96 €**	**-3,544.17 €**	**-883,925.06 €**	**-154,038.01 €**
H2G	Gasoline	Change in tons	-6,368.724	-1,9965.951	-605.173	-3.981	-25.556	-1.794
		Social cost	-6,094,062.44 €	-1,727,054.76 €	-37,520.75 €	-6,767.95 €	-393,561.42 €	-220,292.06 €
	Diesel	Change in tons	-1,498.785	-4,764.636	0.221	-0.035	-87.373	-0.701
		Social cost	-1,279,010.86 €	-412,141.02 €	13.70 €	-58.82 €	-1,345,543.25 €	-86,127.07 €
		Total Social Cost	**-7,373,073.29 €**	**-2,139,195.78 €**	**-37,507.06 €**	**-6,826.76 €**	**-1,739,104.67 €**	**-306,419.13 €**

Source: own table and calculations.

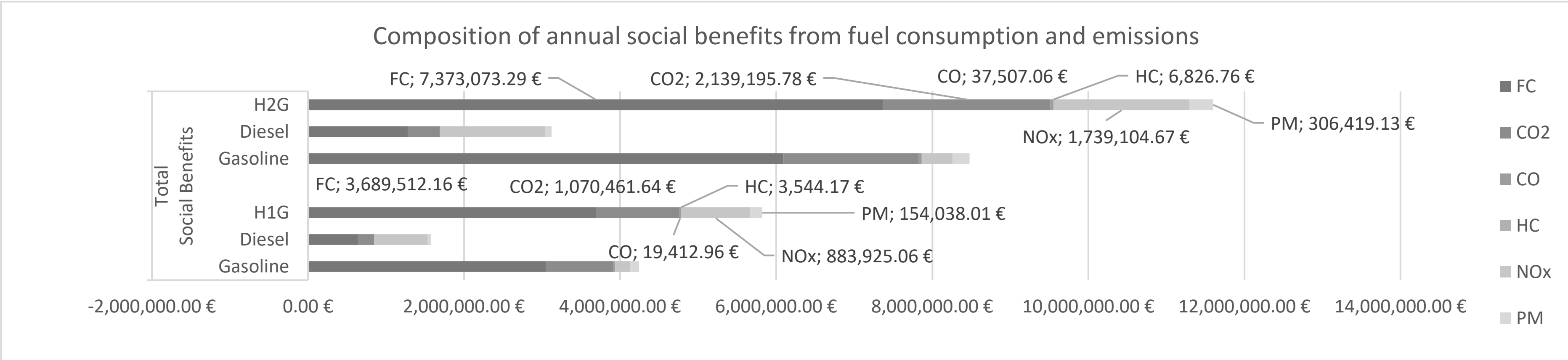

Figure 7-1: Annual social benefits from fuel consumption and emissions. Source: Own figure and calculations.

8 RESULTS

Now, should there – from the perspective of normative welfare theory – be a general speed limit on German highways? The estimated core impacts from a 130 km/h limit on the two German highway sections in the preceding chapter have revealed many insights. FIGURE 8-1 takes up on these results and juxtaposes social cost and benefits for the central case as derived and estimated above. As the core social cost, travel time losses enter the calculations with about 5m € per year on H_{1G} and 13m € on H_{2G}. However, these annual social costs are compensated by benefits from traffic safety (3.6m on H_{1G} / 3.5m on H_{2G}), fuel economy (3.6m / 7.3m) and emissions reductions (2.1m / 4.2m), which include health impacts as the social accounting price is employed.

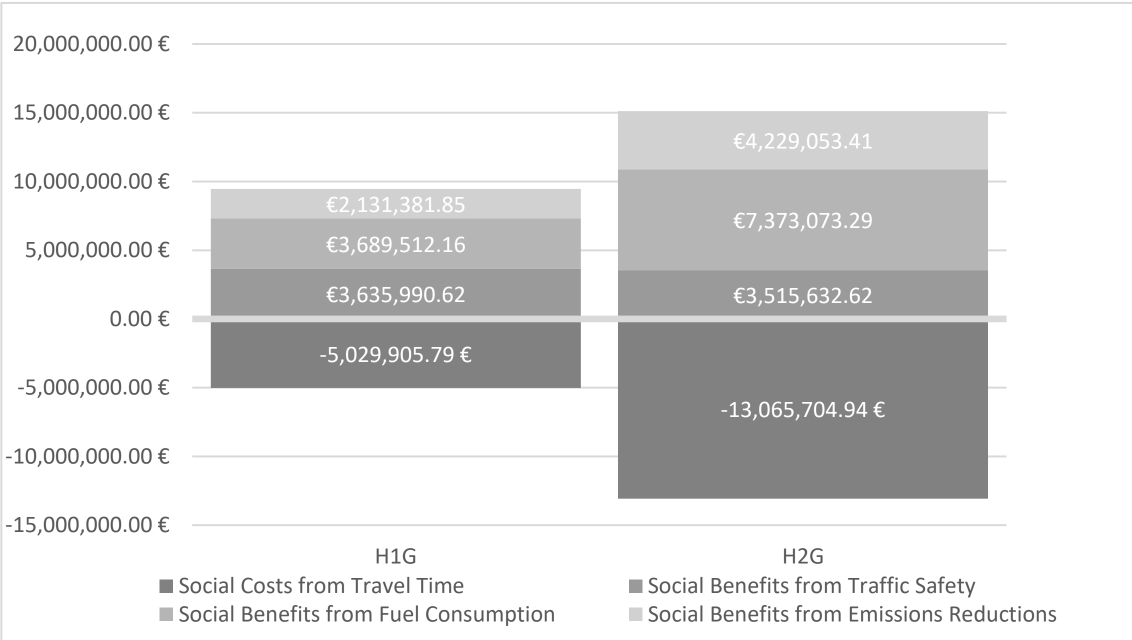

Figure 8-1: Compilation of annual social benefits and costs per highway. Source: own figure and calculations.

In Chapter 3, the Kaldor- Hicks criterion was introduced as a key decision rule. It stated that a policy should be adopted only if the beneficiaries could entirely compensate the losers and would still be better off. It was noted, that this is the case whenever social net benefits are positive. This means, based on the impacts as derived above, a general speed limit of 130 km/h on the two German highway sections H_{1G} and H_{2G} is estimated to result in annual net social benefits of **4,426,978.84 €** and **2,052,054.39 €,** respectively. Consequently, – from the perspective of normative welfare theory and under the central case scenario assumptions – implementing a 130 km/h speed limit on the highways analyzed would be desirable for society.[72]

[72] Net Benefit results are – consistently with the valuation in the previous section – expressed in 2012 Euro.

8.1 Private and External Benefits

The study finds, that society would be better off having a speed limit on the highways investigated. But is a speed limit also desirable when taking the private perspective and ignoring the external effects of transport?

This question gives rise to the fundamental economic motivation for the analysis – the external cost from transport activities. Policies such as speed limits are primarily intended to target these externalities. Economically, internalization of external effects means making the external effects part of the private decision making process (see Korzhenevych et al., 2014, p.1). In the present case, a means for internalization is the posted speed limit. It was shown that the privately chosen driving speeds without a limit are too high from a social perspective, as evident in the welfare increase when speed is reduced. The question is whether having a speed limit is rational from a *private* highway user's point of view or not.

To shed light on this topic, I classify the different cost and benefit components into either private or external. First, time costs are reasonably treated as purely private. Second, fuel economy saves private money of the travelers and is considered as a purely private benefit. In the previous analysis, I valued fuel net of taxes because from the social perspective taxes constitute a transfer to the government (see e.g. Boardman et al., 2014, p.56). This is no longer true from a private point of view, where saving the taxes included in the fuel price results in plain additional benefit. Thus, I price this impact at the fuel price *including* taxes.[73] Third, I follow Korzhenevych et al. (2014), and treat environmental benefits as fully external, thus they do not enter at this point. Fourth, the benefits from traffic safety need to be split into a private and an external component. The question who bears the cost of an accident is not easily answered. Some of the risk of suffering injuries or property damage when using a road is already internalized. Primarily, the internalized costs are those costs covered by the insurance, which a particular transport user has paid for (see Korzhenevych et al., 2014, p. 21). There exist several methods to determine how large the external share of total accident costs is. One approach stems from the well- known handbook Korzhenevych et al. (2014) which uses an estimate of the internalized cost share. This is obtained by "dividing the number of fatalities inside a certain type of vehicle by the number of fatalities in accidents involving this vehicle type" (see Korzhenevych et al., 2014, p.21). This way, the guide estimates the share of internal costs for passenger cars at 76% of total accident costs. Under this classification, I arrive at the composition of net private/ external benefits from the speed limit policy as shown in TABLE 8–1.

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[73] For the fuel price, I use the average price for diesel / gasoline observed at gas stations in 2012. These are 1.377 € for Gasoline and 1.257€ for Diesel (see Table 26 in BMVI (2016b).

TABLE 8–1: CALCULATION OF PRIVATE NET BENEFITS.			
		H_{1G}	H_{2G}
Private Costs	Travel Time	-5,029,905.79 €	-13,065,704.94 €
Private Benefits	Internal share of accident savings	2,763,352.87 €	2,671,880.79 €
	Fuel economy	7,047,400.39 €	14,083,437.50 €
Net Private Benefits		**4,780,847.47 €**	**3,689,613.35 €**
Source: own table and calculations.			

It is an unforeseen result, that on both highways also the private assessment results in positive benefits. The key driver here is the fuel price, as private fuel economy amounts to the largest share of benefits.[74] Indeed, under the assumptions made here, the fuel savings alone compensate for the time opportunity costs, which would be an interesting trade-off to be analyzed in more depth in the future.

Obtaining a positive estimate of private benefits means that also from the private perspective, driving slower would be favorable. At first sight, this would imply irrational behavior of the transport users. However, given that it is not feasible to capture all potential impacts on a highway user's utility, this shall not be claimed as a general implication from the analysis.[75] Apart from other potential impacts which are likely to drive this finding, it is also possible, that imperfect information of the highway users is a cause for this effect. It is well conceivable that travelers do not exactly know, how much fuel (which is the major private benefit here) they save long term, from driving slower. It is even more realistic, that there is a broad underestimation of accident risk, which is causing irrationally high speeds. Also, people often overestimate the time savings they can achieve from speeding, which has been elaborated on by Tscharaktschiew, (2016). All of this may lead to a suboptimal speed choice from a private perspective and subsequently to a suboptimal speed choice from the social perspective. This supports the result that from a perspective of welfare maximization, a speed limit on highways in Germany may be desirable.

It is finally noteworthy that the annual private benefits estimated here are even higher than the social net benefits calculated above. Since all costs in the scenario stem from travel time increases, which are purely private, this effect is due to the higher fuel price from the private point of view. This shows, that the results from the relatively limited case study here are of course sensitive to the assumptions made and parameters defined along the way. Therefore, I perform sensitivity analysis on the central result for the social net benefits by investigating key parameters in the next section.

[74] Indeed, when calculating with the net of taxes fuel price, H_{2G} private benefits turn negative.
[75] Further potential impacts, which are not covered in the main analysis, will be noted in the sensitivity analysis (see section 8.2.2).

8.2 Sensitivity Analysis

8.2.1 Quantitative Sensitivity Analysis – What if?

Theoretically, one could shuffle every parameter and tighten or loosen any assumption made in the CBA, to account for the uncertainty accompanying these necessities. Practically, however, I want to focus on core parameters and assumptions, which have the potential of altering the decision made above and could turn the calculated annual benefits into a negative number.

Travel time is the only cost component in the analysis and thus the first impact to perform sensitivity analysis on. Two aspects are crucial; the difference in travel speeds between Germany and the Netherlands and the VoT. With respect to the former, I calculate net benefits using the maximum of observed annual differences instead of the mean. Thus, assuming a decrease in mean speeds of -3.54 km/h for H_{1G}, the net benefits then are reduced to 3,245,981.29 € but overall the policy remains welfare increasing. On H_{2G} the maximum is a large decrease of -9.09 km/h, which turns annual social benefits negative to -449,930.34 €. In order to equate benefits and costs, mean speeds would – ceteris paribus – need to decrease to roughly 88 km/h on H_{1G} and to 115 km/h on H_{2G}.[76] 88km/h is below the 3rd percentile of H_{1G} and more importantly also below the 2nd percentile of H_{2N} and thus a highly implausible speed level to be provoked by adopting the foreign speed limit policy. 115 km/h on H_{2G} is somewhat more reasonable and the maximum speed difference observed per year would actually drag mean speeds below this value.[77] Here, it is visible that the predicted magnitude for this impact is of supreme importance when making deciding about the desirability of the policy. However, due to the particularities in the accident analysis, road security benefits are likely to be underestimated on H_{2G}. This mitigates the sensitive results for Highway 2 where, despite much higher speed differentials, the accident rates per vehicle kilometer had to be assumed to be identical to those on H_{1G}. In fact, these should be higher and would likely contribute to compensation of the large time opportunity costs.

Because non-business travel time accounts for the major share of time opportunity costs, I also calculate the hourly break-even VoT for non-business travel. This means, again, that net benefits are zero when this VoT were true, holding other factors constant. For H_{1G} the VoT that equates benefits and costs is 20.70 €/h. This value is not only outside of the range presented as applicable in BMVI, (2016b) but also much higher than the average

[76] This means, that I search for the target value of mean speed, which sets benefits equal to cost, holding all other impacts constant (ceteris paribus). Another interpretation often found in sensitivity analyses is that a parameter sets the benefit- cost ratio to parity, which is equivalent to net benefits of 0.

