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Vehicle speed prediction models for consideration of energy demand within road design

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Abstract:

The main motivation of this master thesis is to contribute to the development process of an innovative calculation module used to predict vehicle energy demand (Joule/km) along a road section. This is done through an evaluation of the performance of two existing, and mathematically different Norwegian speed prediction models for light vehicles, developed by SINTEF Technology and Society. Both are considered as possible speed models integrated in the future energy module. The EFFEKT speed model is a traditional regression speed model developed from average section speeds. The SINTEF speed model is expressed as an exponential function developed from the average of continuous speed profiles collected with GPS technology. The predicted speed profiles from both speed models are evaluated through linear regression related to the average of measured speeds along one direction of a two – lane rural case road section in Norway.

Great effort has been made, nationally and internationally, allocated to research regarding speed prediction models. Unlike former research collecting speeds by manual measurements in the field, this study has applied speed data from a database developed by SINTEF Technology and Society. These were continuous speed profiles of high quality at no cost, collected with GPS technology.
Through use of the tools ArcGIS and MATLAB, the relevant data describing the geometry of the road and collected vehicle speeds along the case study section has been extracted from available databases and processed for further use within the analysis of the study.

The study results indicate good accordance between predicted and measured speed for both speed models. While the traditional regression speed model was found to make coarse simplifications of the changes within the speed affecting input variables, the speed model expressed as an exponential function has the ability to reflect such changes in a larger scale. The model characteristics of the speed model expressed as an exponential function is therefore recommended for future improvement and use within speed profile prediction models.

Keywords:

1. Comparison
2. Speed profile prediction model
3. Two – lane rural road
4. Complex alignment

Maren Bysveen

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Preface

This master thesis is written during the spring 2017 by Maren Bysveen at the Department of Civil and Environmental Engineering. The final report constitutes 30 credits of the last semester within the Master of Science education at the Norwegian University of Science and Technology (NTNU).

The aim of this master thesis has been to carry through a research study regarding Norwegian vehicle speed prediction models as a contribution to further development of an innovative module intending to predict vehicle energy demand. This has led to writing of the scientific paper *Comparison of speed prediction models valid for Norwegian two – lane rural roads*, which will be submitted for consideration at the 2018 Transportation Research Board (TRB) Annual meeting. Consequently, the master thesis is divided in two main parts, where the accompanying process report is written as a complement to the scientific paper.

The master thesis is connected to research engaged by the Norwegian Public Road Administration`s Ferry Free E39 Group. Thanks to my supervisors Kelly Pitera and Giuseppe Marinelli at the Department of Civil and Environmental Engineering for great support and collaboration. Special thanks are also given to SINTEF Technology and Society for providing necessary speed data, and to the Norwegian Public Road Administration (NPRA) for giving a scholarship and information about the future road alignment along E39: Klettelva – Hestnes.

Trondheim, June 2017

Maren Bysveen

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Maren Bysveen

Sammendrag

Transportsektorens energiforbruk var i 2014 ansvarlig for 23% av verdens totale CO_2 utslipp, og veitrafikk ble identifisert som den største bidragsyteren i Norge og Europa. Dette vitner om et behov for å redusere transportsektorens energiforbruk, og at det er nødvendig å kunne kvantifisere og vurdere miljøpåvirkninger fra nye og eksisterende veglinjer på en realistisk og nøyaktig måte.

Hovedmotivasjonen for denne masteroppgaven er å bidra til utviklingen av en innovativ beregningsmodul, som tar sikte på å predikere energibehov (Joule/km) for kjøretøy langs en vegstrekning. Dette blir gjort gjennom å vurdere opptredenen til to norske hastighetsmodeller for lette kjøretøy utviklet av SINTEF Teknologi og samfunn, som begge er ansett å være gode alternativer lagt til grunn for den fremtidige energimodulen. EFFEKT modellen er en tradisjonell regresjonsmodell utviklet fra gjennomsnittlige strekningshastigheter. SINTEF modellen er uttrykt som en eksponentialfunksjon og basert på gjennomsnittshastigheter fra kontinuerlige hastighetsprofiler samlet med GPS teknologi. Predikerte hastighetsprofiler fra begge modellene er evaluert gjennom lineær regresjon i forhold til et gjennomsnitt av målte hastigheter langs en retning av en landlig tofelts veg i Norge brukt som case strekning.

En stor innsats er dedikert til forskning innen modeller som kan predikere kjøretøyhastighet, både nasjonalt og internasjonalt. I motsetning til tidligere studier som har samlet hastighetsdata gjennom manuelle målinger i felt, har denne studien benyttet en hastighetsdatabase utviklet av SINTEF Teknologi og samfunn. Databasen inneholder kontinuerlige hastighetsprofiler samlet med GPS teknologi av god kvalitet, helt kostnadsfritt.

Gjennom bruk av verktøyene ArcGIS og MATLAB, har relevant data som beskriver vegens geometri og målte kjøretøyhastigheter langs case strekningen, blitt trukket ut fra tilgjengelige databaser og bearbeidet for videre bruk i studiens analyser.

Studiens resultater indikerer god overenstemmelse mellom predikert og målt kjøretøyhastighet for begge hastighetsmodeller. Det ble videre vist at den tradisjonelle regresjonsmodellen gjør grove forenklinger av variablenes innflytelse, noe som forhindrer hastighets- påvirkende endringer i å bli fanget opp av modellen. Hastighetsmodellen formulert som en eksponential-funksjon viser en bedre evne til å reflektere hastighetspåvirkende endringer i variablene, og denne modellkarakteristikken er derfor studiens anbefaling til videre forbedring og bruk innen hastighetspredikerende modeller.

Summary

The energy consumption within the transport sector was responsible for 23% of the world's total CO_2 emissions in 2014, and road traffic was found to be the largest contributor both in Norway and Europe. This testifies a demand for reducing the energy consumption within the transport sector, and a necessity to be able to quantify and evaluate environmental impacts from new and existing road alignments in a realistic and accurate way.

The main motivation of this master thesis is to contribute to the development process of an innovative calculation module used to predict vehicle energy demand (Joule/km) along a road section. This is done through an evaluation of the performance of two existing, and mathematically different Norwegian speed prediction models for light vehicles, developed by SINTEF Technology and Society. Both are considered as possible speed models integrated in the future energy module. The EFFEKT speed model is a traditional regression speed model developed from average section speeds. The SINTEF speed model is expressed as an exponential function developed from the average of continuous speed profiles collected with GPS technology. The predicted speed profiles from both speed models are evaluated through linear regression related to the average of measured speeds along one direction of a two – lane rural case road section in Norway.

Great effort has been made, nationally and internationally, allocated to research regarding speed prediction models. Unlike former research collecting speeds by manually performed measurements in the field, this study has applied speed data from a database provided by SINTEF Technology and Society. These were continuous speed profiles of high quality at no cost, collected with GPS technology.

Through use of the tools ArcGIS and MATLAB, the relevant data describing the geometry of the road and collected vehicle speeds along the case study section has been extracted from available databases and processed for further use within the analysis of the study.

The study results indicate good accordance between predicted and measured speed for both speed models. While the traditional regression speed model was found to make coarse simplifications of the changes within the speed affecting input variables, the speed model expressed as an exponential function have the ability to reflect such changes in a larger scale. The model characteristics of the speed model expressed as an exponential function is therefore recommended for future improvement and use within speed profile prediction models.

Table of Contents

List of figures, part 1

List of tables, part 1

List of figures, part 2

List of tables, part 2

Definitions

NPRA: National Public Road Administration

NRDB: National Road Databank

TRB: Transportation Research Board

AASHTO: American Association of State Highway and Transport Officials

HCM: Highway Capacity Manual

MATLAB: Matrix Laboratory, numerical computing environment and programming language

ARCGIS: Geographic Information system for working with maps and geographic information

ISA: Intelligent Speed Adaption

STATION: A term for metering (m) along the road

PSL: Posted speed limit

NL: Number of lanes

R: Horizontal radius

S: Vertical slope

ELEV: Elevation

RW: Road width

PART 1: SCIENTIFIC PAPER

Comparison of speed prediction models valid for Norwegian two – lane rural roads

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Abstract

This study compares a traditional regression speed model developed from average section speeds, to a speed model expressed as an exponential function developed from the average of continuous speed profiles collected with GPS technology. The predicted speed profiles for light vehicles are evaluated related to the average of measured speeds along one direction of a two – lane rural case road section in Norway. The study results indicate good conformity between predicted and measured speed for both speed models. Unlike the traditional regression speed model, which are found to make coarse simplifications of the speed affecting input variables, the speed model expressed as an exponential function has the ability to reflect such changes in a larger scale. The model characteristics of the speed model expressed as an exponential function is therefore recommended for future improvement and use within speed profile prediction models.

Keywords: comparison, speed profile prediction model, two – lane rural road, complex alignment

1 Introduction

Operating vehicle speed is an important parameter utilized within road design, transport- and larger cost- benefit analysis. More accurate model predictions of operating vehicle speeds can increase the quality and reliability of such considerations, and have been the motivation for research investigating which variables affect operating speed and how this best could be modeled. This study is connected to research engaged by the Norwegian Public Road Administration's Ferry Free E39 Group, developing an innovative calculation module able to predict energy demand along a road section in joule per kilometer (joule/km). As a contribution to further development of the energy module, the study aims to validate and evaluate the performance of two existing Norwegian speed prediction models developed by SINTEF Technology and Society. Both are considered as good alternatives, and recreated as MATLAB scripts to work as basis for the energy module in the future.

The evaluated speed models have been developed from unequal amounts and quality of speed data. The EFFEKT model is developed from average section speeds collected at 25 Norwegian road sections in the time period 1993 – 1994, and the SINTEF speed model is developed from the average of continuous speed profiles collected from 2011 to 2014 with GPS technology. Regarding a TRB synthesis report (1), the majority of speed prediction models documented through 2011, was developed from linear regression based on speed data collected with

manually operated equipment such as radar or laser gun. Such equipment only allow speed collection at one location, forcing the models to assume constant speed through curves, as in models developed by Krammes et al. (2) and Fitzpatrick and Collins (3). The manually operated speed collection equipment can allow human error, and the measured speeds can also be affected by measurement deviation from the equipment itself. Taken these disadvantages into account, the TRB synthesis report (1) encouraged researchers to use Global Positioning System (GPS) technology within future studies. This technology allows for the continuous collection and processing of speed data, thus the development of more accurate speed models. Researchers as Nie and Hassan (4), Bella et al. (5) and Zuriaga et al. (6) have applied this modern technology like the Norwegian researchers developing the SINTEF speed model.

The estimated model coefficients and input variables found significant, are organized in different ways within the two evaluated speed models. The EFFEKT model is a traditional regression speed model, and the SINTEF speed model is expressed as an exponential function. Within literature, the majority of speed models are presented as standard linear regression equations (1). Others are presented as statistical models as in Misaghi and Hassan (7), Figueroa Medina and Tarko (8) and Bassani et al. (9). There is a large selection of published literature that presents operating speed as a function of road parameters such as curve radius, vertical slope, rate of curvature and traffic flow characteristics. Relatively few models contain variables related to tangents, horizontal-vertical combinations, cross sectional dimensions, sight distance and posted speed limit (1). While many model equations use the radius value R(m) directly like the EFFEKT speed model, McLean (10) revealed that operating speed is dominantly influenced by curve radius expressed as curvature 1/R(m), and recommended both the first and second order term within a speed prediction model. Such curvature formulations are also used within the SINTEF speed model. McLean (10) stated further that even though the regression equation provided a good description in terms of statistical significance, it delivered irregular results for the extremes of input data range. This appeared due to the nonlinear correlation between observed speeds and curvature.

For models predicting speed profiles along a road section, researchers have prevented uneven transitions between speed at different road elements, by introducing driver behavior parameters. Acceleration and deceleration between road elements in addition to the interpretation of sight distance is considered as the most important, and used by Figueroa Medina and Tarko (11), the COBA Manual (12) and Fitzpatrick and Collins (3). While changes in speed and acceleration occur due to changes in all geometric planes of the road such as cross-sectional dimensions, horizontal and vertical alignment, most driver behavior models proposed have evaluated acceleration and deceleration rates related to horizontal curves only. Hu and Donnel (13) is one of few studies which have developed a driver behavior model used to estimate acceleration and deceleration rates for complex roads, evaluating changes of both horizontal and vertical geometry. An evaluation of speed profiles along a complex road alignment, is also performed within this study using a driver behavior module introducing assumed values of maximum acceleration/deceleration rate and visible range.

The speed model validation and evaluation within this study, is limited to prediction of speed profiles for passenger cars along one direction of a two-lane rural road. The results will contribute directly to further development of the energy module, and facilitate future studies on how the energy module itself act related to energy consumption from electrical vehicles in the field. Since the speed models have different mathematical formulations in addition to unequal

amounts and quality of speed data used as basis for the speed model development, this study will additionally contribute to better understanding of how these differences affect the appearance of the predicted speed profiles.

2   Methodology

Both speed models evaluated predict the average of vehicle speed allowed by the geometry of the road in a free flow situation. Speed profiles for light vehicles from both models will therefore be evaluated related to the average of measured free flow speeds along one direction of a case study section. To ensure that the measured speeds were collected from the field in a free flow situation, the case study section needed to fulfill the following requirements.

1. The road section should be a two – lane rural road.
2. The road section should have low intersection density.
3. It is advantageous if the road alignment is characterized by challenging geometry.
4. Presence of measured speed data in the speed database is crucial.

Due to the connection with research engaged by the NPRA, Ferry Free E39 Group, a suited case study section fulfilling the requirements is selected along E39. The chosen E39: Skjennstøbekken – Stokkelva, lies in Halsa municipality in the county of Møre and Romsdal in Norway and has a length of 15,2 km.
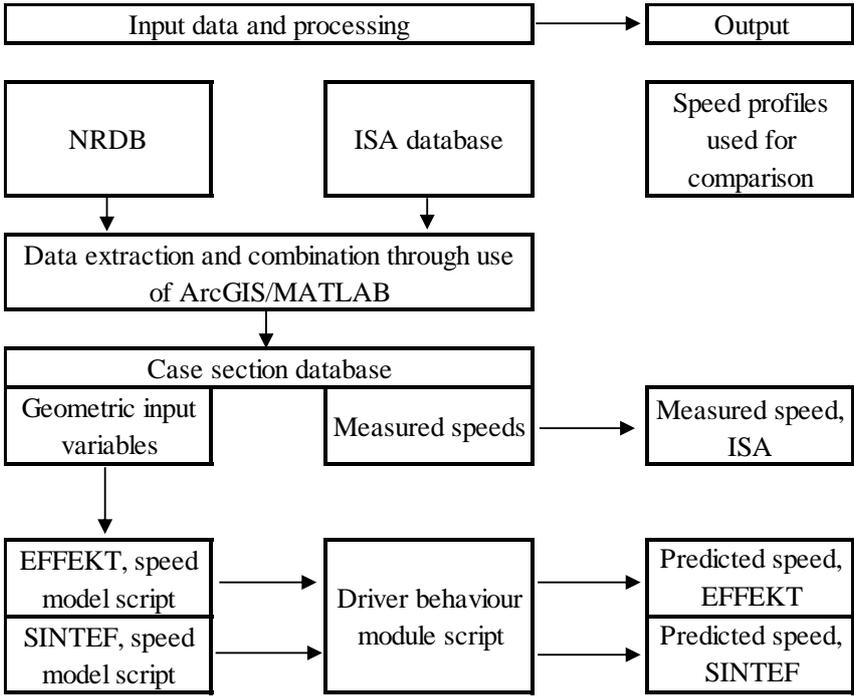
Figure 2.1: Logical procedure of the method used to process the data.

As seen in figure 2.1, the geometric information describing the case section, is extracted from the National Road Databank (NRDB). The measured speeds along the case section is collected from a speed database developed by SINTEF Technology and Society. The data is further organized as a geometric database providing input variables to the evaluated speed models, and

as a database of measured speeds along the case section used for comparison. All data is accessed and processed through use of ArcGIS tools and MATLAB scripts.

Both the EFFEKT and SINTEF speed models are translated into MATLAB scripts able to predict speed profiles along the case section based on the information stored in the geometric database. To improve the predicted speed profile along the transitions caused by changes in the road geometry, a driver behavior module is used. This script evaluates necessary acceleration and deceleration to a maximum allowed value and correct it if necessary, giving the speed profiles a smoother appearance.

The predicted and measured speed data is further exported to Excel for further presentation and evaluation through visual and statistical analysis. Values of the coefficient of determination, R^2, are estimated for the predicted speed data from linear regression with measured speed data and geometric input variables.