[77] Initial mean speeds on H_{2G} were 123.73 km/h. The maximum annual difference to the Dutch Highway counterpart was 9.08 km/h, leading to a maximum expected reduction on H_{2G} of 114.64km/h.

hourly net wage in Germany, exceeding it by more than 100%.[78] Thus, this value seems out of the reasonable range for non-business travel time. The break-even VoT on H_{2G} is considerably lower at 11.67€. This is still a high value but could be considered in the range of plausible values as it is at least covered in the range presented in BMVI, (2016b). Again, the results of Highway 2 are found to be less robust. Overall, the VoT needs to increase to the top of the plausible range to alter the positive policy decision.

A natural parameter to perform sensitivity analysis on is the VSL as it is a parameter subject to much debate. However, in the present case, the contribution of a reduction in fatal accidents to social benefits is very small due to the marginal differences observed in fatalities. I therefore do not analyze this input parameter in more detail.

With respect to fuel consumption, the price is the only input value, which is market determined and hence not subject to much uncertainty. Merely the input prices net of taxes are subject to a slight adjustment by the authors of BMVI, (2016b). When using the original prices observed, this increases net benefits slightly as the fuel prices are raised a touch.[79]

Regarding the emissions calculations there are a few arguments explaining why expected benefits could be significantly lower, especially since PM emissions are certainly underestimated because only tailpipe emissions are included. It is known from the literature presented in Chapter 2 that PM emissions stem largely from abrasion.[80] A point of discussion may be the interpolation of speed-emission figures from the discrete emission factors by speed level. This means I do not observe exact emission factors for speeds above 130 km/h but extrapolate the fitted functions. Since several speed percentiles are above 130 km/h, this may have impacts on the calculated emission reductions especially for the higher percentiles. The UBA provides a single average value per emission item to be applied for speeds above 130 km/h.[81] Indeed, when applying this fixed factor for higher speeds, the emission results change significantly, dragging net benefits on H_{1G} below 1 million € and H_{2G} benefits into a slightly negative range. However, applying a fixed emission value on all speeds above 130 km/h does clearly underestimate the impacts in this case. This is essentially equal to omitting all speed differentials for percentile values above 130 km/h in the valuation. Yet, as evident from FIGURE 6-8, this does not reflect the increasing speed gap at the top 20 - 30% of the speed distribution. Consequently, the largest emission impacts are neglected, for which reason my estimates appear more accurate and are preferred in the analysis here.

[78] For example, in 2012 the average monthly salary net of taxes in Germany was 1,684 € (see Statista 2018). Based on a 40 h week and 4.3 weeks per month this corresponds to a net hourly wage of 9.79 €.
[79] Original prices are 0.722 € for Gasoline and 0.787 € for Diesel. (See Table 26 in BMVI 2016b).
[80] See literature review and again European Environment Agency (2016)
[81] See APPENDIX 17 for the full table provided by the UBA.

8.2.2 Qualitative Sensitivity Analysis – Other potential impacts

Like every CBA, this analysis abstracts from other transport impacts that potentially influence an individual's utility. This section briefly addresses other potential impacts which have not been included quantitatively. It is started with additional conceivable social costs from a general speed limit policy in Germany, which may counteract the findings.

Investment and transaction costs

The analysis abstracts from initial investment costs such as parliament debate and operative implementation of the policy. With the possibility of running a public communications campaign to introduce the policy, operative maintenance costs such as setting up new traffic signs should be small. Public and parliament debate as well as further publicly funded studies for decision-making would expectedly lead to several millions in social costs. These are, however, initial costs likely to be offset by the consecutive annual benefits given the long-time horizon of such a policy.

Image for German car manufacturers and demand reduction

The unlimited highways may provide a competitive advantage for German car manufacturers by creating the image their cars were "Autobahn approved", especially for foreign customers. This could work as a signaling effect and leverage car sales, which may decrease if speed laws were amended. This potential impact is not easily quantifiable and – as noted by a group of German traffic research professors – is not to be favored over road safety from an ethical perspective (see Universitätsprofessoren des Verkehrswesens, 2004, p.3).

Joy of driving fast and Highway tourism

There will be people with a certain willingness to pay for the pleasure they experience when speeding on the German highway. Eliminating the possibility of legally doing this, would thus also constitute a social cost.[82] In addition, several foreigners travel to Germany with the distinct aim of driving a fast car on the German Autobahn. Their utility from enjoying the highway ride and the money they spend on domestically produced goods and services could be included in a CBA. In contrast, many road users on the public

[82] It is debatable whether these preferences should be given standing in a CBA. Veisten et al. (2013) for example, discuss the appropriateness of giving standing to the people's utility from violating traffic laws. The joy of driving fast is not an identical case but due to the high (external) risks of excessive speeds inclusion appears questionable as well.

highways may feel intimidated and are put into danger, which is neutralizing this potential cost item. This was also noted in Universitätsprofessoren des Verkehrswesens (2004). On the other hand, there are several impacts that could be of additional benefit and would exacerbate the positive welfare effects from a speed limit.

Travel time reliability
The time lost when traveling slower could be offset partially by an increase in travel time *reliability*. Reliability can be evaluated by a before-after comparison of travel time variance. So far, this impact is rarely quantified in CBA (see Elvik, 2001, p.15) but there are approaches for estimating the value of reliability (VoR) for Germany.[83] Given the clear reductions in standard deviations of speed observed in the present data, one may find considerable improvements in travel time reliability, which may lead to noteworthy welfare gains.

Marginal excess tax burden
I do not estimate welfare increases from the marginal excess tax burden (METB) which is avoided when fuel consumption decreases. Since the fuel price consumers need to pay is highly distorted by taxes, a demand reduction in fuel results in deadweight loss- savings from the sum of these transactions.

Further Downsizing
Without the possibility of extremely high speeds the long run car engine sizes and thereby fuel consumption and emissions are to decrease further. The general notion of "downsizing" in the car industry may be expected to be accelerated as a speed limit can set incentives for diverting innovation in the automotive industry towards higher fuel efficiency (see Universitätsprofessoren des Verkehrswesens, 2004, p.2).

Property damage accidents
It is also abstracted from accidents with property damage only. As shown in Section 6.3, this accident category constitutes a high share of total accidents. This category could result in either additional private benefits or costs, as it is unclear whether these low-severity accidents are increased or decreased.

[83] TNS Infratest /IVT /ETH Zürich (2015) estimate the WTP for reductions in travel time standard-deviations that can be used in German transport project appraisals.

9 POLITICAL IMPLICATIONS

The analysis finds that a speed limit on the two German highway sections would be beneficial to society from both the benevolent planner *and* the private perspective. This finding is shown to be more robust for the German part of Highway 1 (i.e. the highway km 0 to 79 of the German A61 (H_{1G}). The finding of positive welfare effects on the Highway 2 section are to a certain degree sensitive to the assumptions made. In particular, this is due to higher variance in the permanently posted speed limits, which made the analysis more difficult and made it necessary to adopt the accident results from Highway 1 despite speed differences on H_1 being considerably smaller. However, even with the anticipated underestimation of road safety benefits, the numbers for Highway 2 point in the same direction, which makes the results somewhat more robust.

What does this finding mean for Germany as a whole? As an experiment of thought, the net benefits of Highway 1 (4,426,978 € per year at 158 distance-km) can be scaled up for the entire German highway system. If the roughly 18,037 unlimited highway km were subject to a 130 km/h speed limit, the findings translate into a countrywide annual net benefit of 505 mio €. Of course, this case study is of relatively limited scope. Therefore, the representativeness for the German highway net is not given. For example, a large share of the German highway net has three lanes per direction, which may produce different results. The morphological constitution across Germany differs as well, which predictably changes speed distributions and accident rates. Speed limit compositions can also be different. Consequently, producing reliable estimates of welfare impacts from general speed limits on the country-level is a very complex task and requires further research.

If a speed limit was to be implemented, inevitably the question of the optimal level arises.[84] While it is not in scope of this thesis to answer this question it was pointed out that the level matters significantly for public acceptance. In theory one can identify an optimal limit by maximizing the net benefits as a function of the speed limit. Determining a continuous social benefits function is a highly interesting, but demanding task.

Given the analysis above, it is likely that also on the federal level, the Germany society could benefit from a general speed limit on highways. To support future research, it would be highly recommendable to improve data access and transparency. As it is pointed out in this thesis, collecting data was a considerable effort, especially in Germany. A consolidated road database similar to the system set up in the Netherlands would certainly be of

[84] A theoretical model to calculate optimal speed limits has, e.g. been developed by Jondrow et al. (1983) who introduce a standard neoclassical model to the problem, based on typical assumptions like homogenous (e.g. the same optimal private speed for all) and fully informed agents (e.g. knowledge about value of time and accident probability). They develop a model for the standard trade-off between travel time and safety risk depending on speed and under a restricted budget.

high value for the German road safety research and other topics in transport research. This applies at least to two dimensions; speed measurement data on the one side and detailed speed limit overviews on the other. Up to now, it appears that both is subject to a political momentousness, which causes hurdles to research projects.

10 Conclusion

In this thesis, I analyzed the impact of a general speed limit of 130 km/h for passenger cars on two highway sections in the federal state of North Rhine-Westphalia, Germany. Travel speed and accident data were used to quantify the social welfare impacts on travel time, accident victims, fuel consumption and emissions. In the central case, I conclude that on both highways the speed limit would be beneficial from the social *and* private perspective. The latter result indicates a certain irrationality in the speed choice of the highway travelers, which can be explained by omitted impact factors on the utility of highway users as well as time-savings misperceptions from speeding. The former leads to the question whether these findings can be extrapolated from the case study to the highway net in Germany as a whole. This cannot be claimed as the highway system at the national level can vary in many dimensions such as lanes, curvature, slopes etc., which potentially alters the effects. Additionally, the impacts found on the two highways differ in magnitude. However, the qualitative decisions are identical and sufficiently robust to their core assumptions. Furthermore, the present work demonstrates a roadmap of how to evaluate several cost and benefit categories consistently and provides a broad overview of relevant literature as well as further potential impacts to be covered.

Next, it is to be asked, why Germany sticks to its exceptional no-speed limit policy. Two core reasons for this may be the existing research gap and political importance of the topic. Improving the limited possibilities of obtaining data on travel speeds and detailed speed limit overviews can help fostering independent research on the topic.

Many interesting aspects could be covered in future research. The accident analysis has discovered the need for larger scale analysis of speed limit impacts on accidents in Germany. A very interesting question arose about the private trade-off between travel-time savings and fuel consumption, which targets the question under which assumptions about the VoT and fuel prices speeding leads to private welfare gains. Moreover, the sensitivity analysis has exposed several further impacts, which are not covered here but can be analyzed and estimated. Studies of larger scale would improve the reliability in assessing the social desirability of speed limits on a federal level. There are many questions to be targeted and indeed – in the case of speed, there may be a lot to gain from implementing a limit. Speed appears to be one of the rare cases, where restrictions are preferable over free choice.

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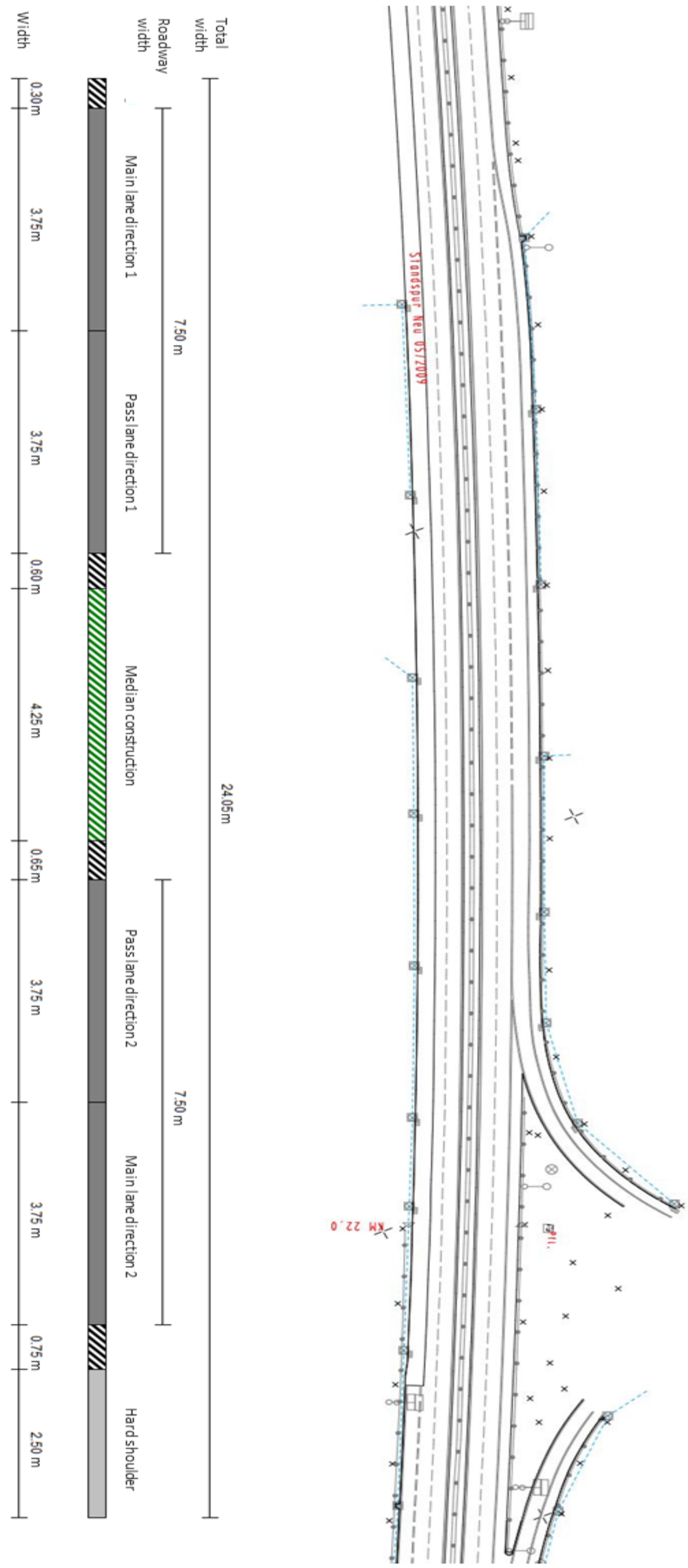
APPENDIX

Appendix 1: Illustration of a two- lane highway (birds view and cross-section).

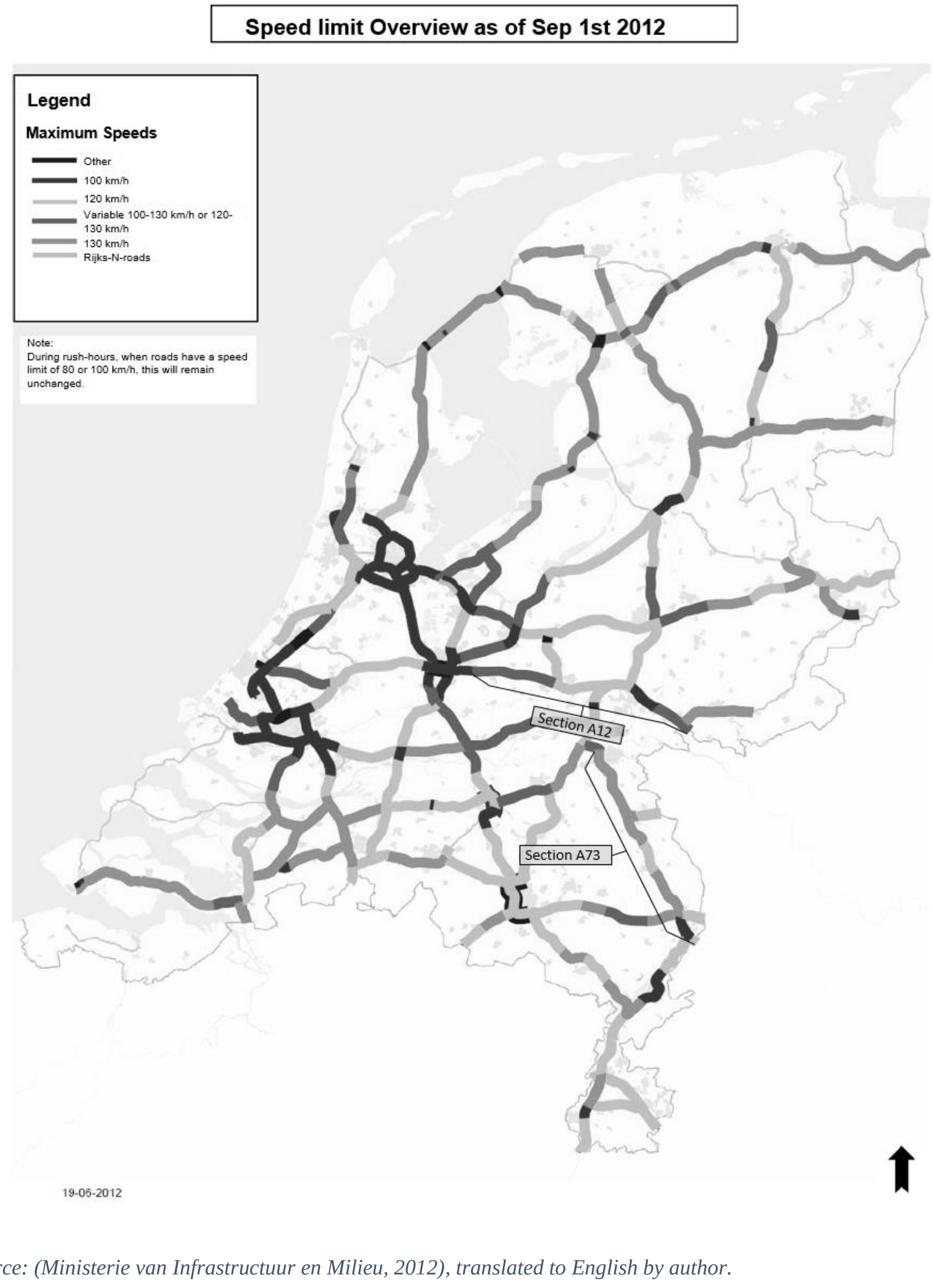


Appendix 2: A snapshot on maximum speeds in Europe.

GENERAL PASSENGER CAR SPEED LIMITS IN EUROPE, 2017 (IN KM/H)			
Country	Urban areas	Rural roads	Motorways
Austria	50	100	130
Belgium	30-50	70-90	120
Czech Republic	50	90	130
Denmark	50	80	130 (110 for certain sections)
Finland	50 (sections with 30, 40, or 60)	100 (80 in winter)	120 (100 near cities)
France	50	90 (80 in wet weather, for novice drivers)	130 (110 in wet weather and for novice drivers)
Germany	50	100	None (130 recom-mended)
Greece	50	90	130
Hungary	50	90	130 (110 on ”motor roads”)
Iceland	50	90 (paved roads) 80 (gravel roads)	n.a.
Ireland	<=60 (can be 60 on arterial roads, 30 in built up areas)	80, 100	120
Italy	50	70-90 (110 on some main dual carriage-ways)	130 (110 in wet weather, 100 for nov-ice drivers. Motorway operator may increase speed limit up to 150 if stringent re-quirements are met)
Lithuania	50	90 (70 on gravel roads and for novice drivers)	120,130 (110 in win-ter, 90 for novice driv-ers)
Luxembourg	50	90	130 (110 in wet weather)
Netherlands	30-50	60-80	100*-130
Norway	50 (30 on residential streets)	80	90,100,110
Poland	50 (60 at nighttime)	90, 100, 120	140
Portugal	50	90	120
Serbia	50	80, 100	120
Slovenia	50	90 (110 on express-ways)	130
Spain	50	90,100	120
Sweden	30, 40, 50	60,70,80,90,100	110,120
Switzerland	50	80	120
United Kingdom	48 (30 mph)	96, 113 (60, 70 mph)	113 (70 mph)

Note: The table provides an overview of the speed limits for passenger cars of the subsample of European member countries of the International Traffic Safety Data and Analysis Group (IRTAD).
* Applies to so-called through roads, which do not fully meet the standards of highways. For reg-ular motorways the limit is 130 km/h. (see same source as below, Table 27.7 on p. 378).
Source: Adapted from (ITF, 2017), p. 28.

Appendix 3: 2012 speed limit changes in the Netherlands.

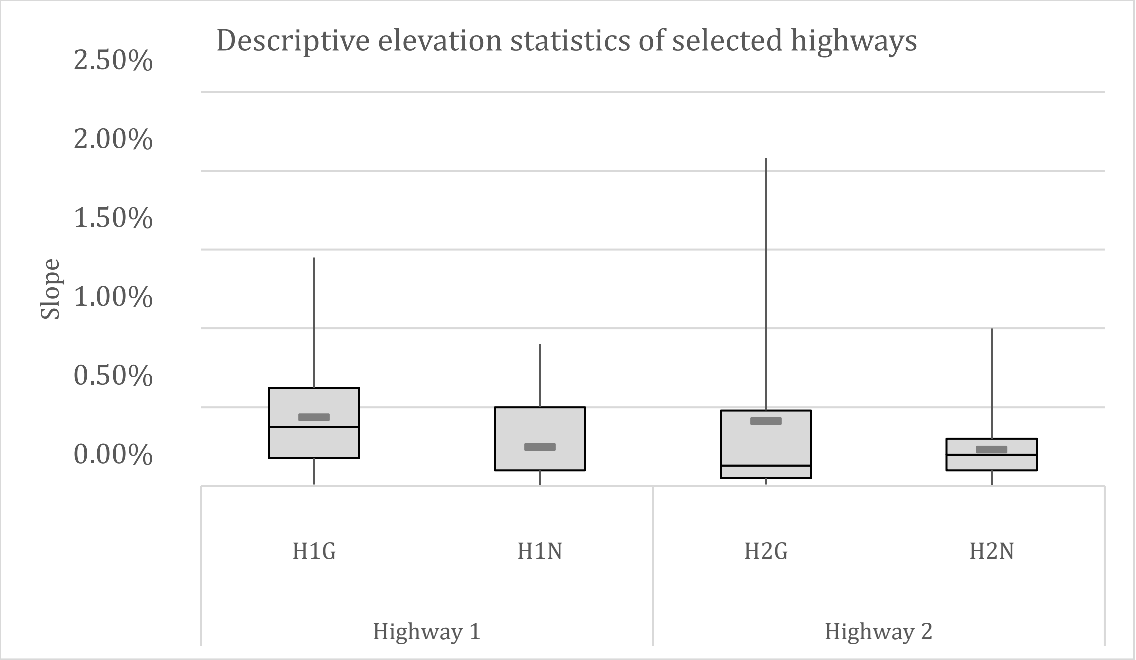


Source: (Ministerie van Infrastructuur en Milieu, 2012), translated to English by author.

Appendix 4: Data collection at German federal level hardly possible.

I tried to obtain data on two central aspects from the German federal highway research institute “Bundesanstalt für Straßenwesen” (BASt). Firstly, I requested *measurement data on real driving speeds* in any possible format. Surprisingly, the institute itself does not collect data on real driving speeds at all. Attached to the response I received the work of Kellermann (1995), who uses historical measurement data to determine relationships between speed and traffic volume in order to infer to the speed distribution in the (West German) highway system in 1992. Analyses that are more current are not available within the BASt. In line with (Molitor 2017) I find that there exists no official institution in Germany that centrally collects data on driving speeds. Secondly, it was necessary to receive an *overview of posted speed limits on the highways in question.* The federal (BASt) had requested such data from the federal states in 2015. In the final report it is noted that due to the political importance of the discussion on speed limits, the federal states have linked the provision of detailed speed limit data to the condition that sharing of the data is only permitted at a highly aggregated level (see Kollmus et al. 2017). According to the same report, a detailed analysis on state (or even highway) level or of the order reasons is not possible.

Appendix 5: Boxplot graph of the elevation profile per highway section.



Note: Slopes are calculated as 1000m intervals. The short additional bar within each plot represents the mean slope per highway section.
Source: own graph and calculations based on data from sources as cited in main text (see Footnote 28).

Appendix 6: Hourly and annual average daily traffic counts by highway, 2015-2017.

Hourly vehicle counts by highway						
	Highway	Observa-tions	Mean count of vehicles per hour	Maximum count of vehi-cles per hour	AADT	Absolute intra-highway Dif-ference in AADT (H_{XG} - H_{XN})
H_{2G}	Lane 1	458,507	541.556	2247		
	Lane 2	458,398	469.5907	2518	**48535**	
	Sum	**916,905**	**1,011**			
						Δ= 827
H_{2N}	Lane 1	683,826	679.7444	2735		
	Lane 2	578,622	314.1644	2840	**47708**	
	Sum	**1,262,448**	**994**			
H_{1G}	Lane 1	266,036	479.0295	1497		
	Lane 2	264,908	381.4018	2384	**41301**	
	Sum	**530,944**	**860**			
						Δ= -5799
H_{1N}	Lane 1	315,612	466.1841	2880		
	Lane 2	368,214	515.0554	1440	**47099**	
	Sum	**683,826**	**981**			

Note: In the data, I observe individual traffic counts by hour, by direction and lane for a given highway. The table provides mean traffic counts over all three years by highway by lane. Since the AADT includes all directions and lanes, traffic counts per lane per hour are added up and multiplied by 2 (directions) * 24 in order to provide an estimate of average daily traffic. Doing so assumes constant traffic for both directions for a given measurement point, which is necessary since most of the measurement stations only depict one direction.
(The minor deviations of the AADT figures when replicated from the table are due to rounded hourly mean values.)
Source: Own table and calculations based on speed data set as described in 6.1.4.

Appendix 7: Summary statistics of collected speed data (all stations).

Summary statistics of collected speed data (all stations).