3   Data

3.1   Geometric data from the National Road Database (NRDB)

The National Road Database (NRDB) is developed by the Norwegian Public Road Administration (NPRA) and contains information on the Norwegian road network. The data describing speed limit, number of lanes, horizontal radius, road elevation, vertical slope and road width of the case study section was downloaded for use within ArcGIS. This information was further assigned to the road axis discretized with a spacing frequency of 5 m. The geometric properties for the case section E39: Skjennstøbekken – Stokkelva is shown in figure 3.1.
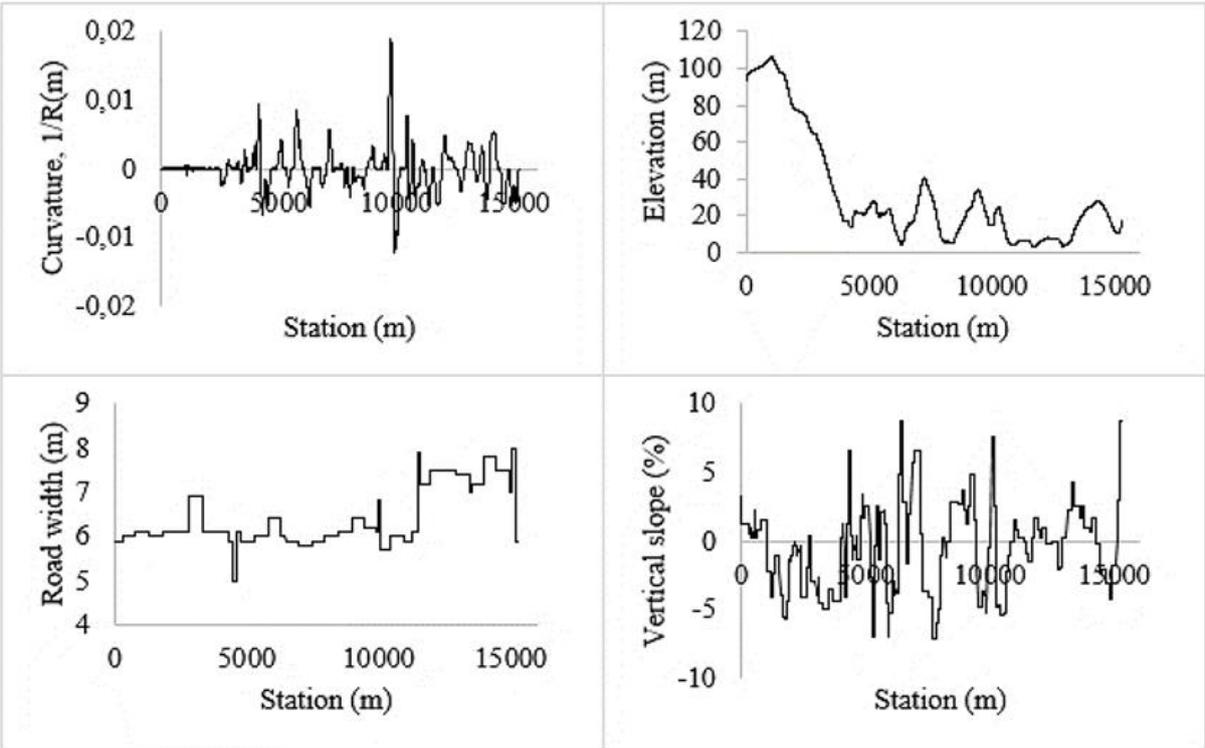
Figure 3.1: Geometric properties for E39: Skjennstøbekken – Stokkelva.

3.2 Measured speed data from the GPS measurement

The NPRA equipped 440 service vehicles with an informative Intelligent Speed Adaption (ISA) system and a speed recorder during the period from April 2011 to April 2014. Informative ISA is defined by SINTEF (14) as a system that signalizes to the driver if he/she is about to surpass the speed limit, without taking control over the vehicle. Vehicle's speed and location have been collected with GPS receivers and continuous monitoring until the end of 2014 (14). The data was provided to SINTEF which filtered and processed it to a database containing 245 million data points from 119 vehicles and 130 000 trips. For use within studies like this, the first and last three kilometers of every trip were deleted in addition to the vehicles information on plate ID. This to remove sensitive information that can identify the driver.

The ISA database was further divided in two sets:

1. **ISA system nonactive:** Contains speed data recorded when the ISA system was not active and did not give any signal to the driver when surpassing the speed limit. This database has been the basis for the development of the speed model referred to as the SINTEF speed model in this study.
2. **ISA system active:** Contains speed data recorded when the ISA system was active and a signal was given to the driver when surpassing the speed limit. Speeds from this part of the database have been used in this study when comparing predicted speed against measured speed.

The case section E39: Skjennstøbekken – Stokkelva is a European highway and the speed limit along this section is 80 km/h, except for two zones of speed limit 60 km/h. Speed data for 36 recorded trips was found in the ISA database along the direction used within this study. Outliers, in form of low speeds or stopped vehicles affected by its surroundings, occurred in the dataset as shown by figure 3.2. These were removed from the dataset or manipulated to ensure measured speeds in a free flow situation. This reduced the standard deviation of the dataset from S = 8,71 km/h to S = 8,37km/h.
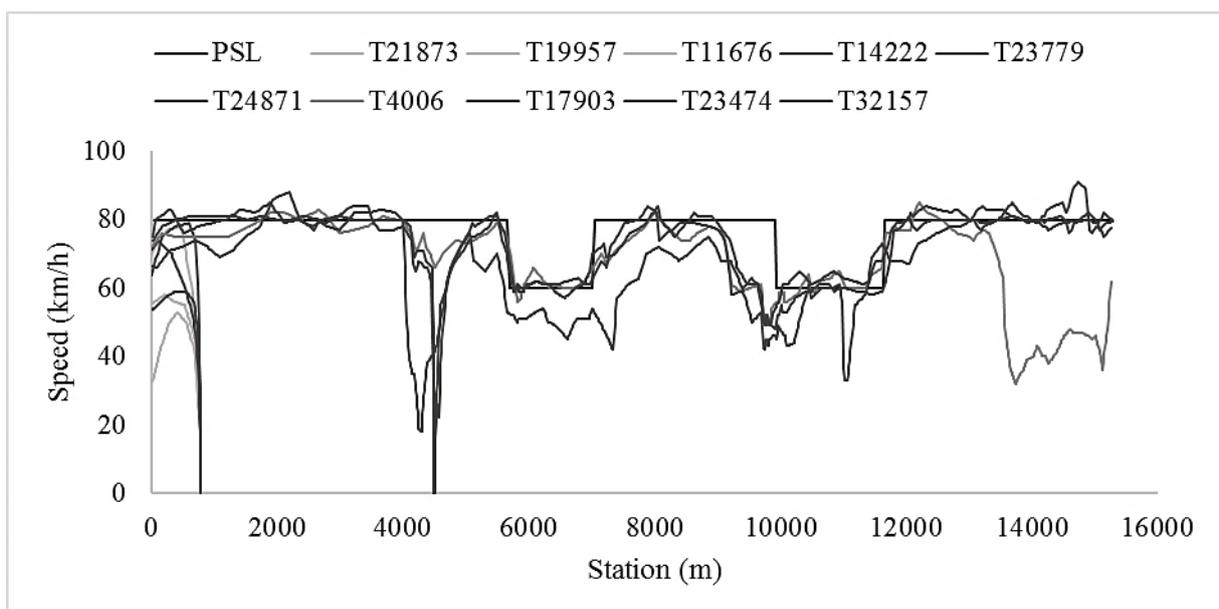
Figure 3.2: Outlier speeds removed or manipulated.

To be able to compare the measured speed profiles to the predicted speed profiles, the datasets was averaged within 25 m sections along the road, and presented every 12,5 m. This section length is related to a calculation principle within the SINTEF procedure related to slope, and was in this study considered as convenient. The original mean of measured speed profile containing the outliers and the manipulated mean of measured speed profile with outliers removed is shown in figure 3.3. The manipulated speed profile was used within further analysis.
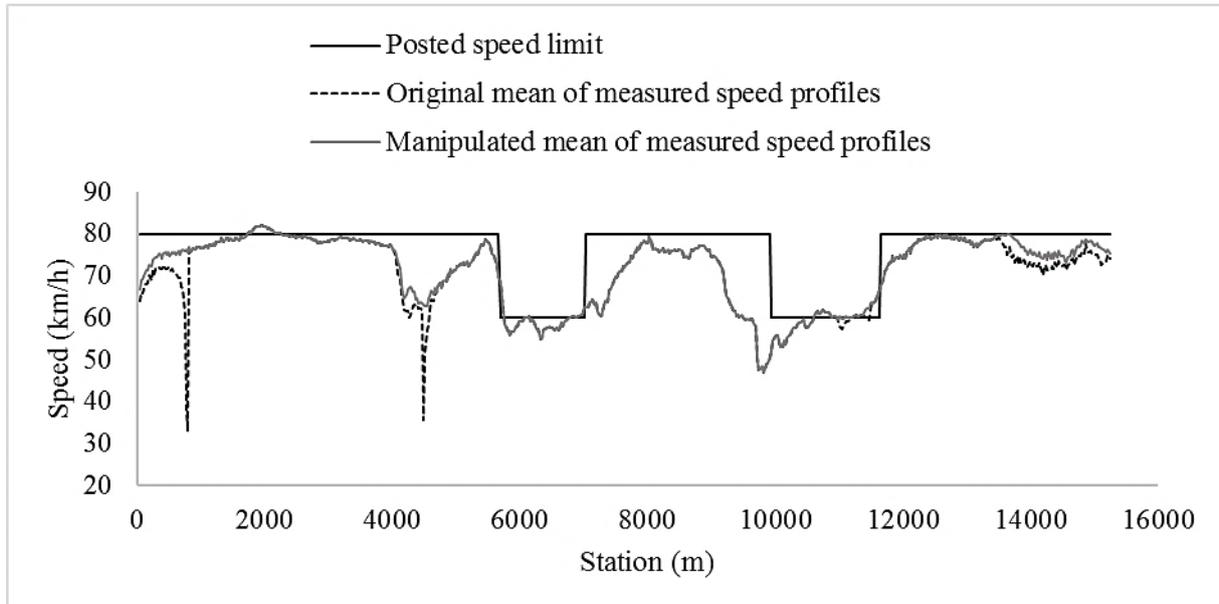
Figure 3.3: Original and manipulated mean of measured speed profile and posted speed limit along E39: Skjennstøbekken – Stokkelva.

4   Evaluated speed models

The EFFEKT speed model is developed from multiple regression analysis of recorded section speeds along selected roads from counties of Norway in the time period 1993 - 1994. The road sections used, had a length of 3 – 5 km and homogeneous geometric standard and traffic volume. The current base speed model, mainly developed for speed prediction in rural areas, is documented in the NPRA report no 358 (15).

The EFFEKT procedure divides a road link into sub sections at points characterized by change in speed limit, and/or change in sign of the vertical slope. Average free flow speed is calculated for each sub section, resulting in a predicted speed profile along the entire road link. For a two – lane road with speed limit 80 km/h or lower, the standard linear regression function represented by equation 4.1 is used for speed prediction.

$$V = 143,1 \cdot HKF + 80,4 \cdot SF + 1,75 \cdot B_d - 155,6 \qquad \text{Equation 4.1}$$

SF: Calculated slope factor (SF) correcting the speed for limitations regarding the vertical slope, S (%) along the sub section.

HKF: Calculated horizontal curve factor (HKF) correcting the speed for limitations regarding the horizontal curves R (m) along the sub section.

8

B_d: Recalculated pavement width (B_d) correcting the speed for limitations regarding road width, RW (m) along the sub section.

The cooperative effect of both the horizontal curvature and slope is taken into account by a comparison of the HKF and SF for each sub section. If the HKF < SF, then SF = 1, which means that no correction for slope should be done in such situations.

The SINTEF speed model is developed from multiple regression analysis of speeds collected by GPS units within an Intelligent Speed Adaption (ISA) system. The development of the speed model is described in detail in an extract from the unpublished report of the SINTEF project 102007265-4 (16).

Equation 4.2 can predict speed at road elements referred to as points or segments for different situations defined by specific linear regression functions $U(x_d, x_s, x_f, x_k)$. The standard linear regression function, containing estimated coefficients (β_x) and variables, is further introduced as an exponent within equation 4.2. The coefficient $C(x_g)$ defines an estimated reference speed for each situation. Within this study, the traffic corrected coefficient $C_k(x_g)$ is used to ensure calculations of average free flow speed.

$$\text{Speed} = C(x_g) \cdot e^{U(x_d, x_s, x_f, x_k)}$$

Equation 4.2

For two – lane road and speed limit 70, 80 or 90 km/h, the linear function $U(x_d, x_s, x_f, x_k)$ is calculated from equation 4.3.

$$U(x_d, x_s, x_f, x_k) \begin{aligned} &= \beta_d(x_d - 8,0) \\ &+ \beta_s x_s + \beta_f x_f \\ &+ \beta_k x_k + \beta_{sk} x_s x_k \\ &+ \beta_{fk} x_f x_k + \beta_{kk} x_k^2 \end{aligned}$$

Equation 4.3

For two – lane road and speed limit 50 or 60 km/h, the linear function $U(x_d, x_s, x_f, x_k)$ is calculated from equation 4.4.

$$U(x_d, x_s, x_f, x_k) \begin{aligned} &= \beta_s x_s + \beta_f x_f \\ &+ \beta_k x_k + \beta_{sk} x_s x_k \\ &+ \beta_{fk} x_f x_k + \beta_{kk} x_k^2 \end{aligned}$$

Equation 4.4

Necessary input parameters for both the EFFEKT and SINTEF speed model are listed in table 4.1, in addition to parameters used within the driver behavior module. The predicted speed profiles delivered directly from both speed models can be considered as speed profiles allowed by the model procedure at each point along the road, for the given input geometry. To improve the speed profiles appearance at transitions characterized by a change in any geometric parameter of the complex road alignment, the speed profiles are processed by a driver behavior module, which evaluates the necessary acceleration or deceleration to achieve the speed change between P_i and $P_{i + \text{visible range}}$ along the speed profile. If this is greater than the maximum allowed acceleration value it will be corrected and new corresponding speeds will be calculated from an integrated polynomial function. In this way, the speed profiles get a smoother appearance and is more comparable to actual speed profiles from the field.

Table 4.1: Model input parameters for the EFFEKT and SINTEF speed model and the driver behavior module

Model	Parameter	Type/Value	Unit
EFFEKT speed model	Posted speed limit, PSL	Vector	km/h
	Number of lanes, NL	Vector/(1, 2, 4 or 6)	-
	Road width, RW	Vector	m
	Horizontal radius, R	Vector	m
	Vertical slope, S	Vector	%
SINTEF speed model	Posted speed limit, PSL	Vector	km/h
	Number of lanes, NL	Vector/(2 or 4)	-
	Road width, RW	Vector	m
	Horizontal curvature, x_k	Vector	m^{-1}
	Positive vertical slope, x_s	Vector	%
	Negative vertical slope, x_f	Vector	%
Driver behavior module	Predicted vehicle speed	Vector	km/h
	Station	Vector	m
	Maximum value of allowed vehicle acceleration	Constant/0,5	m/s^2
	Visible range	Constant/200	m
	Polynomial function grade	Constant/1	-

5   Results

5.1   Predicted speed profiles

The predicted speed profile from the EFFEKT speed model is shown as a black stippled line in figure 5.1. In general, the predicted speed profile follows the speed limit closer than the measured speed. Clear exceptions can be seen around station 4000m, station 10000m and station 12000m and needs to be interpreted together with the road width in figure 3.1. Around these stations the road width is changing up to 1 m, and this change seem to affect both the measured and the predicted speed profile.

The predicted speed profile from the SINTEF speed model is shown as a grey stippled line in figure 5.1. The predicted speed profile follows the speed limit when this change. Within the zones of different speed limit, the predicted speed profile follows the measured speed profile closer than the speed limit. The frequent changes along the predicted speed profile seen together with the geometry in figure 3.1, indicates that the SINTEF speed model is sensitive to changes in curvature, and in some cases too sensitive.
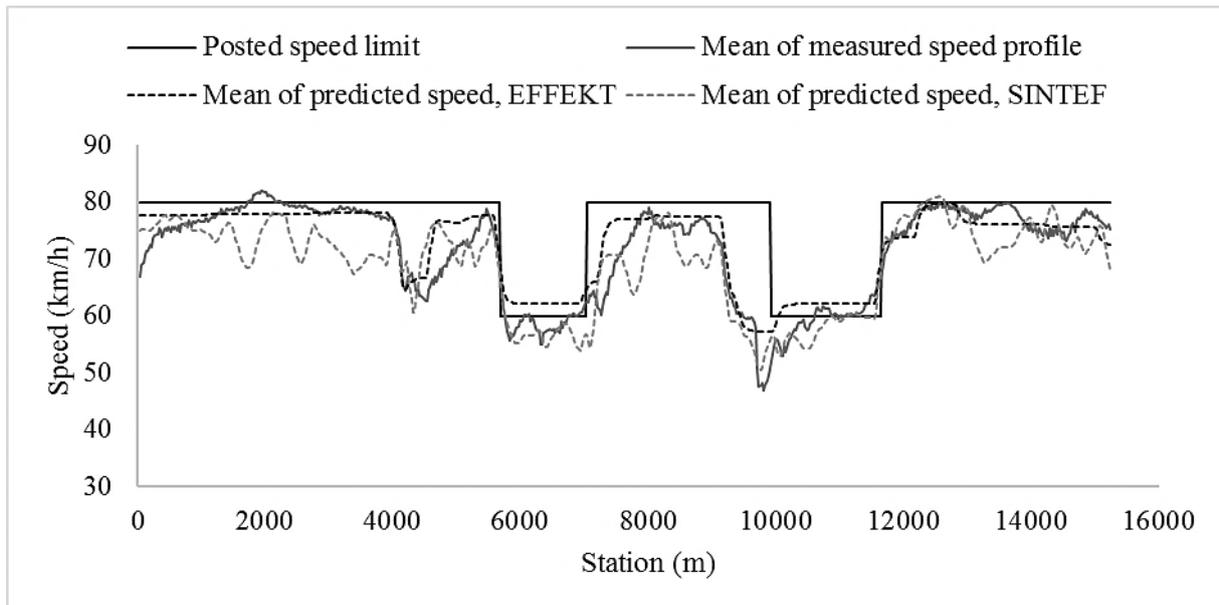
Figure 5.1: Comparison of measured and predicted speed profiles by the EFFEKT and SINTEF speed model

Figure 5.2 show the correlation plot between the measured and the predicted speed data from the EFFEKT and SINTEF speed model, and indicate a close relation between predicted and measured speed profiles. The value of R^2 for the EFFEKT prediction, states that 88% of the variations within the predicted speed profiles can be explained by variations within the measured speed profiles. The points are in general following the regression line, but seem more concentrated around the speed values 60 km/h and 80 km/h, creating horizontal steps. Such steps indicate that the model is not particularly precise, and can be interpreted in relation to the models' ability to reflect changes in the geometry which have caused a change in field speed. These changes are either not registered or simplified by the model in such a way that it will not make a change within the predicted speed profile.

The value of R^2 for the SINTEF prediction, states that 74% of the variations within the predicted speed profiles can be explained by variations within the measured speed profiles. The points are in general following the regression line, but is more concentrated around the speed values 60 km/h and 80 km/h. A predominance of points seems to be placed below the regression line, which means that the model has predicted lower speeds from the given geometry than what is actually held through such areas in the field. This can also be supported by figure 5.1 showing that the grey stippled line, in general lies below the line representing the measured speed profile, with some exceptions. Relevant measures describing the analyzed datasets are summarized in table 5.1.
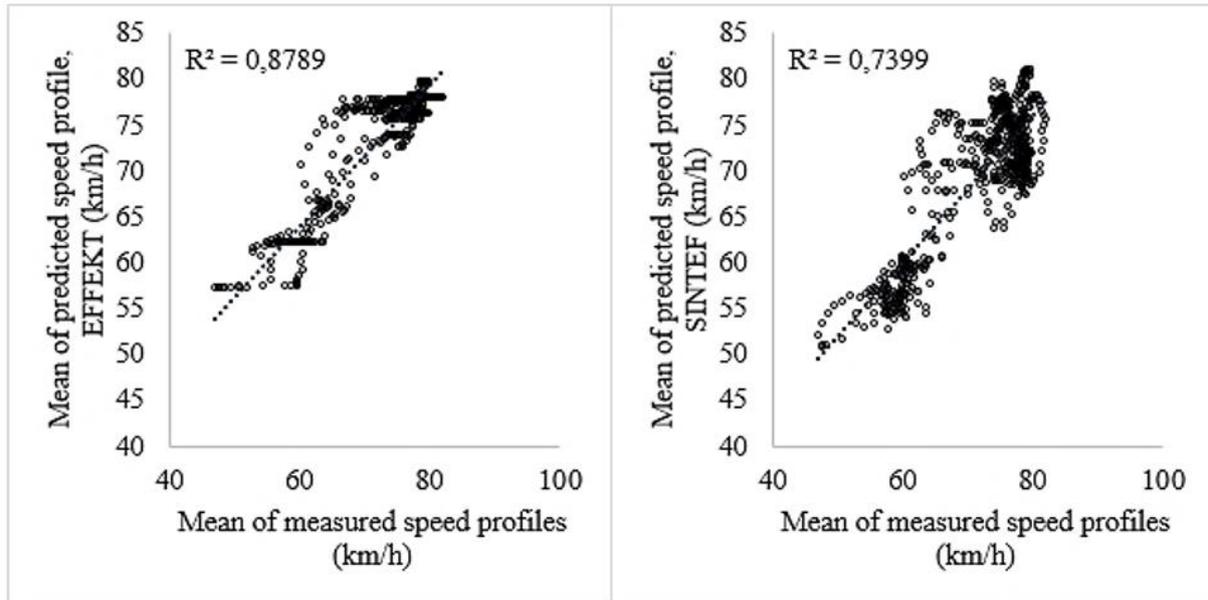
Figure 5.2: Correlation plot with mean of measured speed and mean of predicted speed.

Table 5.1: Summary of relevant measures calculated from the three speed datasets.

Relevant measures describing the speed dataset	EFFEKT	SINTEF	FIELD
Number of speed points in the mean speed profile along the case section, N	609	609	609
Average speed	72,7 km/h	69,1 km/h	71,33 km/h
Variance, S^2	47,38	61,00	70,05
Standard deviation, S	6,88 km/h	7,81 km/h	8,37 km/h
Coefficient of determination, R^2	0,879	0,740	
Adjusted coefficient of determination, R^2	0,879	0,739	
Coefficient of correlation, R	0,938	0,860	
Standard error of the estimate, SSE	2,397	3,987	

5.2 The influence of input parameters

The EFFEKT and the SINTEF speed model are both regression models built up of several sub calculations. A simplification of the relation between predicted speed from the speed models as a function of their input parameters, are shown by equation 5.1 and 5.2. Such consideration of the speed models, allows for a coarse quantification of how influential the input parameters are to the predicted speed profiles from both speed models through linear regression. The resulting coefficients of determination, R^2, is calculated to investigate how much of the changes in the predicted speed profiles can be explained by changes in the input parameters. The combination of change in several input variables was not evaluated, and the final results are summarized in table 5.2.

$$V_{EFFEKT} = f(PSL, NL, RW, S, R) \hspace{2cm} \text{Equation 5.1}$$

$$V_{SINTEF} = f(PSL, NL, RW, S, \frac{1}{R}) \hspace{1.5cm} \text{Equation 5.2}$$

Table 5.2: Summary of linear regression between the input parameters and predicted speed profiles from the EFFEKT and the SINTEF speed model.

Input parameters	The EFFEKT speed model		The SINTEF speed model	
Regression coefficient	r	R^2	r	R^2
Posted speed limit, PSL (km/h)	0,91354	0,83456	0,87014	0,75715
Road width, RW (m)	0,23414	0,05482	0,36723	0,13486
Curvature, 1/R (m^{-1})	0,03808	0,00145	0,05085	0,00259
Slope, S (%)	0,09301	0,00865	0,00643	0,00004
NL, do not change	-	-	-	-

6 Discussion

6.1 Speed model performance

The results presented, indicate that the evaluated speed models in general are good predictors of actual speed, but that both speed profiles deviate to a certain extent from the measured speed profile. Some important differences are seen within the study, which can be explained by the estimated model coefficients, the influence of input parameters and the models' equation form.

The speed models evaluated are developed from multiple regression based on collected speed data of different amount and quality, which makes the estimated coefficients naturally different. Continuous speed profiles are considered as more reliable in literature (1), which should give the SINTEF speed model an advantage.

The predicted speed profiles in figure 5.1 clearly change in accordance with change in speed limit, and the correlation plot from both speed models are characterized by dense point clouds around the speed levels 60 km/h and 80 km/h. In addition to high R^2 values in table 5.2, this indicate a strong influence of speed limit to both predicted and measured speed data. This is because both models, consider speed limit as an input parameter when deciding which equation to use for speed prediction. The EFFEKT speed model used the same equation 4.1 throughout the case section. The SINTEF speed model changed from equation 4.3, including road width, to equation 4.4, excluding road width, when the speed limit changed from 80 km/h to 60 km/h. The exclusion of road width in equation 4.4, underline that road width is considered to have less influence in areas with lower speeds within the SINTEF procedure. The R^2 value in table 5.2, also indicates that road width is more influential to the EFFEKT speed model, which also can explain why the speed profile representing the EFFEKT speed model in figure 5.1, makes clear step changes when road width changes up to 1 m.

As seen from table 5.2, the R^2 value determined from correlation between curvature and predicted speed data from the speed models, is greatest for the SINTEF speed model. This indicates that a larger proportion of the variation within the geometric variable curvature, can

explain the variation within the speed data predicted by the SINTEF speed model, than what is the case for the EFFEKT speed model. Curvature appears to be the least influential input variable for the EFFEKT speed model. The SINTEF equations are using the value of curvature $1/R$ (m^{-1}) in a first and second order regression term, while the EFFEKT equations are using the value of radius R(m) of curvature in a first order regression term. The second order term of curvature $(1/R)^2$, indicate a nonlinear relation between observed speed and curvature and are used by former researchers as McLean (10) stating that this form could cause irregularities in the predicted speed profile. The second order term of curvature can therefore contribute to larger variations within the predicted SINTEF speed profile.

The EFFEKT speed model is more sensitive to changes in slope than the SINTEF speed model, according to the R^2 values in table 5.2. Slope appears to be the least influential input variable for the SINTEF speed model. This result is debatable, and highlights a weakness of the method in using linear regression to rank the influence of input variables in this case. The EFFEKT procedure does not correct speed for slope below 3%. The SINTEF procedure processes slope in a wider range by dividing it in two respective variables of positive slope and negative slope, before it is included in the speed equation. Comparing the two procedures, indicate larger simplifications within the EFFEKT procedure related to slope. The regression analysis is unfortunately not capable of reflecting this.

The greatest contribution to difference between the predicted speed profiles from the EFFEKT and the SINTEF speed model, is assumed to be caused by the model equation form used to calculate vehicle speed. The standard linear regression function which is shown by equation 4.1 and used within the EFFEKT procedure, makes the predicted speed profile appear as a step function. Within the SINTEF procedure, the linear regression function is introduced as an exponent as shown by equation 4.2. The exponential function contributes to greater variations within the predicted speed profile. If the linear term, $U(x_d, x_s, x_f, x_k)$, has a negative value, the output function will be flat and almost linear. As soon as the value of the linear term gets positive, the output function will increase significantly faster than the value of the linear term. The function will consequently fluctuate depending on the sign of the linear term value. The discussed mathematical difference has vital importance for the predicted speed profile performance. As seen from table 5.1, the greatest statistical variation appears within the dataset of field speeds and the closest prediction of variation is performed by the SINTEF speed model. On the other side, the average value of predicted speed data from the EFFEKT speed model is closer to the average speed value from field data. These statistical measures seen together with the correlation plot in figure 5.2, shows that the SINTEF speed model in larger scale have the ability to reflect speed affecting changes within the input parameters than the EFFEKT procedure. The SINTEF speed profile in figure 5.1 also shows that the equation can be too sensitive to input variable changes, due to the exponential function and greater influence from road curvature. Even though the speed profile from the EFFEKT procedure correlates better to the measured speed profile, this study has shown that the EFFEKT procedure makes coarse simplifications of speed affecting changes within the input parameters when using the standard linear regression equation.

6.2 The driver behavior module

The driver behavior module is the only link within the method of this study which has allowed external influence related to change in the speed predictions boundary conditions. The values listed in table 4.1 was used when correcting the predicted speed profiles from both speed models. Changes or improvements of the driver behavior module can affect the correlation between the predicted speed directly. The following aspects should be considered for further use and improvement of the driver behavior module.

The value of visible range could either be shortened or extended and affect the detail of the smoothening process. Evaluating the acceleration between speed values at points closer to each other, will increase the total amount of speeds considered and leave the speed profile less smoothened. Evaluating the acceleration between speed values at points far from each other will reduce the total amount of speeds considered and leave the speed profile too much smoothened.

Visible range is introduced as a constant number to the current version of driver behavior module used within this study. An alternative way could be to establish an equation based on identified significant variables affecting the visible range and further introduce it as a sliding average inspired by earlier reported practices (12). This could make the module consider what happens in front of and the back of the evaluation point P_i.

At point P_i along the predicted speed profile, the necessary acceleration to achieve the speed at $P_{i + visible\ range}$ is evaluated to maximum allowed acceleration rate. The necessary acceleration is related to speed change due to variations within all the geometric planes of the road such as cross-sectional dimensions, horizontal and/or vertical curvature. A suited value of maximum acceleration rates reflecting safety and comfort requirements related to both horizontal and vertical geometry at the same time was not found in literature, and the assumed value of 0,5 m/s^2 was used.

Few studies reported are allocated to driver behavior models for complex road alignments, and the majority of available driver behavior models are considering horizontal curves only. Researches as Fitzpatrick and Collins (3) and Figueroa Medina and Tarko (11) stated a lower acceleration rate than deceleration rate, indicating that these should be separated in a model situation. Future improvement of the driver behavior module is therefore recommended to be allocated to estimation and modeling of separate acceleration and deceleration rates for complex road alignments.

6.3 Validity and reliability

This study aimed to compare the performance of two Norwegian speed prediction models along a case study section. The characteristics of the case road section is typical for a Norwegian two – lane rural road. Similar performance can therefore be expected when predicting speed for light vehicles along other Norwegian two-lane rural roads. The geometric features extracted directly from NRDB required some extent of processing, but have acted as a good basis for this study and will also be satisfactory for future studies.

The greatest advantage of this study, is related to use of the ISA speed database. This is a massive database of field speeds recorded from different trips in normal traffic operation from all parts of Norway. It consists of continuous speed profiles collected with GPS technology

ensuring great reliability of the dataset. Unlike former studies performing data collection from field, this study has applied cost free speed measures of good quality.

Since the SINTEF speed model is developed from speeds within the database ISA nonactive, measured speeds within the database ISA active was used in this study due to validity considerations. When SINTEF evaluated how the Intelligent Speed Adaption system (ISA) did affect the drivers speed, they evaluated the percentage of distance driven exceeding the activation threshold (PDA). The activation threshold for the ISA system is 4 km/h above the speed limit (14). The analysis revealed that the PDA related to the speed databases ISA system nonactive and ISA system active was 5,9% and 3,4%, indicating that the operating speed was affected and the speed limit exceedance reduced due to ISA technology. The known differences between the databases were not considered as large enough to be a limiting factor within this study, and have not affected the results in a negative way.

The ISA database can with great confidence be used as basis for future studies and provide great opportunities for further development related to speed and acceleration/deceleration models able to handle complex road alignments.

7 Conclusion

Both speed models evaluated have shown strengths and weaknesses within this study, comparing predicted speed profiles to measured speed and evaluating influence of input variables through linear regression. The coefficient of determination for the EFFEKT and SINTEF speed model was $R^2 = 0,88$ and $R^2 = 0,74$, respectively. Even though the predicted speed profile from the EFFEKT speed model indicate higher correlation with the measured speed, the study results show that the SINTEF speed model has greater ability to reflect changes within geometric input parameters in general. Such speed model characteristics is recommended for future use within consideration of travel time, route effectiveness, road design consistency, road capacity, energy demand and vehicle emissions.