Panel 1: mean speeds and 85th percentile speeds by highway for the years 2015-2017 (km/h)

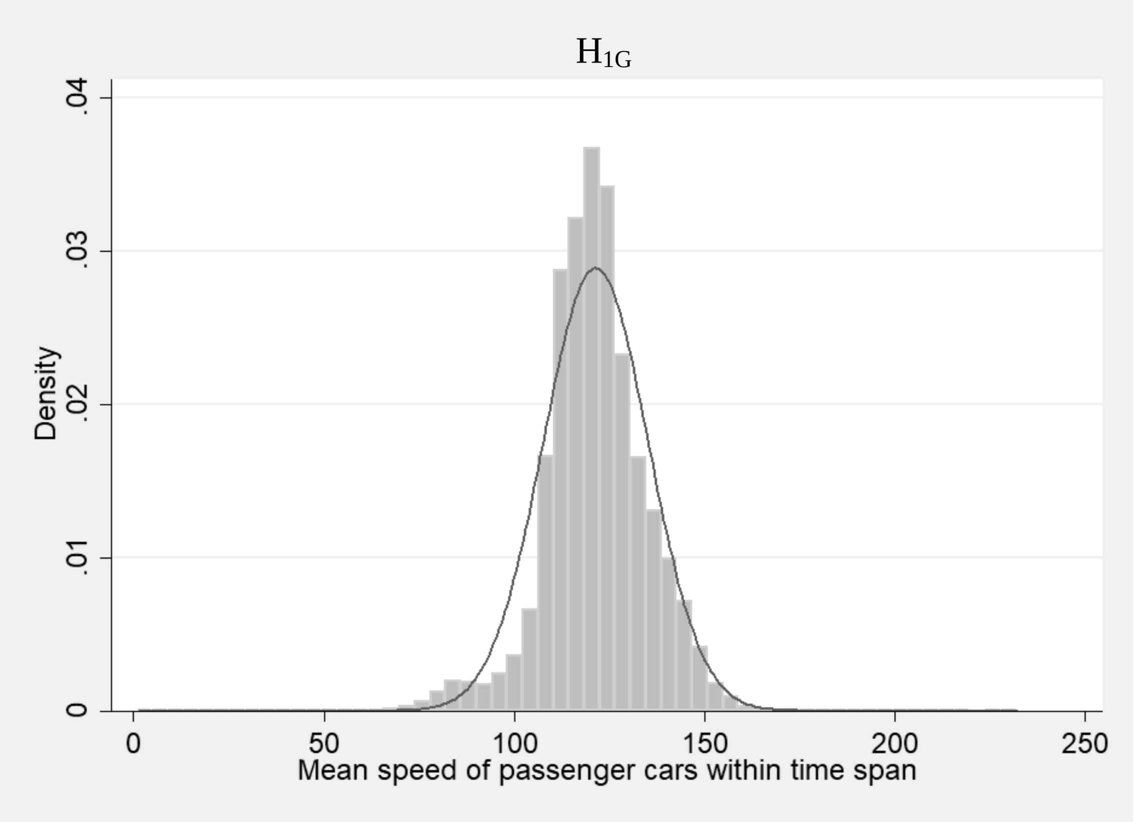
		2015		2016		2017	
		Mean speed	85th percentile speed	Mean speed	85th percentile speed	Mean speed	85th percentile speed
Highway 2	H_{2G}	124.409	137.466	123.310	135.792	123.476	136.703
		(16.685)	(11.260)	(16.758)	(12.735)	(17.023)	(12.014)
		305802	311020	304906	311742	293400	294630
	H_{2N}	112.376	120.661	113.173	122.196	113.814	123.239
		(14.258)	(6.677)	(15.082)	(8.357)	(15.029)	(8.342)
		328313	397669	308338	363105	344646	406297
Highway 1	H_{1G}	121.777	131.208	122.099	131.641	120.299	130.560
		(13.380)	(10.989)	(13.848)	(11.718)	(14.113)	(10.444)
		175560	179640	169509	175012	173655	177643
	H_{1N}	118.851	125.943	118.563	126.326	118.121	126.466
		(9.372)	(3.876)	(11.465)	(5.236)	(12.202)	(5.612)
		201684	213530	203601	207768	197948	200856

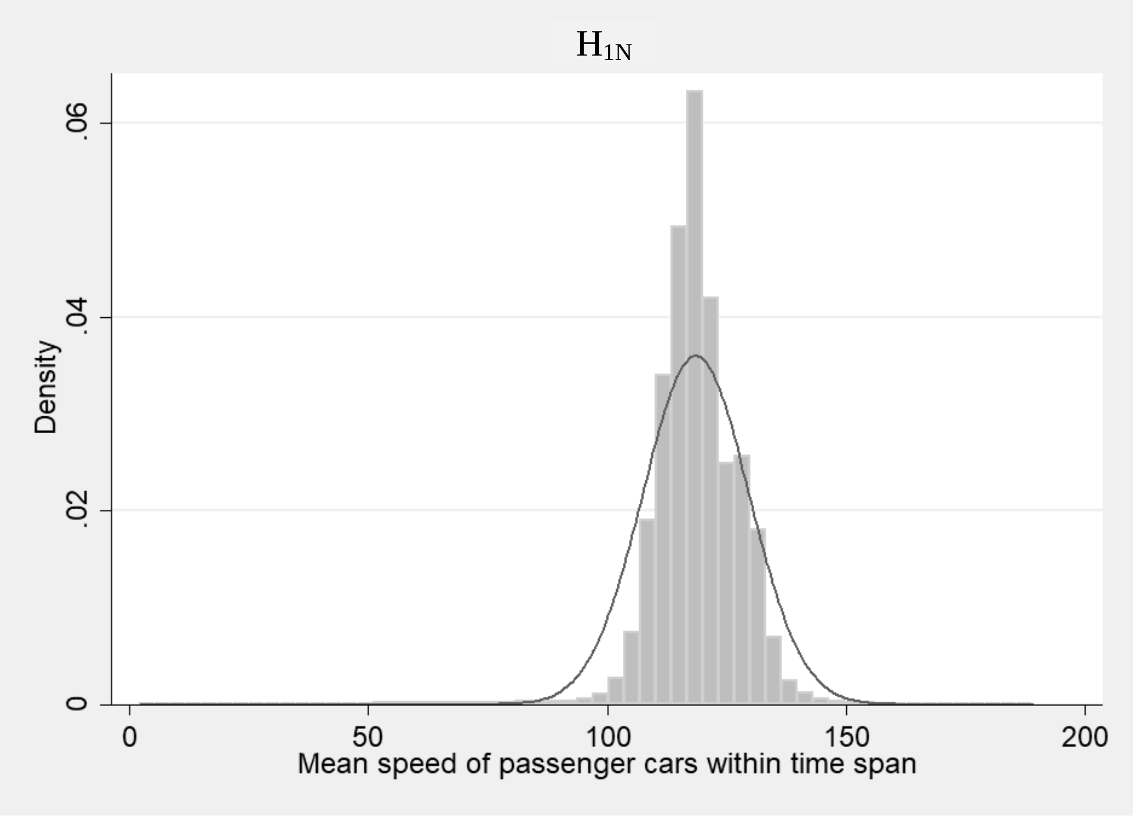
Panel 2: differences in mean speeds and 85th percentile speeds as well as their respective std. Dev.

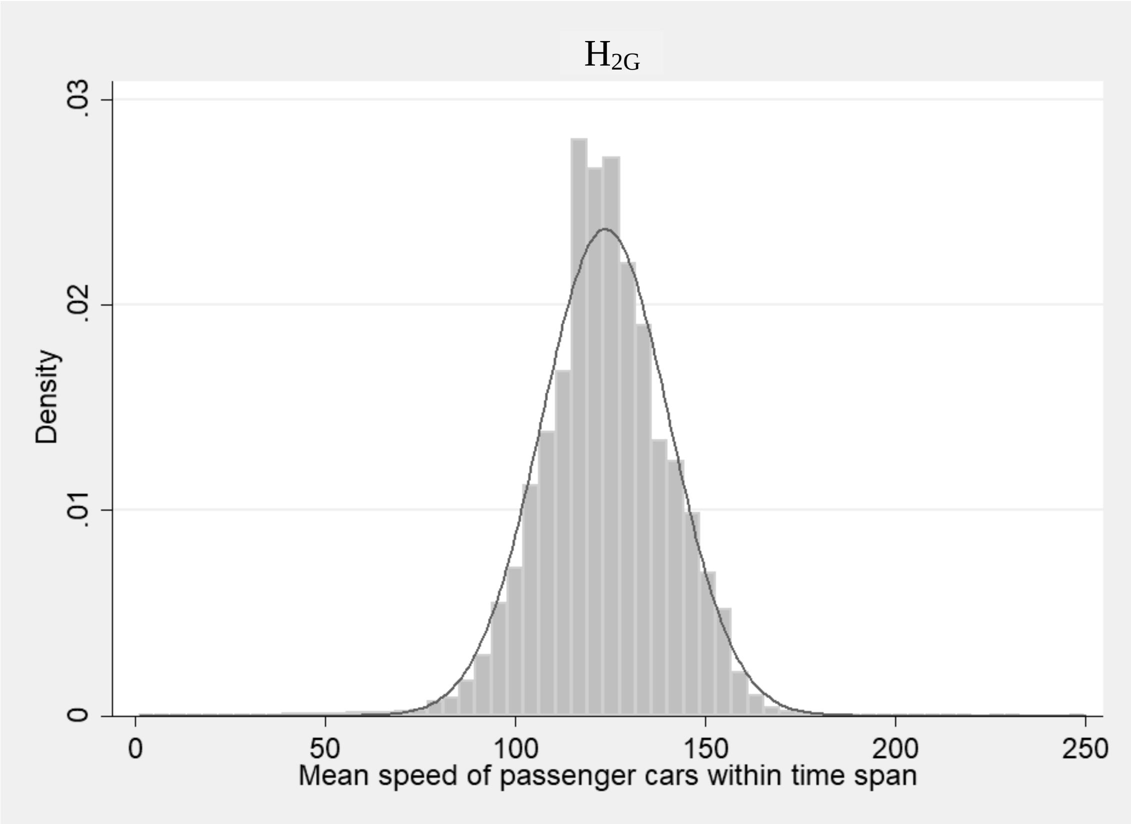
H_{2G}-H_{2N}	Mean	-12.033	-16.804	-10.137	-13.596	-9.662	-13.464
	Std. Dev.	-2.426	-4.583	-1.675	-4.378	-1.994	-3.672
H_{1G}-H_{1N}	Mean	-2.926	-5.265	-3.537	-5.315	-2.178	-4.094
	Std. Dev.	-4.008	-7.114	-2.383	-6.482	-1.911	-4.832

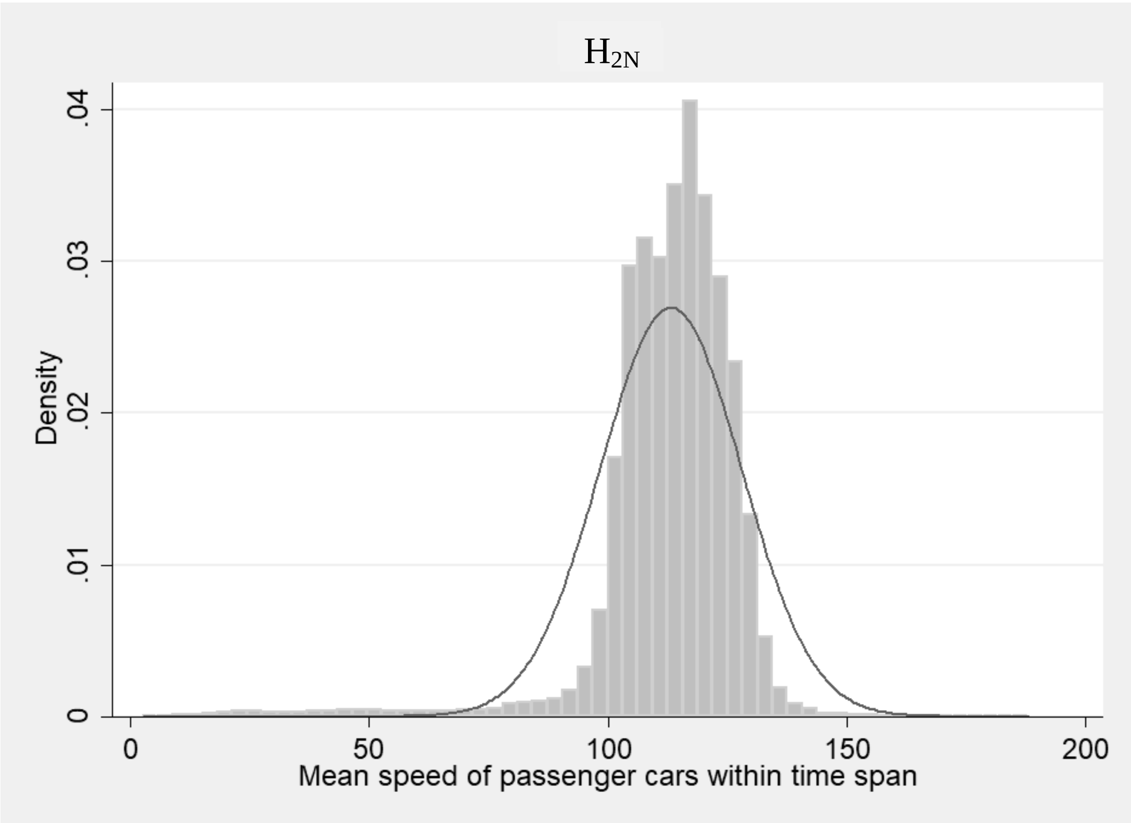
Note: Panel 1 reports means speeds and 85th percentile speed by year and highway. Standard deviations written in brackets, the third line for each highway is the number of observations. Mean speeds are yearly averages over hourly observations while I have daily values per station for the 85th percentile which is then averaged per year and highway. All available stations are included. Panel 2 calculates differences between the German and the Dutch value for mean speeds and 85th percentile as well as their corresponding standard errors.
Source: Own table based on data as cited in 6.1.4.

Appendix 8: Distribution of mean speeds by highway compared to normal distribution.