8 Acknowledgements

9 References

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PART 2: PROCESS REPORT

1 Introduction

1.1 Motivation and Background

Climate change is an increasing concern in many sectors both in Norway and around the world. Air sampling data is one way to document the root cause, and as seen in figure 1.1 there is a documented atmospheric increase of accumulated heat-trapping gases such as CO_2 and N_2O.
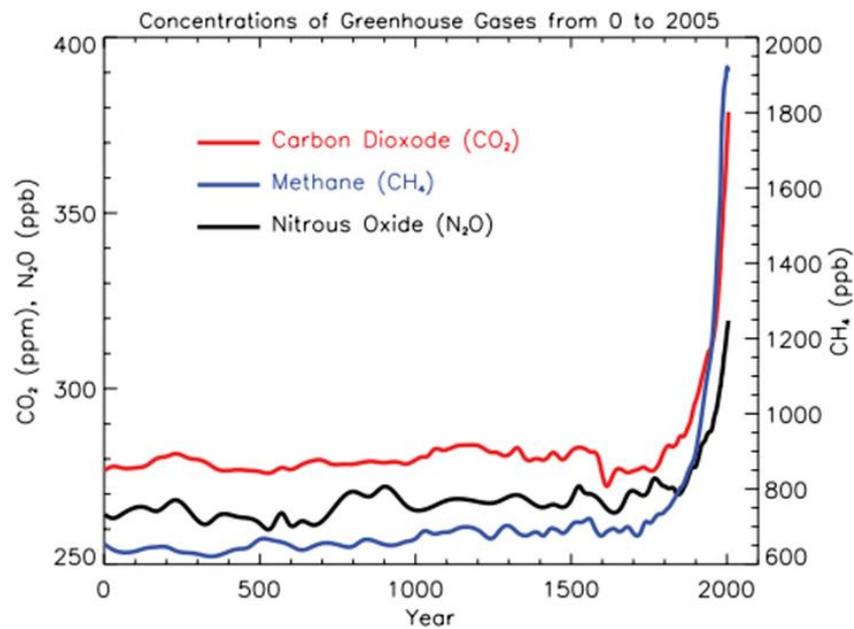
Figure 1.1: Atmospheric concentrations of important long-lived greenhouse gases over the last 2000 years (17).

Furthermore, the energy consumption within the transport sector was responsible for 23% of the world's total CO_2 emissions in 2012. Statistics illustrated by figure 1.2 from Statistics Norway (SSB), show that road traffic was responsible for 76% of all energy consumption within the transport sector, and was therefore found to be the largest contributor in Europe and Norway the same year (18). This demonstrates a demand for reduction of energy consumption within the transport sector and road traffic.

As a reaction to knowledge on climate change and sources of emission, preventive regulations and strategies have occurred. The current Norwegian National Transport Plan 2014 – 2023 (19) is characterized by stringent demands regarding environmental impacts from road traffic.

Norwegian climate policy is aiming for Norway to cut the emissions of greenhouse gases and become completely carbon neutral by 2050 (20). For the transport system, this means an increased priority to coordinate transport and city planning including heavy development of public transport and the bicycle network. Additionally, it is necessary to build road infrastructure smarter and greener.
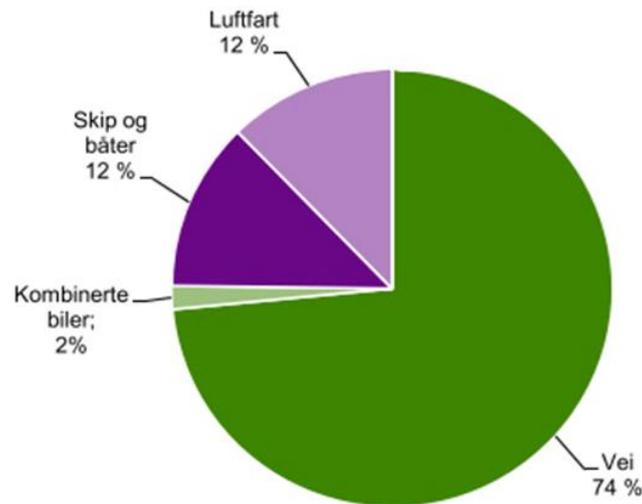
Figure 1.2: Distribution of energy consumption in European transport sector in 2012 (18).

One way to reach this goal, is to develop infrastructure which is more appropriate to handle electric and alternative fueled vehicles, and continue as a leading nation when it comes to supporting new technologies such as electrical- and hydrogen vehicles (20). In addition to focusing on vehicles, it is also believed that the design of road infrastructure can be optimized in order to minimize, or at least reduce the energy demand required by vehicles traveling along a roadway. This idea of reducing energy demand along roadways is the basis for a research project which this master thesis is a part of.

To lead road design towards a greener approach it is necessary to be able to quantify and evaluate environmental impacts from new and existing road sections in a realistic way and investigate how traffic on a road section contributes to the total amount of greenhouse gases. In Norway, such evaluations are already addressed within cost benefit analysis, done by the Norwegian Public Road Administration (NPRA) using the tool EFFEKT 6.6 for larger road and transport projects. The tool EFFEKT has an integrated model for calculating fuel consumption and further emissions of vehicles on planned and existing roads (15). A simplified flow scheme of the calculation steps after the EFFEKT procedure is shown in figure 1.3. It delivers base fuel

consumption for vehicles along a road section in liters per kilometer (L/km) based on modeled vehicle speed. The values of base fuel consumption are further multiplied to CO_2 equivalents ending up as a final measure for vehicle emissions.

Source	Input fuel consumption model	Constant parameters	Output fuel consumption model	Climate calculations
Speed model of EFFEKT	$V_{subsection, light}$ $V_{subsection, heavy}$	Weight of vehicle Frontal area Air density Air resistance coefficient Rotational frequency for engine Regression coefficients Adjustment factors	Base fuel consumption along subsection for light and heavy vehicles (L/km)	
International Roughness Index (IRI value) as an indicator for pavement evenness	$IRI_{subsection}$			

Standard share, light vehicles:		CO_2 ekv/L
Gas	60 %	2,75
Diesel	40 %	3,32

Standard share, heavy vehicles:		CO_2 ekv/L
Gas	0 %	2,75
Diesel	100 %	3,32

Figure 1.3: Flow scheme of calculation of fuel consumption after the EFFEKT procedure.

The calculation steps for models delivering fuel consumption and emissions, such as within the EFFEKT procedure, tends to be overly attached to vehicle engine characteristics and distributions of vehicle- or engine type for the analyzed road section. This undermines the ability to make realistic environmental evaluations of non-traditional vehicles such as electrical or hybrid vehicles. The usefulness of the results of such models is therefore threatened by rapid development of vehicle and fuel technology.

A more future oriented way to evaluate the environmental impacts from different designs of road alignments, is suggested by Giuseppe Marinelli through his post-doctoral work at NTNU in co-operation with the Norwegian Public Road Administration`s Ferry Free E39 Group. His research documentation aims to describe a procedure to calculate the energy demand for travels along a road section as joule per kilometer (joule/km). Necessary energy demand to overcome the resistances along a roadway, can be calculated for any vehicle using well known calculation principals from physics. Since the procedure is related to road characteristics and vehicle engine characteristics are omitted, it is a more evident measure to consider for road design as a purpose.

The procedure calculating energy demand, further known as the NTNU Energy Module, takes into account the geometry of the road, vehicle mass and frontal area and predicted operating vehicle speed as shown in figure 1.4.

Model input		Model calculations	Model output
Road information	**Vehicle information**	Rolling resistance (N)	Work, W (Joule)
Road information	Predicted speed (km/h)	Interial resistance (N)	W = F(N)* s(m)
Slope (%)	Mass (kg)	Air resistance (N)	
Curvature (1/R)	Frontal area (m^2)	Grade resistance (N)	
Station (m)		Horizontal curve resistance (N)	
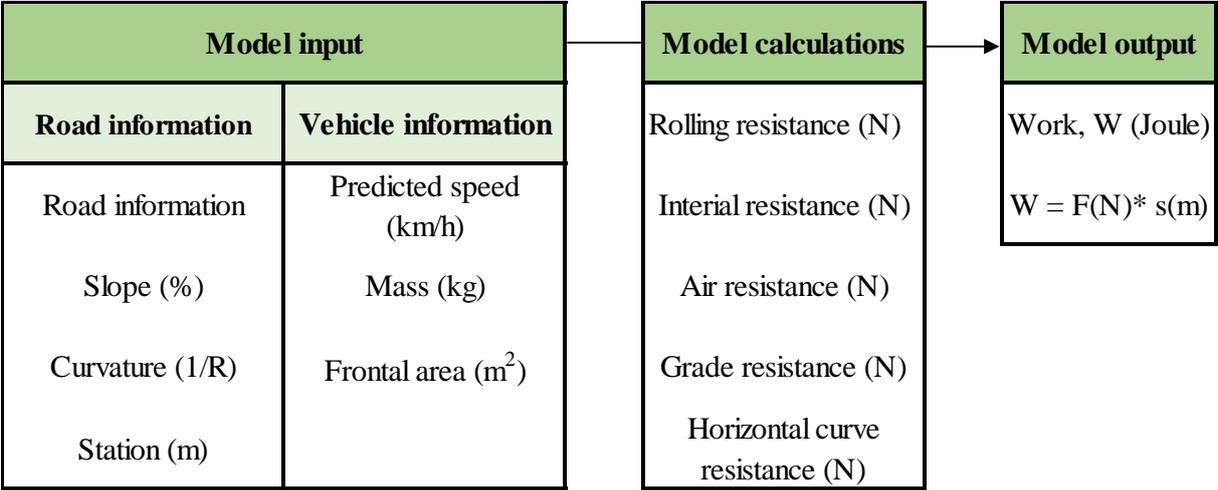
Figure 1.4: Flow scheme of energy demand calculation within the NTNU Energy Module.

In conformance with former models calculating fuel consumption and emissions, the NTNU Energy Module is dependent on predicted vehicle speed. Consequently, the result will get affected by the accuracy of predicted vehicle speed and how this is related to actual field speeds allowed by the geometry of the road. As a contribution to further development of the NTNU Energy Module, this thesis aims to validate and evaluate two Norwegian speed prediction models developed by SINTEF Technology and Society. Both are considered as good alternatives, and recreated as MATLAB scripts within this study to work as basis for the NTNU Energy Module.

1.2 Research scope and objective

The research scope of this master thesis is to validate and evaluate the performance of two Norwegian speed prediction models developed by SINTEF Technology and Society. The speed model further known as the EFFEKT model is a traditional regression speed model developed from average section speeds, and is integrated in the current version of the cost- analysis tool EFFEKT 6.6. The speed model further known as the SINTEF model is recently developed and aims to replace the EFFEKT speed model in the future. The SINTEF speed model is expressed as an exponential function and is developed from the average of continuous speed profiles collected with GPS technology.

The speed model validation and evaluation within this study, is limited to prediction of vehicle speed for passenger cars along one direction of a two-lane rural road. Speed profiles from both speed models will be predicted along the chosen case section E39: Skjennstøbekken – Stokkelva for further comparison to the average of measured free flow speeds. The research question for this master thesis is defined as follows:

How does predicted vehicle speed from the EFFEKT speed model and the SINTEF speed model correlate with measured speed data from the field?

As mentioned previously, answering this question will specifically contribute to further development of the NTNU Energy Module, and facilitate future studies on how the energy module itself acts related to measured energy consumption from electrical vehicles in the field.

Since the speed models evaluated within this study have different mathematical procedures, the findings will additionally contribute to a better understanding of how the mathematical formulation affect the speed model performance.

1.3 Thesis structure

This master thesis has been an individual project proceeded during the spring 2017. It is connected to research engaged by the Norwegian Public Road Administration`s Ferry Free E39 Group, led by Giuseppe Marinelli at NTNU. A table describing the division of labor within this thesis work can be seen in Appendix 2.

Kelly Pitera and Giuseppe Marinelli have been the supervisors for the thesis and co-authors for the scientific paper. Regular meetings have taken place allowing discussions of the development of the thesis direction and unforeseen challenges. Pitera have mainly given guidance regarding the working process and details within writing a report and scientific paper. Marinelli have mainly provided experience within the tools MATLAB and ArcGIS and guidance related to paper writing. Both have been a great help during the development of the resulting thesis.

The thesis document is divided in two main parts, where the scientific paper *Comparison of speed prediction models valid for Norwegian two – lane rural roads* constitute part 1 and an accompanying process report constitute part 2. The paper serves as a dissemination of the thesis work and present the results and discussion. This will be submitted for consideration for the 2018 Transportation Research Board (TRB) Annual meeting. The process report supplements the paper and includes the theoretical framework established through a literature review and a more detailed description of how different parts of the method have been accomplished.

2 Theoretical framework

A literature review was performed, mainly during the autumn 2016, but sporadic searching was also done during the spring 2017 as the research of the thesis work was developed, and possible directions were indicated. The literature was accessed through the search engines BIBSYS (oria.no), google scholar and directly within the resources and databases of Transportation Research Board (trb.org).

In the beginning, the search was aiming for literature describing energy consumption from the transport sector and possible ways to model road traffic emission scenarios. When the master's thesis research idea was clearly defined, the search was aiming for available literature regarding vehicle speed prediction models to get an overview of the range of use, the development and the state of the art regarding them.

Using the search words 1 to 4, often in combination with 5 to 7, led to relevant literature. The references of the first search rounds often led to new literature, used within this thesis research as a theoretical framework described in this section.

1. Operating speed model
2. Vehicle speed modeling
3. Speed prediction model
4. Speed factors

5. Two lane rural road
6. Global Positioning System technology (GPS)
7. Design consistency

2.1 Vehicle speed

Vehicle speed is described in literature as the most important parameter in road- and traffic engineering. It is a necessity when evaluating the road network related to road design, road safety and design consistency, and when performing transport and cost- benefit analysis considering road route effectiveness, road capacity, energy consumption of vehicles and road traffic emissions etc.

The Norwegian Public Road Administrations Handbook V120 (21), states that the least allowed horizontal curve radius along a road section is derived from an equilibrium between the forces

acting on a vehicle in a curve. This important relation used within Norwegian road design is described by equation 2.1:

$$R_{h,min} = \frac{V^2}{127(e_{max} + f_k)}$$

Equation 2.1

V   =   Posted speed limit (including additional speed safety factors)

e_{max} =   Maximal super elevation

f_k =   Design side friction

The posted speed limits along a road section in Norway is anchored in Vegtrafikkloven (22) and ideally set as a compromise between traffic safety, environmental effects and the ability to navigate the road. The Ministry of Transport, the Norwegian Public Road Administration (NPRA) and local government administrations have the authority to change the speed limits of the road at all time. The SINTEF report A26649 (23) states that this can lead to situations where the speed limit does not match the complexity of the roads geometry, and allow for sections where the speed limit is higher than what the drivers can perform safely.

When using speed as a parameter for evaluation within transport and road planning, it is important to distinguish between design speed, free flow speed, operating speed, running speed, average running speed and posted speed limit. A survey of available definitions reported by Fitzpatrick et al. (24) revealed that definitions of the Green Book, AASHTO (25) and Highway Capacity Manual (26) are frequently used, even outside the United States. Many researchers abroad are supporting and basing their research work allocated to vehicle speed on the following definitions.

Design speed: Is defined by AASHTO (25) as a selected speed used to determine the various geometric design features of the roadway.

Free flow speed: As defined by HCM (26), a vehicle has a free flow speed in situations not affected by its surroundings. It is further defined as the theoretical speed of a vehicle when traffic density and flow rate on the study segment both are equal to zero.

Operating speed: Is defined by AASHTO (25) as the speed that drivers are observed operating their vehicles. The 85th percentile (V_{85}) of the distribution of observed speeds is the most frequently used measure for the operating speed associated with a particular location or geometric feature.

Running speed: Is defined by AASHTO (25) as the speed at which an individual vehicle travels over a highway section. The running speed is the length of the highway section divided by the running time required for the vehicle to travel through the section.

Average running speed: Is defined related to section speeds by AASHTO (25). The average running speed is the sum of distances traveled by vehicles on a highway section during a specified time period divided by the sum of their running times.

Posted speed limit: Is defined by AASHTO (25), as the maximum allowed speed along a road section established by law.

Operating speed is considered as the closest theoretical speed can get to actual speed of the majority of vehicles traversing a road section. When performing analyses where vehicle speed is involved as an input parameter, the result will be more correct and realistic if they are based upon operating speed. Achieving a modeled operating vehicle speed that is as actual as possible is therefore of great interest, and Fitzpatrick et. al (24), among many others, are working to determine what and how surrounding variables affects operating vehicle speed, and how speed prediction models can be formulated in the best way.

2.2 Speed model development and range of use

The TRB synthesis report (1) sums up the current level of research regarding speed prediction models in North America and Europe through 2011 and has acted as a state of the art for recent contributors. As described within the report, numerous speed models have been developed for different uses and purposes. Greatest attention is given by researches to prediction of operating speed for passenger cars, at single road elements such as horizontal curves and straight tangent lines. Many models are developed to evaluate design consistency and operating speed is often represented by the 85th percentile of the distribution of all observed speeds. Some of the reported ranges of use, development procedures and characteristics of speed data used as basis are described below.

Lamm and Smith (27) established safety criteria used to evaluate design consistency related to operating vehicle speed. Misaghi and Hassan (7) have stated further that design consistency is the most important factor influencing road safety because it refers to how the geometry of the road corresponds to the drivers' expectations. Speed prediction models for use within verification of design consistency related to safety criteria are suggested by Fitzpatrick and

Collins, 2000 (3), among others. Similar procedures and accompanying speed models aiming to avoid road geometry that can create confusion, surprises and possible collisions is also suggested by Misaghi and Hassan (7) and Zuriaga et al. (6):

1. Evaluate the value of operating speed differential between two successive elements of a road (7).
2. Evaluate the difference between the operating speed and design speed values for specific elements of the road (7).
3. Evaluate changes in operating speed as a function of the roadway geometry (6).

Some speed models found in literature, predict speeds along complex road sections containing both curves and tangents. Such speed models are used within transport and cost- benefit analysis to calculate travel time, road capacity and environmental impacts both in Norway and Great Britain. The Norwegian EFFEKT speed model for two – lane road is evaluated within this study and described further in section 3.4. The British version of the speed model for two – lane road based upon a study of vehicle speed, traffic flow and geometry relationships carried out in 1991, calculates speed on a road link after the procedure presented in The COBA Manual (12).

Within speed prediction model development, both measured speed data and data describing the geometry of the road is essential. Most speed prediction models available have their model coefficients estimated from speed data collected from the field. By 2011, speed data was often collected with equipment like manually operated radar and laser gun, which can allow human error. Deviation from measure devices can affect the measured speeds, and the drivers might change their driving characteristics if test equipment are interpreted as speed enforcement. In addition, radar and laser gun only allow speed collection at one location, usually in the middle of a curve or a tangent. Speed models based on such data must further assume constant operating speed through curves, as in the models developed by Krammes et al. (2) and Fitzpatrick and Collins (3).

The TRB synthesis report (1) encouraged researchers to use Global Positioning System (GPS) technology when collecting speed data. This technology allows continuous collection and processing of speed data and development of more accurate speed models. Researchers as Nie and Hassan (4), Bella et al. 2014 (5) and Zuriaga et al. 2010 (6) have used this technology within their research. The SINTEF speed model evaluated within this study and described in section 3.5, is also based upon speeds collected with GPS technology.

Speed affecting variables, represented by road geometric features have been collected in different ways. International studies have found these variables from field observations and measurements, use of as built data, digital maps, AutoCAD drawings or recreation of the road geometry through use of the GPS registrations indicating the drivers' path in ArcView. If the relationship between the measured speed and variable seem to be statistically significant at a chosen confidence level, often 95%, it will be included in the speed prediction model.

Depending on the model purpose and amount of available data used for development, the model coefficients are structured as numerical or statistical terms, often in a linear, polynomial or exponential equation form. The TRB synthesis report (1) stated that the majority of existing operating speed models by 2011 uses conventional linear regression equations. Researchers as Bassani et. al (9, 28) and Figueroa Medina and Tarko (8) proposed statistical mean speed and distribution models able to predict any speed percentile of vehicle speed, and not only the well reported 85th percentile of speed.

The fact that the format of existing speed models, their independent variables and estimated coefficients are very different from one model to another, underlines that no speed model is universally accepted. The TRB synthesis report (1) and Misaghi and Hassan (7), states that since driver behavior and road design varies from country to country, development of a country dependent speed model is essential. The speed models' validity is also limited from where, when and how the dataset used to estimate model coefficients are collected.

2.3 Model input variables

Road characteristics

Although speed models can only be used within their validity range, experiences and research findings can benefit development across model categories, especially concerning what and how input variables should be included.

There is a large selection of published literature that presents operating speed as a function of road parameters such as horizontal curve radius, vertical grade, rate of curvature and traffic flow characteristics. Relatively few models contain variables related to tangents, horizontal-vertical combinations, cross-sectional dimensions, sight distance and posted speed limit (1). The format of input variables, especially horizontal curvature, have been evaluated in former research. While many models use the radius value R (m) of horizontal curvature in their

equations, McLean (10) and Fitzpatrick and Collins (3) recommended use of the inverse of radius, curvature (1/R). McLean (10) also introduced a second order term of curvature $(1/R)^2$ in the proposed speed model, further stating that the regression equation delivered irregular results for the extremes of input data range. This was assumed to occur due to the nonlinear correlation with observed speeds and curvature.

A study reported by Figueroa Medina and Tarko (8) presents a free-flow speed model where cross sectional dimensions are introduced. This model was further used as basis in later research of Bassani et. al 2016 (9) categorizing the input variables after the following effects:

1. **Input variables contributing to a reduction in operating speed dispersion when increasing:** The curvature (1/R), the presence of sidewalks and safety barriers on both sides, the intersection density, the lane width, the shoulder width on right side, the ramp density on the left side.

2. **Input variables contributing to an increase in operating speed dispersion when increasing:** The posted speed limit, the driveway density on right side, the longitudinal grade, pedestrian and right side ramp density, presence of a lay-by on both sides.

Driver behavior

For models predicting speed profiles along a road section, researchers are usually considering driver behavior to some extent. Within this study, the meaning of driver behavior is limited to driver characteristics as deceleration, acceleration and the interpretation of available sight distance along the road. How this is implemented, calculation procedures and estimated values used in available speed prediction models vary.

Figueroa Medina and Tarko (11) and the COBA Manual (12) include sight distance as a speed model input variable. Within this study, sight distance is referred to as visible range and introduced through a separate driver behavior module as described in section 3.6.

Reported studies that consider driver behavior, adjust predicted speed related to acceleration and deceleration rates. This procedure is used to improve the transitions between road elements characterized by a change in geometry and consequently the predicted speed. While changes within speed and acceleration occur due to changes in all geometric planes of the road, such as cross-sectional dimensions, horizontal and vertical alignment, most models proposed have only evaluated acceleration and deceleration rates related to horizontal curves.

Fitzpatrick and Collins (3) developed regression equations for a speed profile prediction model able to adjust the speed when approaching and departing curves according to deceleration and acceleration rates based on data collected at horizontal curves. Figueroa Medina and Tarko (11) developed speed equations for curves, tangents and transition sections. Deceleration and acceleration rates based on observations in horizontal curves are introduced within the equations predicting speed when decelerating or accelerating at the specific transition sections between curves and tangents. Hu and Donnel (13) is one of few studies which have developed a driver behavior model used to estimate acceleration and deceleration rates for complex road alignments including both horizontal and vertical geometry.

3 Procedure

The methodology of the study, a summary of database descriptions and evaluated speed models is presented in the scientific paper *Comparison of speed prediction models valid for Norwegian two – lane rural roads*. Further details and reflections regarding preparatory work, use of the speed models, use of the driver behavior module and processing of relevant data is described in later sections within this chapter.

The relevant data for the case road section was extracted and organized as a MATLAB database after a methodology developed by Giuseppe Marinelli. This consists of a procedure and accompanying MATLAB codes and ArcGIS tools. The detailed description can be found in his final research report *Geometric design for energy optimization* (29) when published. This was used for the first time within this thesis work. Feedback on various problem solving was given to the author on the way.

3.1 Preparatory work

While both the EFFEKT speed model and the SINTEF speed model, were documented formally and informally, as well as contained and utilized within road planning tools, it was necessary to recreate the functional models as MATLAB scripts for use within this research. First, simple modeling of speed and investigation of the models' equations in Excel was performed to figure out the best way to organize the calculation procedure of both speed models. Two meetings were also arranged with some of the speed model developers at SINTEF Technology and Society during February and March of 2017 to ensure a full understanding of the speed models. Short summaries of these meetings can be found in Appendix 3.

Exploring speed prediction during the phase of preparatory work was possible due to an existing MATLAB database describing road geometry and measured speeds along E39: Orkanger – Vinjeøra, developed and provided by Giuseppe Marinelli. Geometric information and measured speed stored for specific trips in the MATLAB database was first extracted to Excel. By applying the speed models' equations on the geometric information, speed profiles predicted by the models could be compared to measured speed as illustrated in figure 3.1. This gave good insight and made the subsequent coding in MATLAB easier. As an example, the blue line in figure 3.2 show the predicted speed profile produced by the SINTEF equations and coefficients organized in an excel sheet using the geometric information along the road where the trip T18211 occurred as input. The red line in figure 3.2, show the measured speed for the recorded

trip T18211. The EFFEKT procedure was mathematically difficult to organize correct in Excel due to its demand of dividing a road alignment into subsections. This was further solved when translating the speed model into a MATLAB script, organizing the output from the calculation procedure as a matrix.
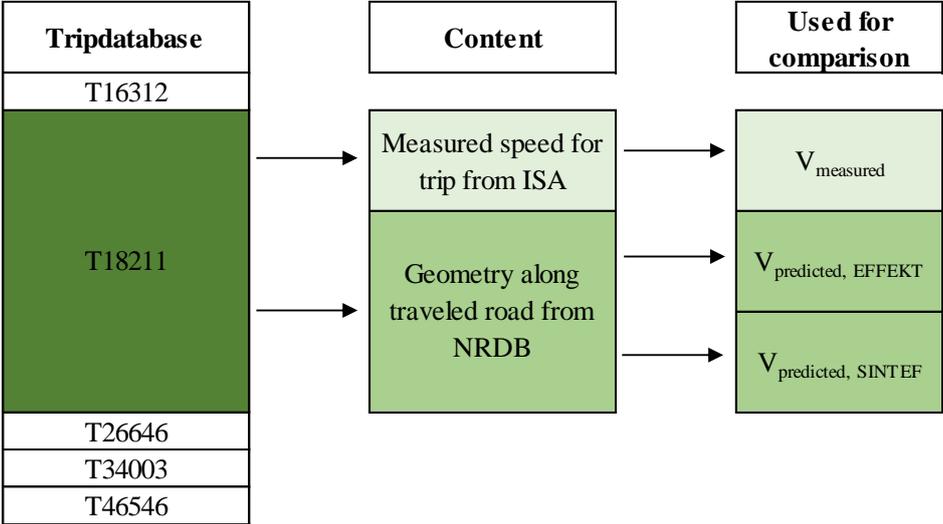
Figure 3.1: Use of existing database to compare predicted and measured speed for one specific trip.
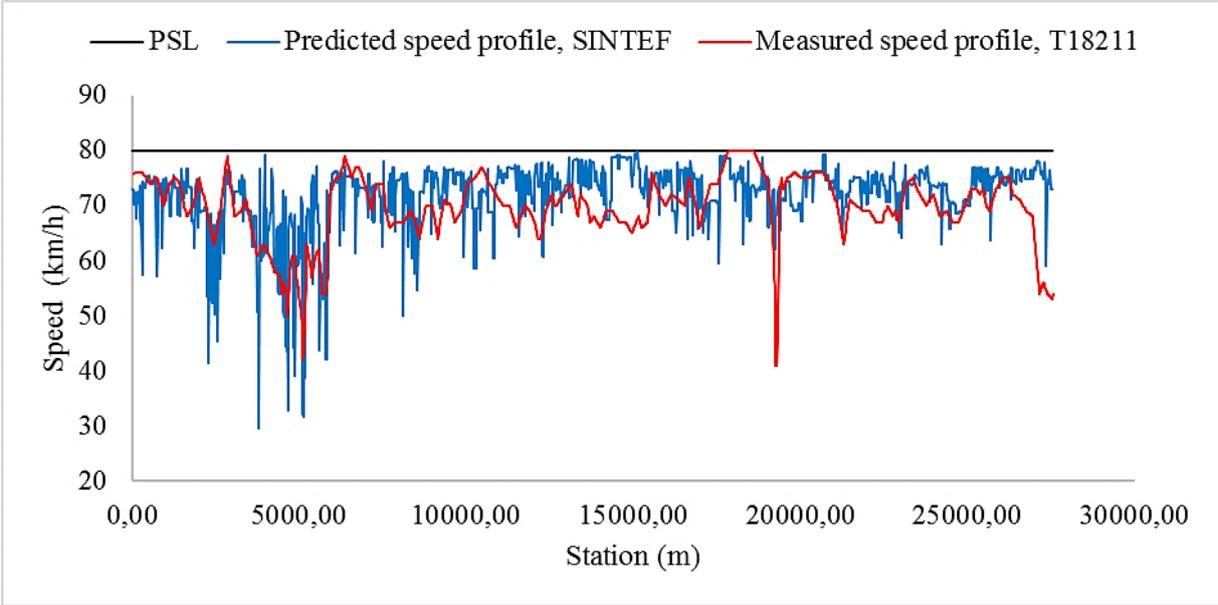
Figure 3.2: Comparison in Excel of predicted and measured speed for trip T18211 using the SINTEF speed model.

The first speed profiles based on geometry directly transferred from the road information database, NRDB, had a stressed appearance. When studying the geometry data closer, illogical

18

and sudden changes in directions and values of horizontal curves and slope were found, indicating jagged datasets. Discussion of this phenomena with SINTEF researchers involved in the SINTEF speed model development process, revealed the data inside NRDB describing a road line could be disturbed by other close road features and adopt geometric information from each other when extracted.

To avoid as much irrelevant disturbance from the input dataset, the geometric data describing slope was sorted along the road alignment inside the ArcGIS environment before being introduced to the speed models. The geometric data describing horizontal curvature was calculated from the dataset containing values of radius R (m) and further processed after a methodology developed by Marinelli (30). This MATLAB script smoothens the dataset describing horizontal curvature as illustrated in figure 3.3 using polynomial functions.
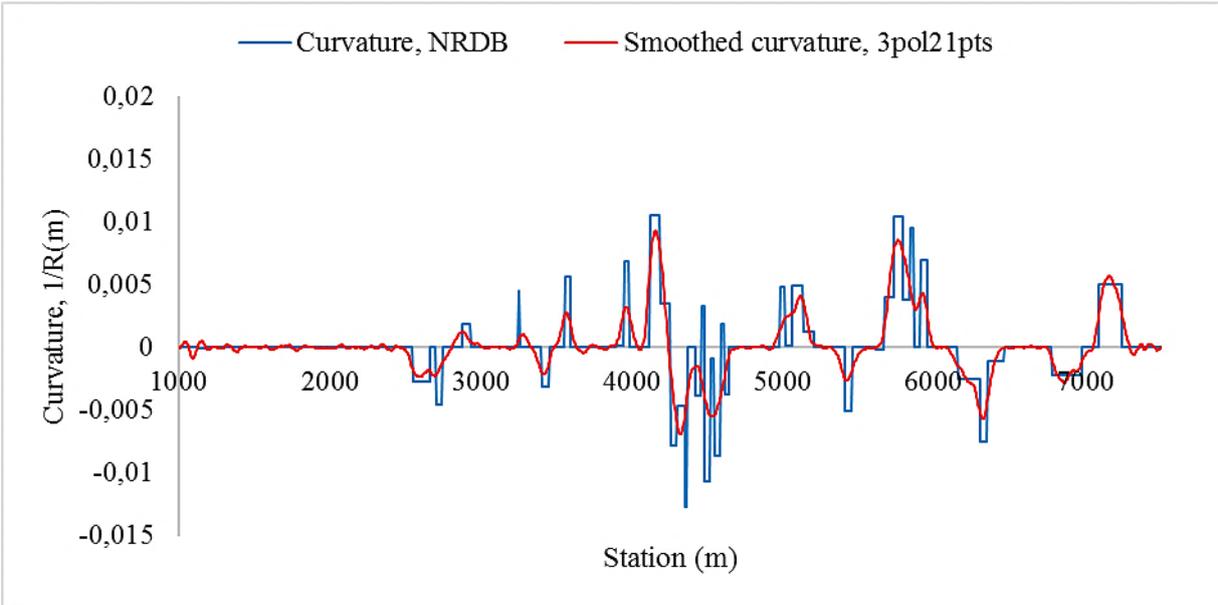
Figure 3.3: Smoothed horizontal curvature using a third-degree polynomial function of 21 points.

3.2 Database description and processing

Geometric data from the National Road Database (NRDB)

The geometric information needed in this thesis work, was extracted from the National Road Database (NRDB) (31). The database is developed by the Norwegian Public Road Administration in collaboration with Ementor ASA as the primary supplier of data. Geodata AS, ViaNova IT, Norkart AS and Triona AB are sub suppliers of data. The content of the NRDB is shown in the map vegkart.no and can be accessed through an ArcGIS add-in[1].

Through ArcGIS the following data was downloaded for the area Møre and Romsdal, which covers the necessary input data for both speed models evaluated:

- Fartsgrense_Møre_og_Romsdal (*speed limit*)
- Feltstrekning_Møre_og_Romsdal (*number of lanes*)
- Kurvatur_horisontalelement_Møre_og_Romsdal (*horizontal curvature*)
- Kurvatur_vertikalelement_Møre_og_Romsdal (*vertical curvature*)
- Vegbredde_Møre_og_Romsdal (*road width*)

The data containing speed limit information, was the most complete dataset extracted from NRDB. A line acting as a clip feature for the chosen case section E39: Skjennstøbekken - Stokkelva was therefore established from this dataset. Based on this road clip feature line, specific data describing the other road properties was extracted using a 25m buffer. Geometric lines containing the relevant information, such as posted speed limit (PSL), number of lanes (NL), horizontal radius (R), vertical elevation (ELEV), vertical slope (S) and road width (RW), were further processed along the case road section, and used as described in figure 3.4 and the belonging section.