H2G
Density
Mean speed of passenger cars within time span
0
.01
.02
.03
0
50
100
150
200
250

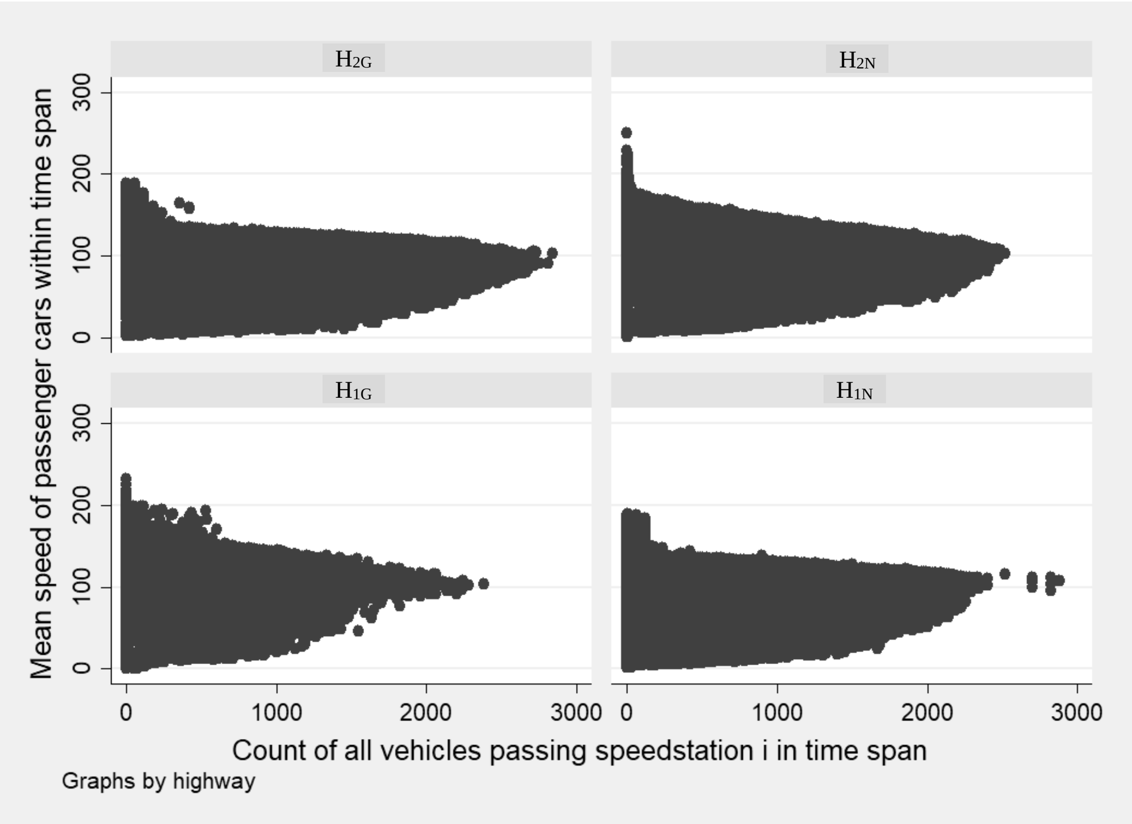

H2N
Density
Mean speed of passenger cars within time span
0
.01
.02
.03
.04
0
50
100
150
200

Appendix 9: Observed top speeds and corresponding traffic intensities on German road sections, 2015-2017.

Top Speeds and traffic intensities						
	Variable	Obs	Mean	Std. Dev.	Min	Max
H_{1G}	Mean Speed	24	207.8333	9.946232	200	232
	Vehicle Count	24	1.791667	1.141287	1	5
H_{2G}	Mean Speed	48	209.0625	11.20298	200	250
	Vehicle Count	48	2.333333	1.226192	1	5

Source: own table based on speed data as described in 6.1.4.

Appendix 10: Scatter Plot and correlation of mean speed to traffic intensity (all vehicles) by highway, 2015-2017.



Corr (mean speed, traffic counts)

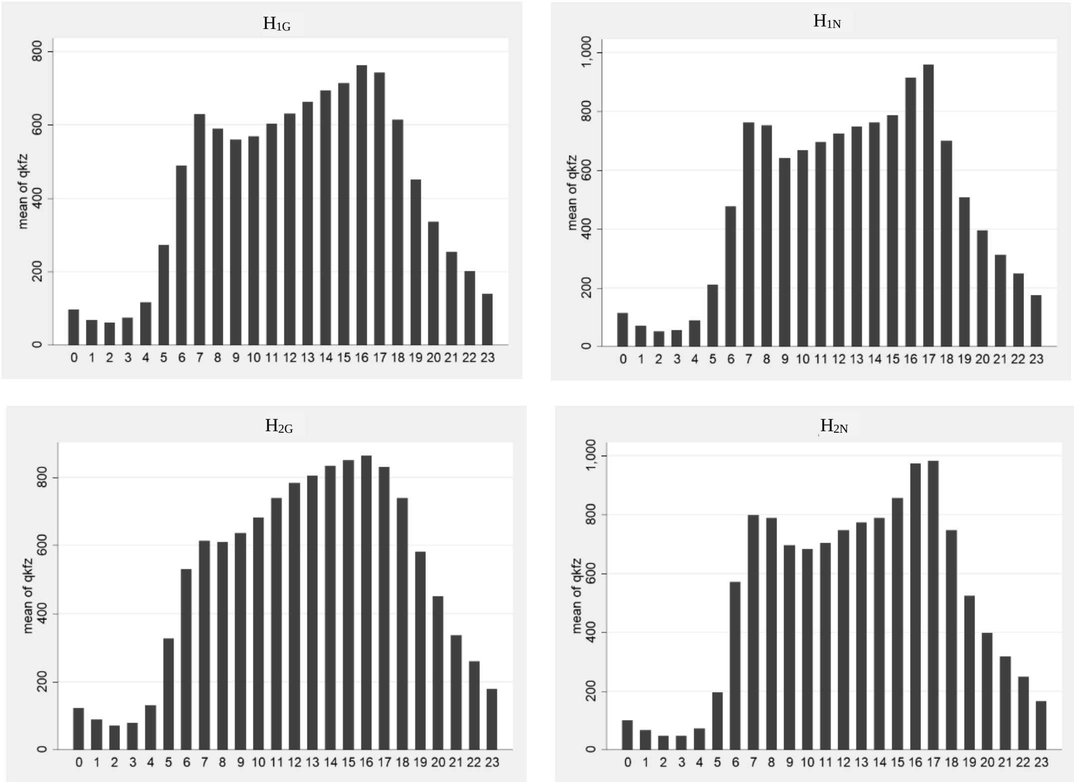
H_{1G} -0.3667

H_{1N} -0.4082

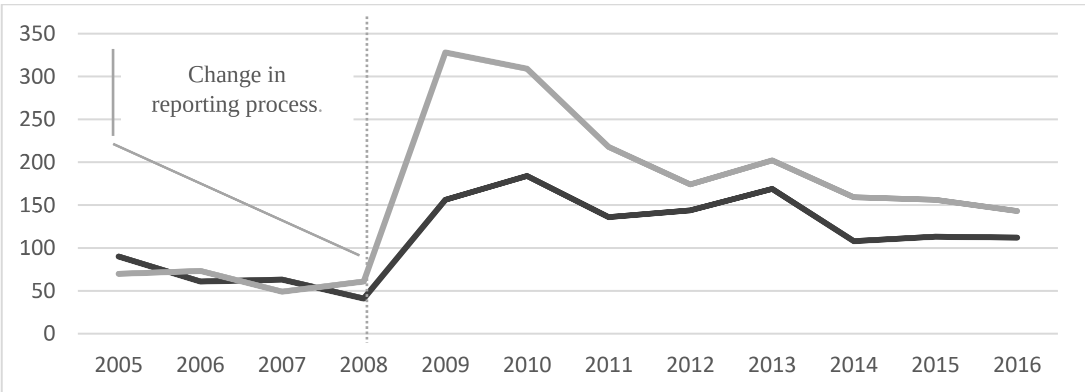
H_{2G} -0.5178

H_{2N} -0.5244

Appendix 11: Mean hourly traffic intensity by highway, 2015-2017 average.



Appendix 12: Number of reported category 4 accidents (property damage only) over time.



Note: The graph demonstrates the number of reported category 4 accidents (property damage) irrespective of speed limit on H1G (light grey) and H2G (dark grey) over time. The graph shows a sharp incline in reported property damage accidents after 2008 when police officers in North Rhine-Westphalia were obliged to report them. The initial steep rise is partially offset in the following years, which may be due to a general time trend. However, the accident counts in the following years visibly remain above the pre-2008 level.

Appendix 13: Annual total counts of accidents and victims per highway and year by severity category.

Annual total accident and victim counts								
	Fatal		**Serious Injury**		**Light Injury**		**Total**	
	Acc.	Pers.	Acc.	Pers.	Acc.	Pers.	Acc.	Pers.
H_{1G}								
PHASE 1	**3**	**(3)**	**69**	**(81)**	**140**	**(238)**	**212**	**(322)**
2016	1	(1)	16	(24)	39	(70)	56	(95)
2015	0	(0)	14	(15)	35	(50)	49	(65)
2014	1	(1)	17	(17)	35	(62)	53	(80)
2013	1	(1)	18	(21)	27	(50)	46	(72)
2012 (Q4)			4	(4)	4	(6)	8	(10)
PHASE 2	**9**	**(10)**	**121**	**(152)**	**267**	**(449)**	**397**	**(611)**
2012 (Q1-3)	1	(1)	8	(12)	23	(43)	32	(56)
2011	3	(4)	17	(18)	28	(39)	48	(61)
2010	1	(1)	21	(23)	34	(56)	56	(80)
2009	1	(1)	10	(14)	25	(48)	36	(63)
2008	3	(3)	17	(19)	34	(71)	54	(93)
2007	0	(0)	19	(29)	39	(57)	58	(86)
2006	0	(0	19	(26)	47	(73)	66	(99)
2005	0	(0	10	(11)	37	(62)	47	(73)
H_{1N}								
PHASE 1	**3**	**(3)**	**21**	**(29)**	**12**	**(16)**	**36**	**(48)**
2016	0	(0)	12	(18)	6	(7)	18	(25)
2015	2	(2)	9	(11)	1	(3)	12	(16)
2014	1	(1)	0	(0)	5	(6)	6	(7)
PHASE 2	**13**	**17)**	**65**	**(88)**	**53**	**(87)**	**131**	**(192)**
2012 (Q1-3)	1	(1)	0	(0)	2	(2)	3	(3)
2011	2	(3)	0	(0)		(1)	2	(4)
2010	0	(0)	3	(3)	1	(3)	4	(6)
2009	0	(0)	13	(18)	7	(12)	20	(30)
2008	2	(5)	11	(12)	9	(16)	22	(33)
2007	2	(2)	8	(9)	10	(20)	20	(31)
2006	0	(0)	19	(25)	11	(16)	30	(41)
2005	6	(6)	11	(21)	13	(17)	30	(44)
TOTAL	**28**	**(33)**	**276**	**(350)**	**472**	**(790)**	**776**	**(1173)**

Note: The table lists total accident and victim figures by highway by severity category for each year. The persons do not need to correspond directly to accidents of the same category. Traffic fatalities of course need to belong to a fatal accident. Severely injured people can be attributed to either fatal or severe injury accidents. Light injured people to either category
Source: Own table based on accident data as described in section 6.1.4.

Appendix 14: Speed percentiles by highway, in km/h (average 2015-2017).

Percentile (Upper Bound)	**H_{1G}**	**H_{1N}**	**H_{2G}**	**H_{2N}**
1	81.00	77.21	81.00	45.74
2	87.00	100.00	89.00	71.41
3	92.00	103.82	92.00	82.68
4	97.00	105.53	95.00	90.42
5	100.00	106.63	97.00	94.49
6	103.00	107.46	99.00	97.00
7	105.00	108.12	101.00	99.12
8	106.00	108.69	102.00	100.84
9	107.00	109.19	103.00	102.25
10	108.00	109.63	104.00	103.46
11	108.00	110.02	105.00	104.48
12	109.00	110.39	105.00	105.29
13	109.00	110.74	106.00	105.97
14	110.00	111.07	107.00	106.57
15	110.00	111.39	108.00	107.09
16	111.00	111.70	108.00	107.56
17	111.00	111.99	109.00	108.00
18	112.00	112.27	110.00	108.40
19	112.00	112.55	110.00	108.78
20	112.00	112.82	111.00	109.15
21	113.00	113.08	112.00	109.50
22	113.00	113.34	112.00	109.86
23	113.00	113.59	113.00	110.19
24	114.00	113.84	113.00	110.52
25	114.00	114.07	114.00	110.85
26	114.00	114.30	114.00	111.17
27	115.00	114.53	115.00	111.50
28	115.00	114.75	115.00	111.82
29	115.00	114.97	116.00	112.13
30	115.00	115.18	116.00	112.44
31	116.00	115.38	117.00	112.77
32	116.00	115.58	117.00	113.05
33	116.00	115.77	118.00	113.35
34	117.00	115.95	118.00	113.64
35	117.00	116.13	118.00	113.92
36	117.00	116.32	119.00	114.19
37	118.00	116.49	119.00	114.47

38	118.00	116.66	119.00	114.75
39	118.00	116.83	120.00	115.00
40	119.00	116.99	120.00	115.28
41	119.00	117.14	121.00	115.55
42	119.00	117.30	121.00	115.82
43	119.00	117.46	121.00	116.09
44	120.00	117.62	122.00	116.36
45	120.00	117.78	122.00	116.64
46	120.00	117.93	122.00	116.91
47	120.00	118.08	123.00	117.17
48	121.00	118.23	123.00	117.45
49	121.00	118.38	123.00	117.73
50	121.00	118.53	124.00	118.00
51	122.00	118.69	124.00	118.29
52	122.00	118.84	124.00	118.58
53	122.00	119.00	125.00	118.86
54	122.00	119.16	125.00	119.15
55	123.00	119.32	125.00	119.44
56	123.00	119.47	126.00	119.74
57	123.00	119.64	126.00	120.01
58	123.00	119.81	126.00	120.31
59	124.00	119.98	127.00	120.61
60	124.00	120.15	127.00	120.91
61	124.00	120.33	128.00	121.21
62	124.00	120.51	128.00	121.50
63	125.00	120.70	128.00	121.80
64	125.00	120.90	129.00	122.07
65	125.00	121.10	129.00	122.35
66	126.00	121.31	130.00	122.63
67	126.00	121.54	130.00	122.90
68	126.00	121.78	130.00	123.16
69	127.00	122.02	131.00	123.41
70	127.00	122.30	131.00	123.68
71	127.00	122.59	132.00	123.94
72	128.00	122.90	133.00	124.19
73	128.00	123.22	133.00	124.45
74	129.00	123.57	134.00	124.70
75	129.00	123.95	134.00	124.95
76	129.00	124.35	135.00	125.18
77	130.00	124.76	136.00	125.43

78	130.00	125.15	136.00	125.68
79	131.00	125.56	137.00	125.92
80	132.00	125.98	138.00	126.17
81	132.00	126.40	138.00	126.42
82	133.00	126.81	139.00	126.67
83	133.00	127.18	140.00	126.93
84	134.00	127.58	141.00	127.17
85	135.00	127.96	141.00	127.45
86	135.00	128.35	142.00	127.72
87	136.00	128.73	143.00	128.01
88	137.00	129.11	144.00	128.32
89	138.00	129.51	144.00	128.65
90	138.00	129.92	145.00	129.00
91	139.00	130.32	146.00	129.36
92	140.00	130.79	147.00	129.76
93	141.00	131.27	148.00	130.20
94	142.00	131.83	149.00	130.74
95	144.00	132.44	151.00	131.37
96	145.00	133.23	152.00	132.10
97	147.00	134.25	154.00	133.17
98	149.00	135.97	156.00	134.85
99	152.00	139.51	160.00	138.12
100	232.00	189.00	250.00	188.00

Appendix 15: Second order polynomial trends for calculation of emission factors by speed level.