Measured speed data from the ISA database

The National Public Road Administration equipped 440 service vehicles with an informative Intelligent Speed Adaption (ISA) system and a speed recorder during the period from April 2011 to April 2014. Informative ISA is defined by SINTEF as a system that signalizes to the driver if he/she is about to surpass the speed limit, without taking control over the vehicle (14). Vehicle's speed and location have been collected with Global Positioning System (GPS) receivers and continuous monitoring until the end of 2014. The data was further provided to SINTEF which filtered and processed it to a database containing 245 million data points from

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[1] http://www.vegdata.no/2014/07/28/rask-tilgang-til-nvdb-data-i-arcmap/

119 vehicles and 130 000 trips. For use within studies like this thesis, the first and last three kilometers of every trip were deleted in addition to information on plate ID of the vehicle. This to remove sensitive information that can identify the driver. Every trip recorded contains the information listed in table 3.1, collected every second.

Table 3.1: Trip information inside the ISA database (29).

Number	Field name	Description
01	Timestamp	Day and time for current point
02	Distance	Distance traveled since trip start (engine start)
03	Latitude	Latitude coordinate of current point
04	Longitude	Longitude coordinate of current point
05	Limit	Posted speed limit at current point
06	Speed	Current vehicle speed
07	Sound	Speed check system active/inactive
08	Vehicle_ID	Identifying number for each vehicle
09	Length_CM	Length of the vehicle in cm
10	Width_CM	Width of the vehicle in cm
11	Self_Weight_KG	Weight of the vehicle, without the driver, in kg
12	Total_Weight_KG	Weight of the vehicle, including the driver, in kg
13	Motor_Effeck_KW	Vehicle engine power, expressed in kW

The database was further divided in two sets:

1. **ISA system nonactive:** Contains speed data recorded when the ISA system was not active and did not give any signal to the driver when surpassing the speed limit. This database has been the basis for the development of the speed model referred to as the SINTEF speed model within this study.

2. **ISA system active:** Contains speed data recorded when the ISA system was active and a signal was given to the driver when surpassing the speed limit. Speeds from this part of the database have been used within this study and compared to predicted speed during the analysis of speed model performance.

Given the divisions between the databases, it is important to consider the speed difference. To evaluate the effect of the installed ISA system on drivers chosen speed, SINTEF compared the speeds from the two databases as reported in SINTEF A27040 (14). This was done by calculating the percentage of distance driven exceeding the activation threshold for ISA (PDA), in addition to studying changes in average speed and speed variations. The activation threshold for the ISA system was set to 4 km/h above the speed limit.

The analysis revealed that the PDA with ISA system nonactive was 5,9% and the PDA with ISA system active was 3,4%. Based on the results, SINTEF states with 95% confidence that the ISA system has a positive effect, and reduced the proportion of distance travelled with speeds higher than 4 km/h above speed limit. For the speed limits 70, 80 and 100 km/h, there was a significant reduction in average speed when the ISA system was active. More speed variations were observed for speeds at speed limits 50, 60, 70, 80 and 100 km/h with the ISA system active compared to speeds recorded without ISA. For speed limit 90 km/h, less speed variation with the ISA system active was observed.

The reported differences between the databases have not been considered as large enough to be a limiting factor within this study. Since the extent of available speeds through the ISA database is exceptionally wide, it has been of great interest to investigate the possible use range within research. The recorded speed data is accessed through the procedure provided by Marinelli (29), which can facilitate the effectiveness of future studies and contribute to easier access to cost free, continuous speed profiles of good quality, as utilized within this study.

The speed data was accessed through the ArcGIS environment already established to process the geometric information along the defined road route. A research window enclosing the road alignment of the case section was defined, and the longitude and latitude coordinates of the vertices of this research window was used as input to the MATLAB codes linked to the ISA system active database. Trips that only have occurred inside the defined area limited by the coordinates, were filtered out for further use. The speed data of 70 available trips was stored as CSV files and further processed in ArcGIS after a conversion to a geographical format.

When all trips were available in the ArcGIS environment, further filtering was performed to sort out the trips occurring inside the area of a 25m buffer along the earlier described road clip feature. This resulted in 64 stored trips occurring along the case section, traveling in both directions. For the direction E39: Skjennstøbekken – Stokkelva evaluated further in this study, speed data from 36 trips were available.

Development of the geometric database and the trip database

As shown by figure 3.4, the extracted geometric and recorded trip data was further used within:

1. Development of a geometric database which further acted as a provider of input variables for the evaluated speed prediction models.
2. Development of a trip database used for further analysis and processing of the collected measured speeds.

To achieve this, points were generated along the road route every 5 m, which was assigned the important attribute field describing the metering, or station (m), along the road route. For further development of the geometric database, geometric information was assigned to each point through a joining process with the geometric feature lines.

Basis	● ● ● ● ● ●	
	- Points along road route every 5 m containing station (m)	
Joined with	Geometric feature lines: - PSL, NL, R, ELEV, S, RW	Trip information from ISA: - Measured speed etc. listed in table 3.1.
		Geometric feature lines - PSL, NL, R, ELEV, S, RW
Resulting database	**Geometric database**	**Trip database**
	Every point contain: - Station (m) - Geometric features	Each trip contain: - Station (m) - Measured speed etc. - Geometric features

Figure 3.4: The combination of data within the development of the geometric and trip database.

The generated points were also used as basis when connecting each collected trip to points along the road route. This was done through a locating and joining process between the geometric points and all collected trip data, assigning the station (m) to the trip information. By linking every trip to the corresponding station (m) along the road route in ArcGIS, further separation of the trips in different direction, was possible due to a MATLAB code able to compare the change in station (m) along the trip to the change in date/time. A second joining

23

process was performed between the speed data represented as points and the geometric feature lines, to include the geometric properties of the road where the trips have occurred.

Tools used to process the trip data within the ArcGIS environment, was made by Marinelli as part of the data processing procedure. They are different from default built-in tools because of their ability to handle iterative processes with several feature classes or files which improves the efficiency of this procedure. The tools allowed processing of all trips together instead of one at a time.

To be able to work with the geometric and speed data within MATLAB, an ArcGIS tool was used for conversion of the geodatabases to CSV files which are readable for MATLAB. Both the geometric and the trip database were further organized as structured databases in MATLAB.

3.3   Case section E39: Skjennstøbekken – Stokkelva

Since this study is connected to research engaged by the Norwegian Public Road Administration's Ferry Free E39 Group, it was natural to choose a suited case section along E39. The speed models will be evaluated related to the predicted average of free flow speed. To ensure free flow measured speeds for comparison, the case section needed to fulfill the following criteria.

1. The road section should be a two – lane rural road.
2. The road section should have low intersection density.
3. It is advantageous if the road alignment is characterized by challenging geometry.
4. Presence of measured speed data in the speed database is crucial.

The chosen case section lies in Halsa municipality in the county of Møre and Romsdal. It starts 60 m past Halsa primary school and ends 110 meters after the E39 crosses the river Stokkelva. The case section E39: Skjennstøbekken – Stokkelva has a length of 15,2 km. A map extract from the ArcGIS environment established within this study, illustrating the existing road alignment, is shown by figure 3.5.

E39: Skjennstøbekken – Stokkelva is a European highway with speed limit 80 km/h, except for two zones of speed limit 60 km/h. The first, is a zone of ca 1,3 km through the area passing Hennset ferry quay. The second, is a zone of ca 2,4 km which starts within Otnes church and ends at Hestnes.
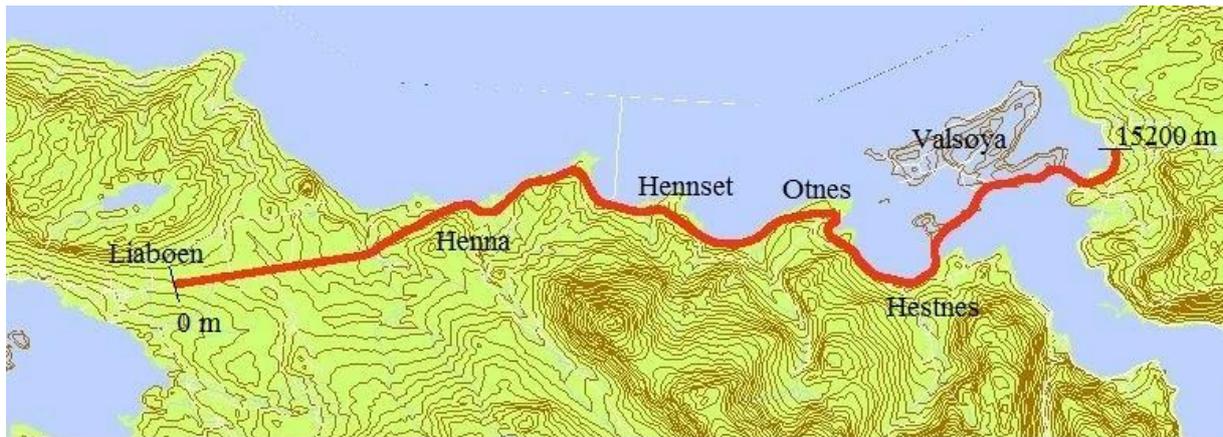
Figure 3.5: Map extract of E39: Skjennstøbekken – Stokkelva.

Two side roads considered as roads that can affect traffic in some way is connected to E39 along this section. The county road 352 Våglandsvegen intersect the E39 at the beginning of the road section, around station 780 m. The county road 354 intersect the E39 at two places at the end of the road section, around station 11400 m and station 15020 m. For this study, the direction from Skjennstøbekken to Stokkelva is defined as the main direction, and further descriptions of geometry, measured speeds and analysis is limited to this direction.

Road geometry

The case section is a two-lane road, and the road width in addition to horizontal curvature is shown by figure 3.6. The elevation together with slope is shown by figure 3.7.
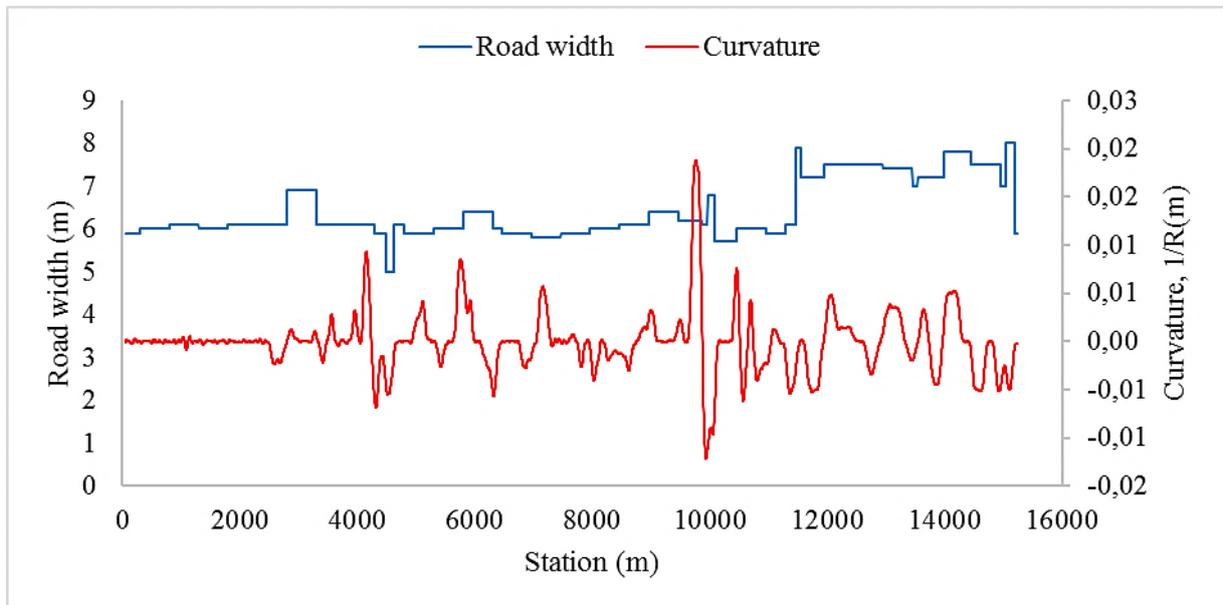
Figure 3.6: Road width and curvature along E39: Skjennstøbekken – Stokkelva.
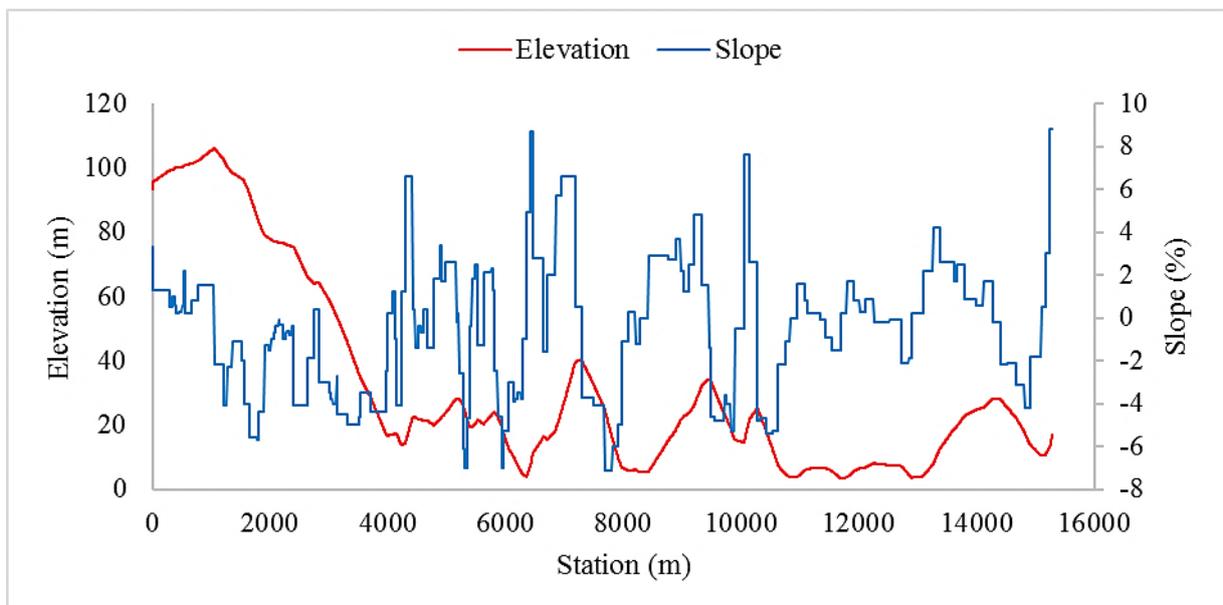
Figure 3.7: Road elevation and slope along E39: Skjennstøbekken – Stokkelva.

Measured speeds

In the direction Skjennstøbekken – Stokkelva, data from 36 trips, shown by figure 3.8, were found in the ISA database. The measured speed profiles are dense, which indicates that the extracted trips from the database have occurred within the same speed range.
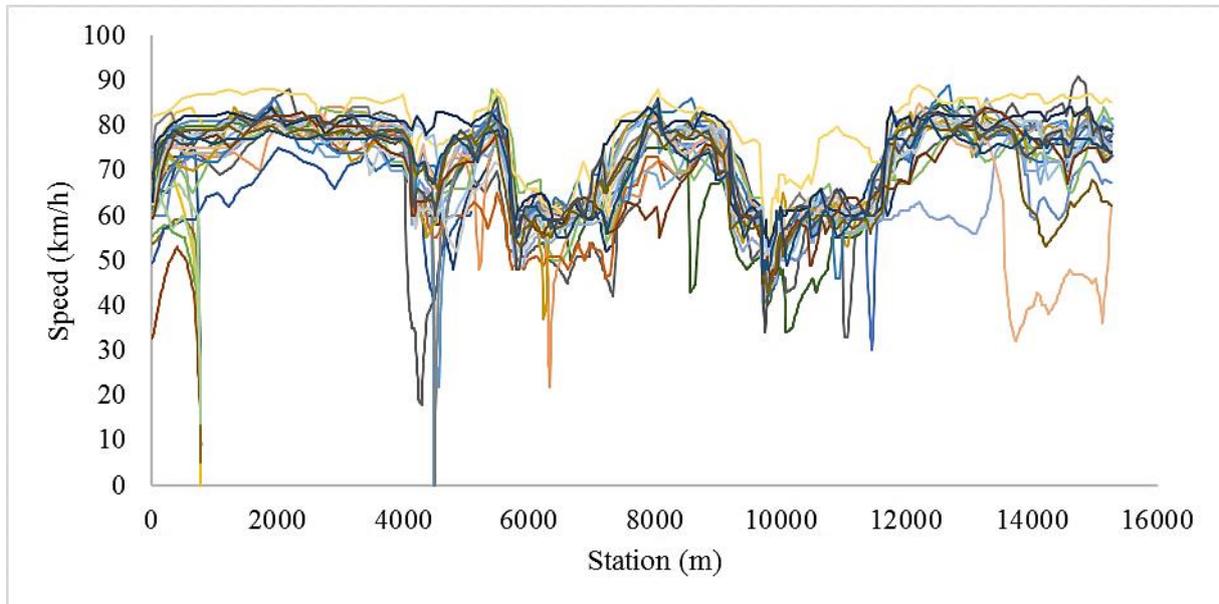

Figure 3.8: Measured speed profiles of filtered trips traveling the direction E39: Skjennstøbekken – Stokkelva.

To be able to compare the measured speed profiles to the predicted speed profiles, the dataset was averaged within 25 m sections along the road, and presented every 12,5 m. This resulted in a speed profile containing the mean of measured speeds, used for comparison with the two predicted mean speed profiles in further analysis.

Outliers occurred in the dataset describing the original and averaged data of measured speed profiles, as seen from figure 3.8 and figure 3.13. It was further revealed that the average value was pulled down by vehicles standing still or driving considerably slower than other collected speeds at four places along the case section. The trips pulling down the average, were not driving in a free flow situation as preferred within this study, and were further deleted or manipulated at the critical places in order to improve the dataset of measured speeds, resulting in the manipulated measured speed profile as shown by figure 3.13.

The first outlier speeds were caused by vehicles making a left turn from E39 to Fv352 Våglandsvegen around station 780 m. Recorded speed from these trips are shown in figure 3.9 and deleted from the manipulated dataset.
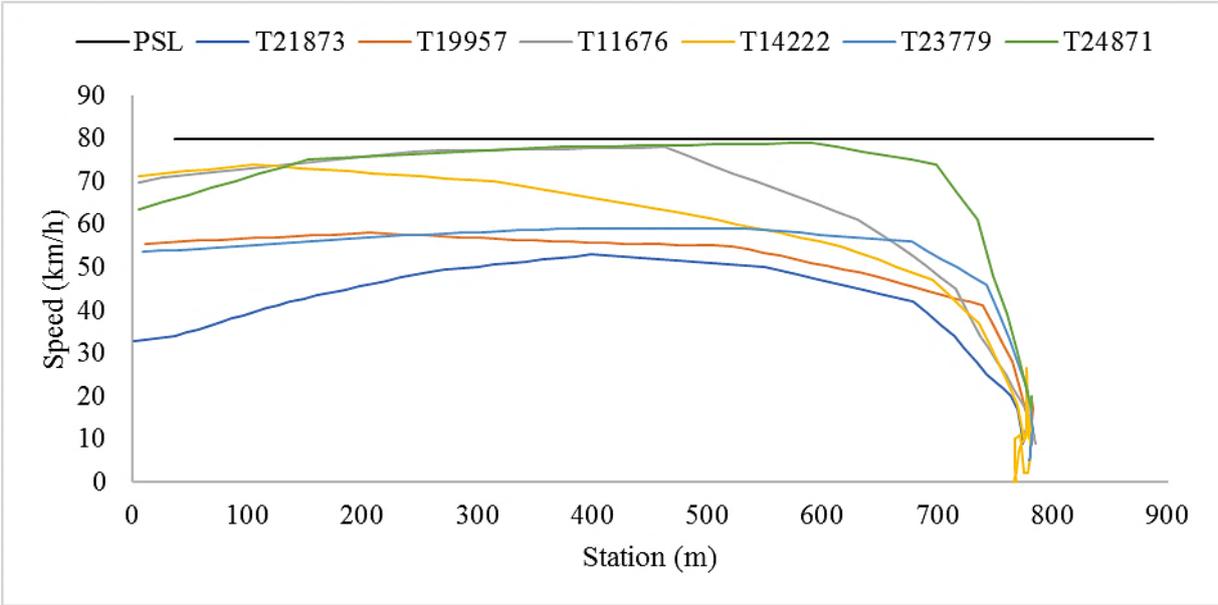
Figure 3.9: Trip data causing outliers between station 700 m and station 800 m.
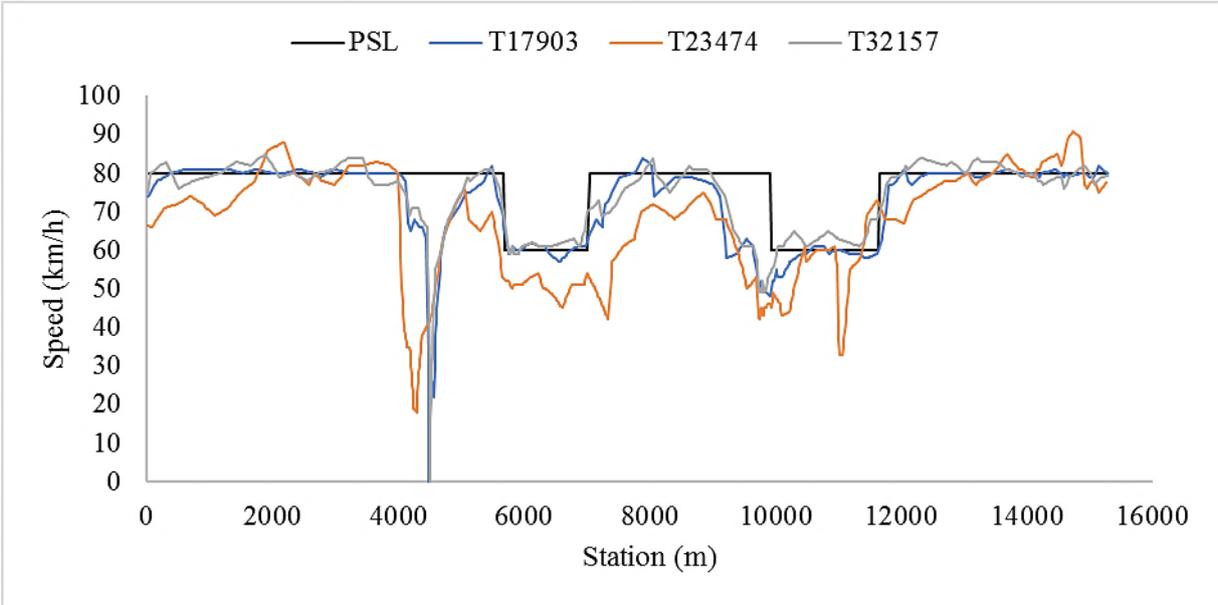
Figure 3.10: Trip data causing outliers around station 4000 m.

The second outlier occurred at a place called Henna around station 4300 m. In this area, two private roads are connecting E39 and there is a narrow bridge crossing the river Hennaelva. According to road width data from NRDB, this is reduced from 6m to 5m in this area, making a meeting situation with wider vehicles challenging. Three vehicles forced to slow down or stop was identified in the original data as shown in figure 3.10. Speed data from these trips are deleted between station 4200 m and station 4700 m in the manipulated dataset.

Both intersections between E39 and Fv 354 were also checked for outlier speeds. Two vehicles were slowing down at the first intersection as seen in figure 3.11. Speed data between station 10500 m and station 12000 m were deleted from the manipulated dataset.
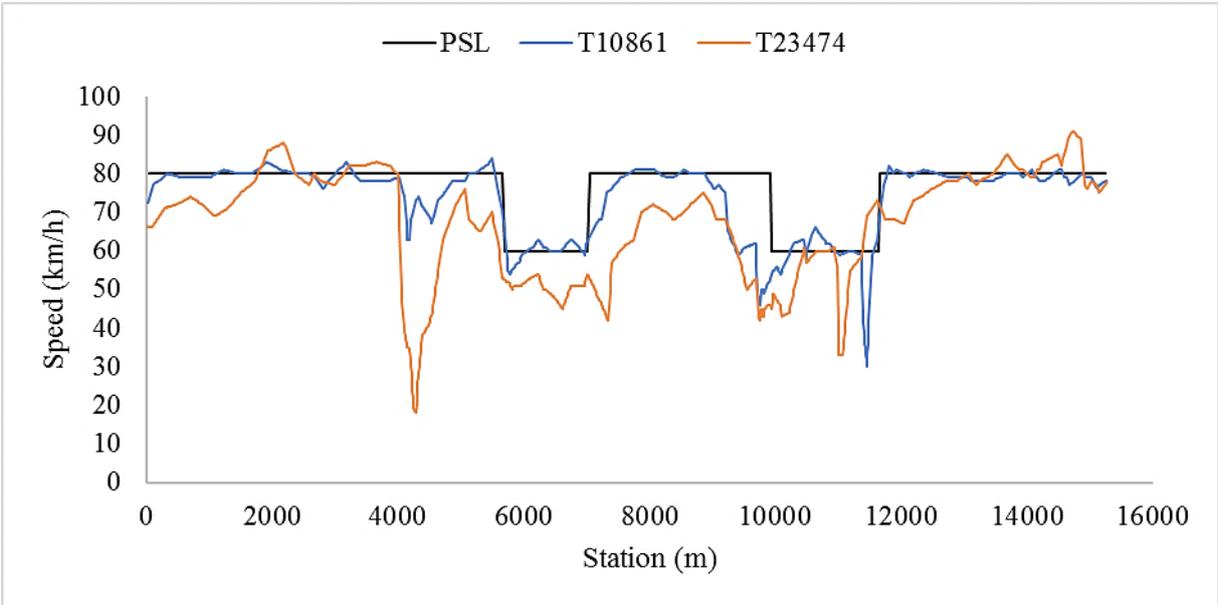
Figure 3.11: Trips causing outliers between station 10500 m and station 12000m.

No vehicle seemed to be noticeably affected by the second intersection with Fv 354, but speed data from a vehicle possibly affected by a slower vehicle in front was identified as shown by figure 3.12. Speed data from this trip was removed from station 13000 m in the manipulated dataset.
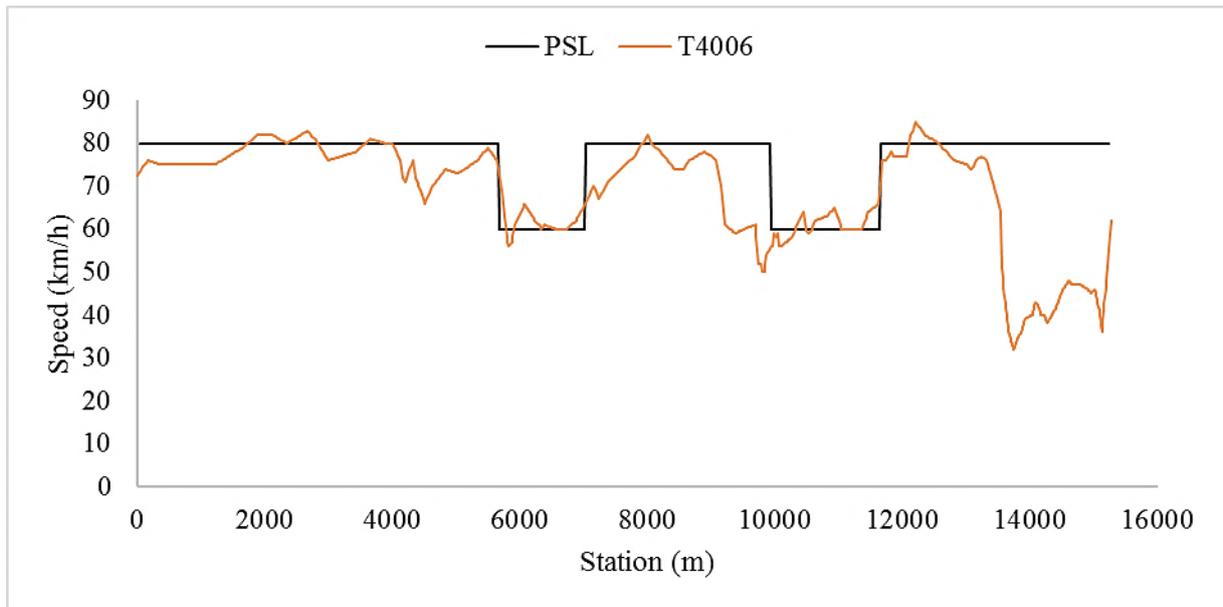
Figure 3.12: Trip data pulling down the average speed from station 13000m.

Deleting the affected speeds increased the average speed and reduced the variance and standard deviation of the measured speed dataset, as shown in table 3.2. Compared to the original mean speed profile, the sudden changes and irregularities was removed from the manipulated speed profile as seen from figure 3.13. This profile was more convenient for use within this study aiming to compare predicted free flow speed profiles to measured free flow speed profiles.

Table 3.2: Relevant measures for the original and manipulated speed dataset

	Original mean of measured speed	Manipulated mean of measured speed
Number of speed points in the mean speed profile along the case section	609	609
Average speed along case section	70,50 km/h	71,33 km/h
Variance of measured speed data, S^2	75,82 km/h^2	70,05 km/h^2
Standard deviation of measured speed data, S	8,71 km/h	8,37 km/h
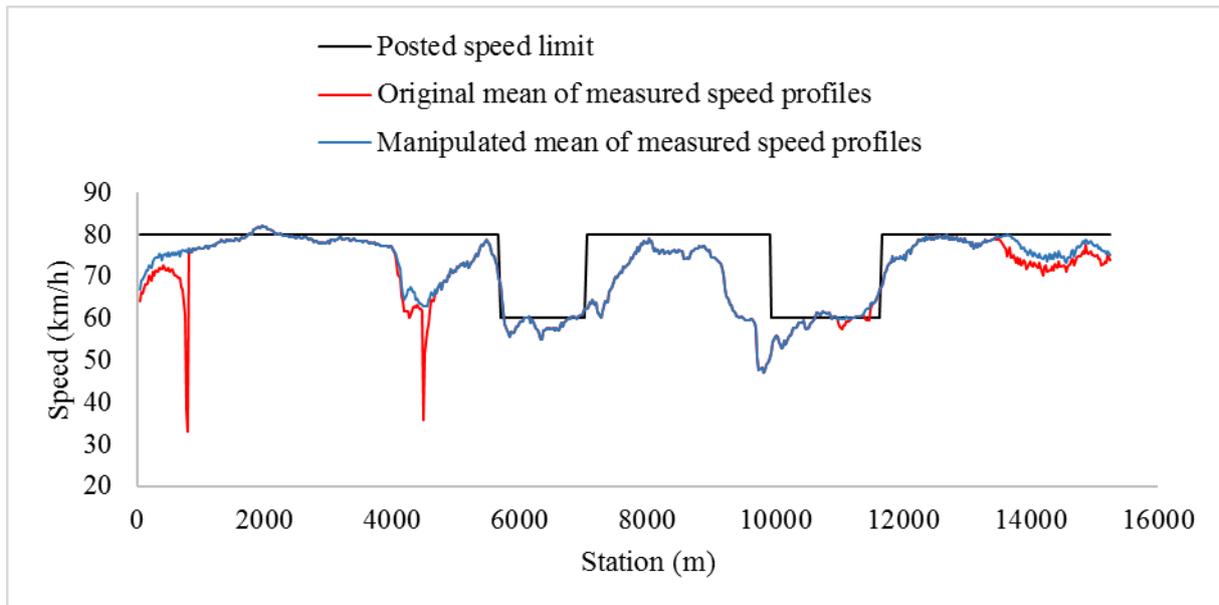
Figure 3.13: Original and manipulated mean of measured speed profile along E39: Skjennstøbekken – Stokkelva.

3.4 Use of the EFFEKT speed model

The EFFEKT speed model is developed from multiple regression analysis of recorded average section speeds along selected roads from counties of Norway in the time period 1993 – 1994. The road sections used, had a length of 3 – 5 km and homogeneous geometric standard and traffic volumes (15, 32).