Gasoline

CO: $y = 0.0011x^2 - 0.1919x + 8.9383$ ($R^2 = 0.9848$)

CO2: $y = 0.0278x^2 - 4.4762x + 309.02$ ($R^2 = 0.9877$)

FC: $y = 0.01x^2 - 1.6033x + 110.69$ ($R^2 = 0.9877$)

HC: $y = 7E\text{-}06x^2 - 0.0012x + 0.0628$ ($R^2 = 0.98$)

NOx: $y = 4E\text{-}05x^2 - 0.0064x + 0.3368$ ($R^2 = 0.977$)

PM: $y = 3E\text{-}06x^2 - 0.0005x + 0.0209$ ($R^2 = 0.9983$)

Diesel

CO: $y = 2E\text{-}06x^2 - 0.0006x + 0.0521$ ($R^2 = 0.8033$)

CO2: $y = 0.0131x^2 - 2.0968x + 194.6$ ($R^2 = 0.9771$)

FC: $y = 0.0047x^2 - 0.7536x + 69.94$ ($R^2 = 0.9771$)

HC: $y = 8E\text{-}07x^2 - 0.0002x + 0.019$ ($R^2 = 0.9224$)

NOx: $y = 0.0003x^2 - 0.0508x + 2.6775$ ($R^2 = 0.9828$)

PM: $y = 2E\text{-}06x^2 - 0.0003x + 0.0223$ ($R^2 = 0.9934$)

Appendix 16: Central case changes in emissions and fuel consumption by percentile, by highway and fuel type (g/vkm).

Percentile	Gasoline						Diesel					
Highway 1	**FC**	**CO2**	**CO**	**HC**	**NOx**	**PM**	**FC**	**CO2**	**CO**	**HC**	**NOx**	**PM**
1	0.08009	0.25108	0.06763	0.00035	0.00027	0.00010	0.03783	0.12025	0.00107	0.00028	0.01263	-0.00006
2	3.46710	10.86936	0.17940	0.00142	0.01404	0.00079	1.62890	5.17827	-0.00294	-0.00066	0.06890	0.00096
3	4.19596	13.15433	0.27787	0.00202	0.01694	0.00103	1.97152	6.26747	-0.00246	-0.00051	0.09395	0.00108
4	3.59936	11.28398	0.26341	0.00186	0.01451	0.00092	1.69128	5.37658	-0.00166	-0.00032	0.08494	0.00090
5	3.06853	9.61983	0.23456	0.00163	0.01236	0.00079	1.44188	4.58374	-0.00124	-0.00023	0.07415	0.00075
6	2.23465	7.00563	0.17655	0.00122	0.00900	0.00059	1.05007	3.33817	-0.00080	-0.00014	0.05500	0.00054
7	1.64688	5.16297	0.13269	0.00091	0.00663	0.00043	0.77388	2.46017	-0.00054	-0.00009	0.04098	0.00039
8	1.46377	4.58891	0.11918	0.00082	0.00589	0.00039	0.68784	2.18664	-0.00046	-0.00008	0.03664	0.00035
9	1.22618	3.84407	0.10078	0.00069	0.00493	0.00033	0.57620	1.83173	-0.00037	-0.00006	0.03086	0.00029
10	0.93169	2.92085	0.07722	0.00053	0.00375	0.00025	0.43782	1.39182	-0.00027	-0.00004	0.02356	0.00022
11	1.16343	3.64734	0.09664	0.00066	0.00468	0.00031	0.54671	1.73800	-0.00033	-0.00005	0.02946	0.00027
12	0.81852	2.56605	0.06850	0.00047	0.00329	0.00022	0.38463	1.22275	-0.00022	-0.00003	0.02081	0.00019
13	1.03508	3.24497	0.08679	0.00059	0.00416	0.00028	0.48640	1.54627	-0.00028	-0.00004	0.02635	0.00024
14	0.64905	2.03478	0.05479	0.00037	0.00261	0.00017	0.30500	0.96960	-0.00017	-0.00002	0.01659	0.00015
15	0.84686	2.65491	0.07160	0.00049	0.00341	0.00023	0.39796	1.26510	-0.00022	-0.00003	0.02166	0.00020
16	0.43621	1.36752	0.03712	0.00025	0.00175	0.00012	0.20499	0.65165	-0.00011	-0.00002	0.01120	0.00010
17	0.61855	1.93916	0.05270	0.00036	0.00249	0.00017	0.29067	0.92404	-0.00015	-0.00002	0.01589	0.00014
18	0.17302	0.54243	0.01483	0.00010	0.00070	0.00005	0.08131	0.25848	-0.00004	-0.00001	0.00446	0.00004
19	0.35055	1.09899	0.03008	0.00020	0.00141	0.00009	0.16473	0.52369	-0.00008	-0.00001	0.00904	0.00008
20	0.52732	1.65314	0.04530	0.00031	0.00212	0.00014	0.24780	0.78775	-0.00012	-0.00002	0.01361	0.00012
21	0.05155	0.16160	0.00445	0.00003	0.00021	0.00001	0.02422	0.07701	-0.00001	0.00000	0.00133	0.00001
22	0.22344	0.70048	0.01932	0.00013	0.00090	0.00006	0.10500	0.33379	-0.00005	-0.00001	0.00579	0.00005
23	0.39120	1.22642	0.03386	0.00023	0.00157	0.00011	0.18384	0.58441	-0.00009	-0.00001	0.01014	0.00009
24	-0.11071	-0.34708	-0.00963	-0.00006	-0.00045	-0.00003	-0.05203	-0.16539	0.00002	0.00000	-0.00288	-0.00003
25	0.04640	0.14547	0.00404	0.00003	0.00019	0.00001	0.02181	0.06932	-0.00001	0.00000	0.00121	0.00001

Percentile	Gasoline						Diesel					
Highway 1	**FC**	**CO2**	**CO**	**HC**	**NOx**	**PM**	**FC**	**CO2**	**CO**	**HC**	**NOx**	**PM**
26	0.20569	0.64482	0.01792	0.00012	0.00083	0.00006	0.09666	0.30727	-0.00004	-0.00001	0.00535	0.00005
27	-0.32538	-1.02006	-0.02849	-0.00019	-0.00131	-0.00009	-0.15290	-0.48608	0.00007	0.00001	-0.00849	-0.00007
28	-0.17244	-0.54061	-0.01511	-0.00010	-0.00069	-0.00005	-0.08104	-0.25761	0.00003	0.00000	-0.00450	-0.00004
29	-0.01950	-0.06113	-0.00171	-0.00001	-0.00008	-0.00001	-0.00916	-0.02913	0.00000	0.00000	-0.00051	0.00000
30	0.12237	0.38363	0.01074	0.00007	0.00049	0.00003	0.05750	0.18281	-0.00002	0.00000	0.00320	0.00003
31	-0.44065	-1.38144	-0.03884	-0.00026	-0.00177	-0.00012	-0.20708	-0.65829	0.00009	0.00001	-0.01154	-0.00010
32	-0.30003	-0.94059	-0.02646	-0.00018	-0.00121	-0.00008	-0.14099	-0.44822	0.00006	0.00001	-0.00786	-0.00007
33	-0.16688	-0.52315	-0.01473	-0.00010	-0.00067	-0.00005	-0.07842	-0.24930	0.00003	0.00000	-0.00438	-0.00004
34	-0.76058	-2.38441	-0.06739	-0.00045	-0.00306	-0.00021	-0.35742	-1.13624	0.00014	0.00001	-0.01999	-0.00017
35	-0.62991	-1.97476	-0.05585	-0.00037	-0.00253	-0.00017	-0.29601	-0.94103	0.00012	0.00001	-0.01656	-0.00014
36	-0.49915	-1.56484	-0.04428	-0.00030	-0.00201	-0.00014	-0.23457	-0.74569	0.00009	0.00001	-0.01313	-0.00011
37	-1.12025	-3.51199	-0.09976	-0.00067	-0.00450	-0.00031	-0.52644	-1.67357	0.00020	0.00002	-0.02953	-0.00026
38	-0.99529	-3.12024	-0.08868	-0.00059	-0.00400	-0.00027	-0.46772	-1.48689	0.00017	0.00002	-0.02624	-0.00023
39	-0.87436	-2.74113	-0.07794	-0.00052	-0.00351	-0.00024	-0.41089	-1.30623	0.00015	0.00001	-0.02306	-0.00020
40	-1.52091	-4.76806	-0.13607	-0.00091	-0.00611	-0.00042	-0.71473	-2.27213	0.00026	0.00002	-0.04020	-0.00035
41	-1.40726	-4.41175	-0.12596	-0.00084	-0.00565	-0.00039	-0.66132	-2.10233	0.00024	0.00002	-0.03720	-0.00032
42	-1.28792	-4.03764	-0.11533	-0.00077	-0.00517	-0.00035	-0.60524	-1.92406	0.00022	0.00002	-0.03406	-0.00029
43	-1.17054	-3.66963	-0.10487	-0.00070	-0.00470	-0.00032	-0.55008	-1.74870	0.00020	0.00002	-0.03096	-0.00027
44	-1.83860	-5.76402	-0.16529	-0.00110	-0.00739	-0.00051	-0.86403	-2.74674	0.00030	0.00002	-0.04873	-0.00042
45	-1.72240	-5.39972	-0.15491	-0.00103	-0.00692	-0.00047	-0.80942	-2.57314	0.00028	0.00002	-0.04566	-0.00039
46	-1.60760	-5.03984	-0.14465	-0.00096	-0.00646	-0.00044	-0.75547	-2.40165	0.00026	0.00002	-0.04263	-0.00036
47	-1.49561	-4.68872	-0.13463	-0.00090	-0.00601	-0.00041	-0.70284	-2.23433	0.00024	0.00002	-0.03967	-0.00034
48	-2.18766	-6.85832	-0.19756	-0.00132	-0.00879	-0.00060	-1.02807	-3.26822	0.00034	0.00002	-0.05814	-0.00049
49	-2.07218	-6.49628	-0.18721	-0.00125	-0.00832	-0.00057	-0.97380	-3.09570	0.00032	0.00002	-0.05508	-0.00047
50	-1.95478	-6.12824	-0.17668	-0.00118	-0.00785	-0.00054	-0.91863	-2.92031	0.00030	0.00002	-0.05198	-0.00044
51	-2.66292	-8.34826	-0.24143	-0.00161	-0.01070	-0.00074	-1.25141	-3.97823	0.00039	0.00002	-0.07094	-0.00060
52	-2.54079	-7.96538	-0.23046	-0.00153	-0.01020	-0.00070	-1.19402	-3.79578	0.00037	0.00002	-0.06770	-0.00057

Percentile	Gasoline						Diesel					
Highway 1	**FC**	**CO2**	**CO**	**HC**	**NOx**	**PM**	**FC**	**CO2**	**CO**	**HC**	**NOx**	**PM**
53	-2.41979	-7.58604	-0.21957	-0.00146	-0.00972	-0.00067	-1.13715	-3.61501	0.00035	0.00002	-0.06449	-0.00055
54	-2.29635	-7.19906	-0.20846	-0.00139	-0.00922	-0.00063	-1.07915	-3.43061	0.00033	0.00002	-0.06122	-0.00052
55	-3.01935	-9.46565	-0.27491	-0.00183	-0.01213	-0.00084	-1.41891	-4.51072	0.00042	0.00002	-0.08063	-0.00068
56	-2.89608	-9.07922	-0.26379	-0.00175	-0.01163	-0.00080	-1.36099	-4.32658	0.00041	0.00002	-0.07736	-0.00065
57	-2.76404	-8.66526	-0.25187	-0.00167	-0.01110	-0.00077	-1.29893	-4.12931	0.00039	0.00002	-0.07385	-0.00062
58	-2.62968	-8.24406	-0.23973	-0.00159	-0.01056	-0.00073	-1.23580	-3.92859	0.00036	0.00002	-0.07028	-0.00059
59	-3.36169	-10.53891	-0.30735	-0.00204	-0.01350	-0.00093	-1.57980	-5.02218	0.00045	0.00002	-0.09000	-0.00076
60	-3.22755	-10.11837	-0.29520	-0.00196	-0.01296	-0.00090	-1.51676	-4.82178	0.00043	0.00002	-0.08643	-0.00073
61	-3.08625	-9.67541	-0.28240	-0.00187	-0.01239	-0.00086	-1.45036	-4.61069	0.00041	0.00002	-0.08266	-0.00069
62	-2.93603	-9.20444	-0.26877	-0.00178	-0.01179	-0.00081	-1.37976	-4.38626	0.00039	0.00002	-0.07866	-0.00066
63	-3.66783	-11.49864	-0.33671	-0.00223	-0.01473	-0.00102	-1.72367	-5.47954	0.00047	0.00001	-0.09843	-0.00082
64	-3.50756	-10.99619	-0.32214	-0.00214	-0.01408	-0.00097	-1.64835	-5.24011	0.00044	0.00001	-0.09416	-0.00079
65	-3.34356	-10.48205	-0.30722	-0.00204	-0.01343	-0.00093	-1.57128	-4.99510	0.00042	0.00001	-0.08978	-0.00075
66	-4.07582	-12.77771	-0.37554	-0.00249	-0.01637	-0.00113	-1.91541	-6.08908	0.00049	0.00001	-0.10962	-0.00091
67	-3.88998	-12.19509	-0.35859	-0.00238	-0.01562	-0.00108	-1.82807	-5.81144	0.00047	0.00001	-0.10465	-0.00087
68	-3.68981	-11.56755	-0.34032	-0.00226	-0.01481	-0.00103	-1.73400	-5.51239	0.00044	0.00001	-0.09930	-0.00083
69	-4.41392	-13.83763	-0.40821	-0.00270	-0.01772	-0.00123	-2.07430	-6.59419	0.00051	0.00000	-0.11898	-0.00099
70	-4.18151	-13.10902	-0.38694	-0.00256	-0.01679	-0.00117	-1.96508	-6.24698	0.00048	0.00000	-0.11275	-0.00093
71	-3.93637	-12.34051	-0.36448	-0.00241	-0.01580	-0.00110	-1.84988	-5.88076	0.00044	0.00000	-0.10618	-0.00088
72	-4.61710	-14.47462	-0.42868	-0.00284	-0.01854	-0.00129	-2.16979	-6.89776	0.00050	0.00000	-0.12474	-0.00103
73	-4.34859	-13.63283	-0.40400	-0.00267	-0.01746	-0.00121	-2.04360	-6.49661	0.00047	0.00000	-0.11753	-0.00097
74	-5.01054	-15.70805	-0.46676	-0.00309	-0.02011	-0.00140	-2.35469	-7.48555	0.00052	-0.00001	-0.13564	-0.00111
75	-4.67897	-14.66858	-0.43620	-0.00288	-0.01878	-0.00131	-2.19887	-6.99021	0.00048	-0.00001	-0.12672	-0.00104
76	-4.32773	-13.56743	-0.40376	-0.00267	-0.01737	-0.00121	-2.03380	-6.46546	0.00043	-0.00001	-0.11727	-0.00096
77	-4.94947	-15.51659	-0.46300	-0.00306	-0.01987	-0.00139	-2.32599	-7.39433	0.00047	-0.00002	-0.13433	-0.00110
78	-4.60300	-14.43040	-0.43090	-0.00284	-0.01848	-0.00129	-2.16317	-6.87672	0.00044	-0.00002	-0.12498	-0.00102
79	-5.23128	-16.40006	-0.49098	-0.00324	-0.02100	-0.00147	-2.45844	-7.81537	0.00047	-0.00003	-0.14226	-0.00116

Percentile	Gasoline						Diesel					
Highway 1	**FC**	**CO2**	**CO**	**HC**	**NOx**	**PM**	**FC**	**CO2**	**CO**	**HC**	**NOx**	**PM**
80	-5.87413	-18.41540	-0.55270	-0.00364	-0.02358	-0.00165	-2.76055	-8.77578	0.00051	-0.00004	-0.15998	-0.00130
81	-5.48998	-17.21108	-0.51692	-0.00341	-0.02203	-0.00154	-2.58002	-8.20187	0.00047	-0.00004	-0.14958	-0.00121
82	-6.16080	-19.31410	-0.58146	-0.00383	-0.02472	-0.00173	-2.89527	-9.20407	0.00050	-0.00005	-0.16810	-0.00136
83	-5.81212	-18.22098	-0.54889	-0.00362	-0.02333	-0.00163	-2.73141	-8.68315	0.00046	-0.00005	-0.15864	-0.00128
84	-6.50091	-20.38036	-0.61534	-0.00405	-0.02609	-0.00183	-3.05511	-9.71221	0.00049	-0.00006	-0.17769	-0.00143
85	-7.22381	-22.64666	-0.68526	-0.00451	-0.02899	-0.00203	-3.39485	-10.79222	0.00052	-0.00007	-0.19770	-0.00159
86	-6.85295	-21.48400	-0.65047	-0.00428	-0.02750	-0.00193	-3.22056	-10.23816	0.00049	-0.00007	-0.18762	-0.00151
87	-7.58590	-23.78179	-0.72156	-0.00475	-0.03044	-0.00214	-3.56502	-11.33319	0.00051	-0.00009	-0.20795	-0.00167
88	-8.34487	-26.16116	-0.79537	-0.00523	-0.03348	-0.00235	-3.92170	-12.46709	0.00053	-0.00010	-0.22904	-0.00183
89	-9.09603	-28.51605	-0.86871	-0.00571	-0.03650	-0.00257	-4.27472	-13.58933	0.00055	-0.00012	-0.24996	-0.00199
90	-8.69516	-27.25933	-0.83090	-0.00546	-0.03489	-0.00245	-4.08633	-12.99044	0.00052	-0.00012	-0.23903	-0.00191
91	-9.45602	-29.64462	-0.90537	-0.00595	-0.03794	-0.00267	-4.44390	-14.12717	0.00053	-0.00013	-0.26025	-0.00207
92	-10.17640	-31.90302	-0.97626	-0.00641	-0.04083	-0.00288	-4.78246	-15.20343	0.00054	-0.00015	-0.28041	-0.00223
93	-10.88757	-34.13254	-1.04652	-0.00687	-0.04368	-0.00308	-5.11668	-16.26593	0.00054	-0.00017	-0.30036	-0.00238
94	-11.54460	-36.19233	-1.11187	-0.00729	-0.04631	-0.00327	-5.42547	-17.24755	0.00053	-0.00019	-0.31886	-0.00252
95	-13.42639	-42.09174	-1.29723	-0.00850	-0.05386	-0.00381	-6.30984	-20.05898	0.00054	-0.00024	-0.37156	-0.00292
96	-13.87301	-43.49188	-1.34322	-0.00880	-0.05565	-0.00394	-6.51974	-20.72625	0.00051	-0.00027	-0.38441	-0.00302
97	-15.41719	-48.33290	-1.49780	-0.00980	-0.06184	-0.00438	-7.24546	-23.03330	0.00048	-0.00032	-0.42808	-0.00335
98	-16.23992	-50.91216	-1.58395	-0.01036	-0.06513	-0.00462	-7.63213	-24.26253	0.00039	-0.00036	-0.45201	-0.00352
99	-16.38735	-51.37434	-1.60851	-0.01050	-0.06571	-0.00468	-7.70144	-24.48288	0.00021	-0.00041	-0.45788	-0.00354
100	-112.08810	-351.39619	-11.66160	-0.07512	-0.44892	-0.03281	-52.67930	-167.46749	-0.01041	-0.00588	-3.24650	-0.02331

Percentile	Gasoline						Diesel					
Highway 2	**FC**	**CO2**	**CO**	**HC**	**NOx**	**PM**	**FC**	**CO2**	**CO**	**HC**	**NOx**	**PM**
1	11.84120	37.12215	1.85031	0.01103	0.04690	0.00422	5.56709	17.69778	0.01222	0.00348	0.45046	0.00164
2	-0.01460	-0.04578	0.27164	0.00136	-0.00029	0.00033	-0.00600	-0.01908	0.00491	0.00126	0.04706	-0.00037
3	-1.33755	-4.19323	-0.00228	-0.00021	-0.00547	-0.00022	-0.62819	-1.99703	0.00234	0.00056	-0.01495	-0.00046
4	-1.14935	-3.60320	-0.05525	-0.00045	-0.00466	-0.00026	-0.53997	-1.71656	0.00105	0.00024	-0.02211	-0.00032
5	-0.78073	-2.44759	-0.04696	-0.00035	-0.00316	-0.00019	-0.36682	-1.16612	0.00054	0.00012	-0.01666	-0.00021
6	-0.71425	-2.23917	-0.04745	-0.00034	-0.00288	-0.00018	-0.33560	-1.06687	0.00042	0.00009	-0.01602	-0.00018
7	-0.74741	-2.34312	-0.05303	-0.00038	-0.00301	-0.00019	-0.35119	-1.11643	0.00038	0.00007	-0.01735	-0.00019
8	-0.49485	-1.55136	-0.03635	-0.00026	-0.00199	-0.00013	-0.23252	-0.73919	0.00023	0.00004	-0.01170	-0.00012
9	-0.33800	-1.05964	-0.02549	-0.00018	-0.00136	-0.00009	-0.15883	-0.50490	0.00014	0.00003	-0.00811	-0.00008
10	-0.25222	-0.79071	-0.01943	-0.00013	-0.00102	-0.00007	-0.11852	-0.37676	0.00010	0.00002	-0.00612	-0.00006
11	-0.25495	-0.79926	-0.01999	-0.00014	-0.00103	-0.00007	-0.11980	-0.38084	0.00009	0.00002	-0.00625	-0.00006
12	0.14569	0.45673	0.01150	0.00008	0.00059	0.00004	0.06846	0.21763	-0.00005	-0.00001	0.00358	0.00004
13	-0.01498	-0.04695	-0.00120	-0.00001	-0.00006	0.00000	-0.00704	-0.02237	0.00001	0.00000	-0.00037	0.00000
14	-0.23120	-0.72482	-0.01868	-0.00013	-0.00093	-0.00006	-0.10864	-0.34538	0.00008	0.00001	-0.00576	-0.00006
15	-0.49859	-1.56306	-0.04070	-0.00028	-0.00201	-0.00013	-0.23429	-0.74481	0.00015	0.00003	-0.01250	-0.00012
16	-0.24537	-0.76923	-0.02009	-0.00014	-0.00099	-0.00007	-0.11530	-0.36654	0.00008	0.00001	-0.00616	-0.00006
17	-0.56759	-1.77940	-0.04687	-0.00032	-0.00228	-0.00015	-0.26672	-0.84790	0.00017	0.00003	-0.01432	-0.00013
18	-0.92997	-2.91545	-0.07741	-0.00053	-0.00374	-0.00025	-0.43701	-1.38924	0.00026	0.00004	-0.02357	-0.00022
19	-0.71361	-2.23715	-0.05953	-0.00040	-0.00287	-0.00019	-0.33533	-1.06603	0.00020	0.00003	-0.01811	-0.00017
20	-1.10812	-3.47395	-0.09311	-0.00063	-0.00446	-0.00030	-0.52073	-1.65539	0.00030	0.00004	-0.02824	-0.00026
21	-1.52878	-4.79273	-0.12934	-0.00088	-0.00615	-0.00041	-0.71840	-2.28381	0.00039	0.00006	-0.03911	-0.00036
22	-1.31935	-4.13618	-0.11181	-0.00076	-0.00531	-0.00036	-0.61999	-1.97095	0.00034	0.00005	-0.03379	-0.00031
23	-1.76685	-5.53906	-0.15068	-0.00102	-0.00710	-0.00048	-0.83028	-2.63946	0.00043	0.00006	-0.04541	-0.00041
24	-1.56426	-4.90395	-0.13361	-0.00090	-0.00629	-0.00042	-0.73508	-2.33682	0.00038	0.00005	-0.04024	-0.00036
25	-2.02968	-6.36305	-0.17439	-0.00118	-0.00816	-0.00055	-0.95380	-3.03212	0.00047	0.00006	-0.05239	-0.00047
26	-1.83485	-5.75225	-0.15787	-0.00106	-0.00738	-0.00050	-0.86224	-2.74106	0.00042	0.00006	-0.04740	-0.00043
27	-2.31864	-7.26895	-0.20060	-0.00135	-0.00932	-0.00063	-1.08959	-3.46381	0.00052	0.00007	-0.06009	-0.00054

Percentile	Gasoline						Diesel					
Highway 2	**FC**	**CO2**	**CO**	**HC**	**NOx**	**PM**	**FC**	**CO2**	**CO**	**HC**	**NOx**	**PM**
28	-2.11432	-6.62839	-0.18317	-0.00123	-0.00850	-0.00057	-0.99357	-3.15857	0.00047	0.00006	-0.05484	-0.00049
29	-2.62450	-8.22781	-0.22855	-0.00154	-0.01055	-0.00071	-1.23332	-3.92074	0.00056	0.00007	-0.06828	-0.00060
30	-2.42188	-7.59258	-0.21116	-0.00142	-0.00973	-0.00066	-1.13811	-3.61804	0.00051	0.00006	-0.06305	-0.00056
31	-2.94057	-9.21869	-0.25766	-0.00173	-0.01182	-0.00080	-1.38186	-4.39294	0.00059	0.00007	-0.07678	-0.00068
32	-2.75427	-8.63463	-0.24159	-0.00162	-0.01107	-0.00075	-1.29431	-4.11462	0.00055	0.00006	-0.07196	-0.00063
33	-3.30542	-10.36248	-0.29128	-0.00195	-0.01328	-0.00090	-1.55332	-4.93800	0.00064	0.00007	-0.08659	-0.00076
34	-3.11012	-9.75023	-0.27435	-0.00184	-0.01250	-0.00085	-1.46154	-4.64624	0.00060	0.00006	-0.08152	-0.00071
35	-2.91925	-9.15185	-0.25776	-0.00173	-0.01173	-0.00080	-1.37185	-4.36111	0.00056	0.00006	-0.07656	-0.00067
36	-3.50150	-10.97721	-0.31050	-0.00208	-0.01407	-0.00096	-1.64547	-5.23095	0.00064	0.00006	-0.09207	-0.00080
37	-3.31173	-10.38228	-0.29394	-0.00197	-0.01331	-0.00091	-1.55629	-4.94745	0.00060	0.00006	-0.08712	-0.00076
38	-3.12208	-9.78772	-0.27736	-0.00186	-0.01254	-0.00086	-1.46717	-4.66413	0.00056	0.00006	-0.08218	-0.00071
39	-3.73043	-11.69491	-0.33273	-0.00222	-0.01499	-0.00102	-1.75306	-5.57298	0.00065	0.00006	-0.09842	-0.00085
40	-3.53841	-11.09292	-0.31587	-0.00211	-0.01422	-0.00097	-1.66282	-5.28611	0.00061	0.00006	-0.09340	-0.00081
41	-4.15640	-13.03030	-0.37247	-0.00249	-0.01670	-0.00114	-1.95324	-6.20935	0.00069	0.00006	-0.10996	-0.00094
42	-3.96297	-12.42390	-0.35543	-0.00237	-0.01592	-0.00109	-1.86234	-5.92038	0.00065	0.00005	-0.10489	-0.00090
43	-3.77028	-11.81983	-0.33841	-0.00226	-0.01515	-0.00104	-1.77179	-5.63252	0.00062	0.00005	-0.09984	-0.00086
44	-4.40104	-13.79725	-0.39648	-0.00264	-0.01768	-0.00121	-2.06821	-6.57484	0.00070	0.00005	-0.11680	-0.00100
45	-4.19917	-13.16439	-0.37859	-0.00252	-0.01687	-0.00116	-1.97335	-6.27327	0.00066	0.00005	-0.11149	-0.00095
46	-3.99943	-12.53821	-0.36086	-0.00240	-0.01606	-0.00110	-1.87948	-5.97487	0.00062	0.00005	-0.10624	-0.00091
47	-4.65393	-14.59008	-0.42137	-0.00280	-0.01869	-0.00129	-2.18706	-6.95267	0.00070	0.00005	-0.12387	-0.00105
48	-4.44733	-13.94238	-0.40296	-0.00268	-0.01786	-0.00123	-2.08997	-6.64403	0.00066	0.00004	-0.11843	-0.00100
49	-4.23415	-13.27406	-0.38394	-0.00255	-0.01701	-0.00117	-1.98979	-6.32555	0.00062	0.00004	-0.11280	-0.00096
50	-4.90020	-15.36213	-0.44580	-0.00296	-0.01968	-0.00136	-2.30280	-7.32060	0.00070	0.00004	-0.13080	-0.00110
51	-4.68327	-14.68205	-0.42638	-0.00283	-0.01881	-0.00130	-2.20086	-6.99653	0.00066	0.00004	-0.12506	-0.00105
52	-4.46133	-13.98627	-0.40647	-0.00270	-0.01792	-0.00124	-2.09656	-6.66496	0.00062	0.00003	-0.11919	-0.00100
53	-5.12495	-16.06672	-0.46842	-0.00311	-0.02058	-0.00142	-2.40843	-7.65639	0.00069	0.00003	-0.13718	-0.00115
54	-4.90316	-15.37140	-0.44846	-0.00298	-0.01969	-0.00136	-2.30420	-7.32504	0.00065	0.00003	-0.13129	-0.00110

Percentile			**Gasoline**							**Diesel**		
Highway 2	**FC**	**CO2**	**CO**	**HC**	**NOx**	**PM**	**FC**	**CO2**	**CO**	**HC**	**NOx**	**PM**
55	-4.67377	-14.65226	-0.42778	-0.00284	-0.01877	-0.00130	-2.19640	-6.98235	0.00062	0.00002	-0.12520	-0.00105
56	-5.34952	-16.77073	-0.49113	-0.00326	-0.02148	-0.00149	-2.51397	-7.99190	0.00068	0.00002	-0.14357	-0.00120
57	-5.13359	-16.09379	-0.47160	-0.00313	-0.02061	-0.00143	-2.41249	-7.66931	0.00065	0.00002	-0.13782	-0.00115
58	-4.89419	-15.34328	-0.44992	-0.00298	-0.01965	-0.00136	-2.29999	-7.31167	0.00061	0.00002	-0.13145	-0.00110
59	-5.57760	-17.48576	-0.51425	-0.00341	-0.02239	-0.00155	-2.62116	-8.33266	0.00067	0.00001	-0.15007	-0.00125
60	-5.33330	-16.71988	-0.49205	-0.00326	-0.02141	-0.00148	-2.50635	-7.96769	0.00063	0.00001	-0.14355	-0.00119
61	-6.03512	-18.92009	-0.55836	-0.00370	-0.02423	-0.00168	-2.83617	-9.01619	0.00069	0.00000	-0.16271	-0.00135
62	-5.79266	-18.15999	-0.53627	-0.00355	-0.02326	-0.00161	-2.72223	-8.65398	0.00066	0.00000	-0.15623	-0.00129
63	-5.55122	-17.40307	-0.51423	-0.00340	-0.02229	-0.00155	-2.60877	-8.29328	0.00062	0.00000	-0.14978	-0.00124
64	-6.28987	-19.71876	-0.58419	-0.00386	-0.02525	-0.00176	-2.95590	-9.39681	0.00068	-0.00001	-0.16997	-0.00140
65	-6.05097	-18.96980	-0.56232	-0.00372	-0.02429	-0.00169	-2.84363	-9.03991	0.00065	-0.00001	-0.16357	-0.00135
66	-6.80107	-21.32134	-0.63364	-0.00419	-0.02730	-0.00190	-3.19614	-10.16053	0.00070	-0.00002	-0.18413	-0.00151
67	-6.57102	-20.60014	-0.61253	-0.00405	-0.02638	-0.00184	-3.08803	-9.81685	0.00067	-0.00002	-0.17796	-0.00146
68	-6.35353	-19.91831	-0.59254	-0.00392	-0.02550	-0.00178	-2.98582	-9.49193	0.00064	-0.00002	-0.17212	-0.00141
69	-7.13816	-22.37814	-0.66732	-0.00441	-0.02865	-0.00200	-3.35457	-10.66416	0.00069	-0.00003	-0.19365	-0.00158
70	-6.90555	-21.64890	-0.64590	-0.00427	-0.02772	-0.00193	-3.24525	-10.31665	0.00066	-0.00003	-0.18740	-0.00153
71	-7.71054	-24.17255	-0.72285	-0.00477	-0.03095	-0.00216	-3.62356	-11.51930	0.00071	-0.00004	-0.20953	-0.00171
72	-8.52949	-26.73996	-0.80143	-0.00529	-0.03423	-0.00239	-4.00843	-12.74280	0.00075	-0.00005	-0.23210	-0.00189
73	-8.30730	-26.04339	-0.78090	-0.00515	-0.03334	-0.00233	-3.90401	-12.41086	0.00073	-0.00005	-0.22611	-0.00184
74	-9.14903	-28.68222	-0.86189	-0.00568	-0.03672	-0.00257	-4.29959	-13.66840	0.00077	-0.00006	-0.24935	-0.00202
75	-8.92654	-27.98471	-0.84129	-0.00555	-0.03583	-0.00251	-4.19503	-13.33601	0.00074	-0.00006	-0.24335	-0.00197
76	-9.80473	-30.73783	-0.92596	-0.00610	-0.03935	-0.00275	-4.60774	-14.64801	0.00078	-0.00008	-0.26762	-0.00216
77	-10.68301	-33.49124	-1.01096	-0.00666	-0.04287	-0.00300	-5.02050	-15.96016	0.00082	-0.00010	-0.29195	-0.00235
78	-10.46333	-32.80252	-0.99056	-0.00652	-0.04199	-0.00294	-4.91726	-15.63196	0.00079	-0.00010	-0.28601	-0.00231
79	-11.36569	-35.63144	-1.07810	-0.00710	-0.04561	-0.00320	-5.34133	-16.98009	0.00082	-0.00011	-0.31105	-0.00250
80	-12.28841	-38.52417	-1.16785	-0.00768	-0.04931	-0.00346	-5.77497	-18.35864	0.00085	-0.00013	-0.33669	-0.00270
81	-12.05649	-37.79710	-1.14625	-0.00754	-0.04838	-0.00340	-5.66598	-18.01216	0.00082	-0.00013	-0.33041	-0.00265

Percentile	Gasoline						Diesel					
Highway 2	**FC**	**CO2**	**CO**	**HC**	**NOx**	**PM**	**FC**	**CO2**	**CO**	**HC**	**NOx**	**PM**
82	-12.99028	-40.72453	-1.23733	-0.00814	-0.05212	-0.00366	-6.10483	-19.40725	0.00085	-0.00015	-0.35640	-0.00285
83	-13.93393	-43.68287	-1.32964	-0.00874	-0.05591	-0.00393	-6.54831	-20.81707	0.00086	-0.00018	-0.38271	-0.00306
84	-14.91211	-46.74946	-1.42549	-0.00936	-0.05983	-0.00421	-7.00801	-22.27848	0.00088	-0.00020	-0.41001	-0.00327
85	-14.65499	-45.94339	-1.40144	-0.00921	-0.05880	-0.00414	-6.88718	-21.89435	0.00086	-0.00020	-0.40304	-0.00321
86	-15.61956	-48.96732	-1.49631	-0.00982	-0.06267	-0.00441	-7.34049	-23.33543	0.00086	-0.00023	-0.43002	-0.00342
87	-16.58883	-52.00597	-1.59191	-0.01045	-0.06655	-0.00469	-7.79601	-24.78353	0.00087	-0.00025	-0.45718	-0.00363
88	-17.55570	-55.03711	-1.68758	-0.01107	-0.07043	-0.00497	-8.25041	-26.22805	0.00087	-0.00028	-0.48433	-0.00383
89	-17.24190	-54.05334	-1.65810	-0.01088	-0.06917	-0.00488	-8.10294	-25.75924	0.00084	-0.00028	-0.47579	-0.00377
90	-18.19042	-57.02698	-1.75230	-0.01149	-0.07297	-0.00515	-8.54871	-27.17636	0.00083	-0.00031	-0.50249	-0.00397
91	-19.14552	-60.02120	-1.84740	-0.01211	-0.07680	-0.00543	-8.99758	-28.60330	0.00082	-0.00034	-0.52941	-0.00417
92	-20.06896	-62.91619	-1.93978	-0.01271	-0.08050	-0.00569	-9.43157	-29.98295	0.00080	-0.00037	-0.55551	-0.00437
93	-20.98286	-65.78127	-2.03153	-0.01330	-0.08417	-0.00596	-9.86107	-31.34835	0.00078	-0.00040	-0.58140	-0.00456
94	-21.80710	-68.36525	-2.11503	-0.01385	-0.08747	-0.00619	-10.24844	-32.57979	0.00074	-0.00043	-0.60489	-0.00474
95	-23.96034	-75.11568	-2.33059	-0.01525	-0.09610	-0.00681	-11.26040	-35.79681	0.00069	-0.00051	-0.66578	-0.00520
96	-24.62556	-77.20112	-2.39969	-0.01569	-0.09876	-0.00701	-11.57304	-36.79068	0.00063	-0.00054	-0.68503	-0.00534
97	-26.42374	-82.83843	-2.58293	-0.01688	-0.10597	-0.00753	-12.41814	-39.47726	0.00053	-0.00062	-0.73644	-0.00572
98	-27.60575	-86.54401	-2.70801	-0.01768	-0.11070	-0.00788	-12.97366	-41.24328	0.00039	-0.00069	-0.77104	-0.00596
99	-30.14370	-94.50050	-2.97592	-0.01940	-0.12086	-0.00863	-14.16647	-45.03520	0.00008	-0.00084	-0.84522	-0.00648
100	-172.1554	-539.7071	-17.9738	-0.1156	-0.6894	-0.0504	-80.9100	-257.2128	-0.0171	-0.0093	-4.9972	-0.0357

Appendix 17: Emission factors by speed level for an average 2015 passenger car by fuel type.

Average Diesel vehicle

	80	90	100	110	120	130	>130
FC	40.1570	39.7314	40.6430	44.7432	47.6392	50.8867	56.7559
CO_2	111.7311	110.5470	113.0833	124.4915	132.5492	141.5849	157.9149
CO	0.0175	0.0126	0.0100	0.0125	0.0092	0.0072	0.0075
HC	0.0073	0.0069	0.0065	0.0057	0.0053	0.0057	0.0065
NOx	0.4936	0.5646	0.5930	0.6714	0.8468	1.1338	1.4845
PM	0.0068	0.0064	0.0069	0.0073	0.0083	0.0097	0.0104

Average Gasoline vehicle

	80	90	100	110	120	130	>130
FC	46.7305	46.5712	48.6153	55.3889	63.1100	69.5586	75.3210
CO_2	130.4649	130.0199	135.7270	154.6379	176.1940	194.1974	210.2854
CO	0.3106	0.2926	0.4021	0.6135	1.0270	1.9508	3.9251
HC	0.0115	0.0119	0.0136	0.0150	0.0180	0.0250	0.0414
NOx	0.0524	0.0575	0.0578	0.0691	0.0830	0.1177	0.1302
PM	0.0012	0.0012	0.0016	0.0024	0.0041	0.0060	0.0078

Source: HBEFA provided by UBA.

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