The EFFEKT speed model is divided into five main sections:

1. Calculation of base speed (free flow speed)
2. Correction for traffic volumes and variations
3. Setting a constant speed for each road link
4. Calculation of delay in intersections
5. Setting a delay for each link

The thesis work has only considered free flow speed from the EFFEKT model, thus only the first main section has been used. This part of the model procedure is described within this section and translated into a MATLAB script for further use. The script, able to predict speed profiles, can be seen in Appendix 4. The remaining four model sections are described in detail within the NPRA report no 358 (15). The current base speed model was introduced to the fifth version of EFFEKT, and is mainly developed for speed calculation in rural areas. Free flow speed can be calculated after the EFFEKT procedure for the following situations:

31

- Speed limit 80 km/h or lower and one lane road
- Speed limit 80 km/h or lower and two – lane road
- Speed limit 80 km/h or lower and four- or six – lane road
- Speed limit 90 km/h and two – lane road
- Speed limit 90 km/h and four- or six – lane road
- Speed limit 100 km/h and four- or six – lane road
- Speed limit 110 km/h and four- or six – lane road

The EFFEKT procedure, divides a road link into sub sections after the criteria below illustrated by figure 3.14. Speed is then calculated for each sub section along the road link using the equations presented within this section.
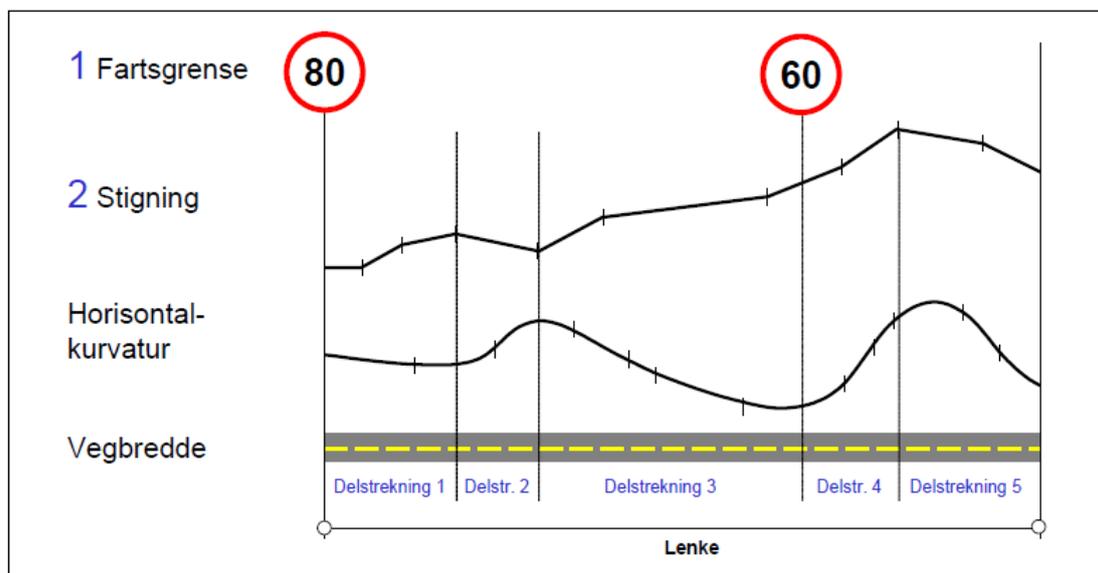
Figure 3.14: Subdivision of road links after the EFFEKT procedure(15).

Criterion 1, Speed limit: If the speed limit varies within a road link, the road is divided into sub sections that all have the same speed limit.

Criterion 2, Slope: New sub sections are established between the lowest and the highest point (or opposite) along sub sections that have the same speed limit.

Input parameters

The EFFEKT speed model made use of the following geometric properties along the road stored in the geometric database in MATLAB.

32

Speed limit

In addition to be the first criterion for subdivision of road links, speed limit (km/h) along a subsection is an important variable when deciding which equations to use for calculation of final speed at a subsection.

Number of lanes

Number of lanes is an important variable, together with speed limit, when deciding which equations to use for calculation of final speed.

Road width

The model takes in road width (m) and recalculate it to pavement width using equation 3.1.

$$B_d = \frac{(B_v + 0,18)}{1,1}$$
Equation 3.1

B_d = Recalculated pavement width along sub section, asphalt shoulders included

B_v = Average road width from shoulder edge to shoulder edge along a sub section

Vertical slope and single slope length

The slope S (%) along a road link is used as the second criterion for dividing it into sub sections and enters again when speed is corrected for grade through the grade factor SF. Since the road is represented by points in this thesis work, a single slope is defined as the slope at the last of two following points. The slope length L_i is further referred to as the distance between the two following geometric points.

Horizontal curve radius and single curve length

The curve radius R (m) enters the procedure when speed is corrected for horizontal curvature through HKF. Since the road is represented by points in this thesis work, a single curve radius is defined as the radius at the last of two following points. The curve length L_i is further referred to as the distance between the two following geometric points.

Correction factors and speed equations

Equation 3.2 – equation 3.14 which gives correction for horizontal and vertical geometry and calculated speed for light vehicles are listed below. Similar equations regarding heavy vehicles are excluded in this thesis work due to study limitations, but can be found in the NPRA report no 358 (15).

Horizontal curve factor (HKF)

Vehicle speed is corrected for limitations from the horizontal curvature introducing a calculated horizontal curve factor (HKF). The equations used to calculate the horizontal curve factor, is chosen based on current speed limit and size of the radius, R (m), at each single point along the sub section. A sub section usually consists of several single curves, and the values of R (m) may change for the points within a subsection. The horizontal curve factor HKF_i is further calculated for each single point (i) along a sub section and weighted by its length L_i, resulting in a total HKF factor for each sub section as shown in equation 4.4. No corrections are done along roads with speed limit 100 km/h or 110 km/h where the road standard is assumed to be high and uniform.

Speed limit 80 km/h or lower:

R < 380 m	$HKF = 1{,}245 - 3{,}945 \cdot R^{-0,468}$
R ≥ 380 m	$HKF = 1$

Equation 3.2

Speed limit 90 km/h:

R < 200 m	$HKF = 0{,}841$
200 m ≤ R < 450 m	$HKF = 0{,}7143 + 0{,}000635 \cdot R$
R ≥ 450 m	$HKF = 1$

Equation 3.3

If a sub section along a road link consists of n points with a radius and a corresponding length L_i within the sub section, the correction factors for each point (HKF_i) are combined to a correction factor for the sub section (HKF_{sub}) through equation 3.4. HKF_{sub} should be used further when speed is calculated for each sub section.

$$HKF_{sub} = \frac{\sum_{i=1}^{n} L_i \cdot HKF_i}{L_{sub}}$$

Equation 3.4

Slope factor (SF)

The variation in slope within each sub section is taken into account when calculating speed, introducing a calculated slope factor SF. The equations used to calculate the slope factor, is chosen based on speed limit and the value of single slope S (%), at each point along a sub section. A sub section usually consists of several single slopes and the values of S (%) may change for the points within a subsection. The grade factor SF_i is further calculated for each single point (i) along a sub section and weighted by its length L_i, resulting in a total SF factor for each sub section as shown in equation 3.7. No corrections for slope are done along sub sections with speed limit 100 km/h or 110 km/h where the standard is assumed to be high and uniform.

Speed limit 80 km/h and lower:

$S \geq 3\%$	$SF = 1{,}086 - 0{,}029 \cdot S$	
		Equation 3.5
$S < 3\%$	$SF = 1$	

Speed limit 90 km/h:

$S \geq 2\%$	$SF = 1{,}0773 - 0{,}0386 \cdot S$	
		Equation 3.6
$S < 2\%$	$SF = 1$	

If a sub section along a road link consists of n points with a slope S_i and a corresponding length L_i within the sub section, the correction factors for each point (SF_i) are combined to a correction factor for the sub section (SF_{sub}) through equation 3.7. SF_{sub} should be used further when speed is calculated for each sub section.

$$ SF_{sub} = \frac{\sum_{i=1}^{n} L_i \cdot SF_i}{L_{sub}} \qquad \text{Equation 3.7} $$

The EFFEKT speed model does not correct speed for downhill driving and negative slope. In such situations, the SF = 1. The cooperative effect of both horizontal curvature and grade are taken into account by a comparison of the horizontal curve factor (HKF) and the slope factor (SF) for each sub section. If $HKF_{sub} < SF_{sub}$, the SF = 1, which means that no correction for slope should be done at the section.

Speed calculation

Speed limit 80 km/h or lower and one lane road:

$$V = SF \cdot (196,8 \cdot HKF + 11,5 \cdot B_d - 190,9) \qquad \text{Equation 3.8}$$

Speed limit 80 km/h or lower and two – lane road:

$$V = 143,1 \cdot HKF + 80,4 \cdot SF + 1,75 \cdot B_d - 155,6 \qquad \text{Equation 3.9}$$

Speed limit 80 km/h or lower and four- or six – lane road:

$$V = 87,3 \cdot HKF \cdot SF \qquad \text{Equation 3.10}$$

Speed limit 90 km/h and two – lane road:

$$V = 91,9 \cdot HKF \cdot SF \qquad \text{Equation 3.11}$$

Speed limit 90 km/h and four- or six – lane road:

$$V = 96,2 \cdot HKF \cdot SF \qquad \text{Equation 3.12}$$

Speed limit 100 km/h and four- or six – lane road:

$$V = 103,1 \text{ km/h} \qquad \text{Equation 3.13}$$

Speed limit 110 km/y and four- or six – lane road:

$$V = 107,2 \text{ km/h} \qquad \text{Equation 3.14}$$

The calculated speed will further be reduced by 4%, if the road is a gravel road. It is also compared to fixed maximum values of speed in table 3.3. The calculated speed is corrected to the corresponding tabled value if the speed limit along the road is 70 km/h or lower and calculated speed is greater than the tabled value.

Table 3.3: Maximum base speed corrections if speed limit <= 70 km/h

Speed limit (km/h)	Speed model situation		
	Narrow roads	Two – lane roads	Multilane roads
110	As calculated	As calculated	As calculated
100	As calculated	As calculated	As calculated
90	As calculated	As calculated	As calculated
80	As calculated	As calculated	As calculated
70	59	68,7	71,4
60	54	62,1	66,6
50	45	51,0	54,0
40	40	40	Not realistic
30	30	30	Not realistic

3.5 Use of the SINTEF speed model

The SINTEF speed model is a regression model generated from speeds collected by GPS units within an Intelligent Speed Adaption (ISA) system installed in NPRA service vehicles, as described earlier. The development of the speed model is described in an extract from the unpublished report describing the SINTEF project 102007265-4 (16). The model procedure described within this section is translated into a MATLAB script and seen in Appendix 5.

Given geometric input format, the model can calculate speed at road points or links. In this study, speed profiles were produced based on a road represented by geometric points as described within chapter 3.2.

Input parameters

The SINTEF speed model uses the following input parameters along the road, which are stored in the geometric database in MATLAB.

Speed limit

Speed limit (km/h) along the road is an important variable when deciding which equations to use for calculation of final speed.

Number of lanes

Number of lanes along the road is an important variable when deciding which equations to use for calculation of final speed.

Road width (x_d)

The variable describes the width of the road from left edge of paved shoulder to right edge of paved shoulder. The road width is given in meters (m).

Positive slope (x_s) and negative slope (x_f)

Slope is introduced to the model as *relative slope*, calculated as a floating average related to a length of 25 m. Relative slope is further divided into positive slope (x_s) and negative slope (x_f), but the absolute value is used for both variables. Since positive and negative slope never occur at the same time, the slope variable that is not in use at a specific point along the road is set to zero. The coefficients of the model ensure the effect of negative slope on the speed.

Curvature (x_k)

The variable describes curvature (m^{-1}) for each point along the road and is calculated as $1/R(m)$ based on horizontal radius.

Equations and coefficients

The following equation 3.15 describes the speed model equation that can be adapted for the three different situations listed below and defined by specific linear regression functions $U(x_d, x_s, x_f, x_k)$. The coefficient $C(x_g)$ defines an estimated reference speed for each situation. Within this study, the traffic corrected coefficient $C_k(x_g)$ is used to ensure calculations of average free flow speed.

1. Two lane road and speed limit 70, 80 or 90 km/h
2. Two lane road and speed limit 50 or 60 km/h
3. Four lane road and speed limit 70, 80, 90 or 100 km/h

$$\text{Speed} = C(x_g) \cdot e^{U(x_d, x_s, x_f, x_k)}$$

Equation 3.15

Two-lane rural road and speed limit 70, 80 or 90 km/h

The linear $U(x_d, x_s, x_f, x_k)$ function is calculated from equation 3.16. The estimated coefficients that are to be used are listed in table 3.4.

$$U(x_d, x_s, x_f, x_k) \begin{aligned} &= \beta_d(x_d - 8{,}0) \\ &+ \beta_s x_s + \beta_f x_f \\ &+ \beta_k x_k + \beta_{sk} x_s x_k \\ &+ \beta_{fk} x_f x_k + \beta_{kk} x_k^2 \end{aligned}$$

Equation 3.16

Table 3.4: Coefficients of the SINTEF speed model.

Parameter	$\widehat{C}(70)$	$\widehat{C}(80)$	$\widehat{C}(90)$	$\widehat{C}_k(70)$	$\widehat{C}_k(80)$	$\widehat{C}_k(90)$
Estimate	63,9	77	85,8	71	82	90
Parameter	$\widehat{\beta}_d$	$\widehat{\beta}_s$	$\widehat{\beta}_f$	$\widehat{\beta}_k$	$\widehat{\beta}_{kk}$	
Estimate	0,0182	-0,0296	-0,0214	-2,383	-485,3	
Parameter	$\widehat{\beta}_{sk}$	$\widehat{\beta}_{fk}$				
Estimate	-3,825	-3,517				

Tow-lane road and speed limit 50 or 60 km/h

The linear $U(x_d, x_s, x_f, x_k)$ function is calculated from equation 3.17. The estimated coefficients that are to be used are listed in table 3.5.

$$U(x_d, x_s, x_f, x_k) \quad \begin{aligned} &= \beta_s x_s + \beta_f x_f \\ &+ \beta_k x_k + \beta_{sk} x_s x_k \\ &+ \beta_{fk} x_f x_k + \beta_{kk} x_k^2 \end{aligned} \qquad \text{Equation 3.17}$$

Table 3.5: Coefficients of the SINTEF speed model.

Parameter	$\widehat{C}(50)$	$\widehat{C}(60)$	$\widehat{C}_k(50)$	$\widehat{C}_k(60)$
Estimate	51,8	60,6	52	61
Parameter	$\hat{\beta}_s$	$\hat{\beta}_f$	$\hat{\beta}_k$	$\hat{\beta}_{kk}$
Estimate	-0,071	-0,0153	-1,983	-334,9

Four-lane road and speed limit 70, 80, 90 or 100 km/h

The linear $U(x_d, x_s, x_f, x_k)$ function is calculated from equation 3.18. The estimated coefficients that are to be used are listed in table 3.6.

$$U(x_d, x_s, x_f, x_k) \quad = \beta_d(x_d - 19) + \beta_s x_s + \beta_f x_f \qquad \text{Equation 3.18}$$

Table 3.6: Coefficients of the SINTEF speed model.

Parameter	$\widehat{C}(70)$	$\widehat{C}(80)$	$\widehat{C}(90)$	$\widehat{C}(100)$
Estimate	74,8	76,5	92	99,6
Parameter	$\widehat{C}_k(70)$	$\widehat{C}_k(80)$	$\widehat{C}_k(90)$	$\widehat{C}_k(100)$
Estimate	76	85	96	103
Parameter	$\hat{\beta}_d$	$\hat{\beta}_s$	$\hat{\beta}_f$	
Estimate	0,0076	-0,0111	-0,0368	

3.6 Use of the driver behavior module

The predicted speed profiles delivered by both speed models can be considered as speed profiles allowed by the model procedure at each point for the given input geometry. To improve the speed profiles appearance at transitions characterized by a change in any geometric parameter of the complex road alignment, the speed profiles are processed by a driver behavior module.

The driver behavior module, seen in Appendix 6, evaluates the necessary acceleration or deceleration along the predicted speed profile to achieve speed changes between two points within a certain distance. This distance is decided by the given visible range. If the necessary acceleration or deceleration needed to achieve the speed change between P_i and $P_{i+visiblerange}$ exceeds the maximum value of allowed vehicle acceleration given to the script, the necessary acceleration value will be replaced by the maximum allowed acceleration value. New corresponding speeds for the corrected acceleration values is calculated using a polynomial function. In this way, the speed profiles get a smoother appearance and is more comparable to actual speed profiles from the field.

Input parameters

Vehicle speed

The predicted speed profile from both the EFFEKT speed model and the SINTEF speed model, is given in to the driver behavior module as a vector expressed in km/h.

Station along the road

The station (m) is a corresponding vector to the predicted speed profile expressing the metering of the speed points along the road section.

Maximum vehicle acceleration

This value can be considered as the maximum acceleration value allowed by the script between changes along road elements, or points along the predicted speed profile. While the changes in speed and acceleration occur due to changes within all geometric planes as mentioned in chapter 2, few studies reported are considering driver behavior along complex road alignments. Requirements from design guidelines were also only related to changes in either the horizontal alignment or the vertical alignment.

Italian road design guidelines (33) use a maximum value of 0,8 m/s^2 for acceleration and deceleration between horizontal elements along the road. A corresponding constant value

representing Norway, was not found in Norwegian design guidelines since acceleration is not considered when determining minimum horizontal curvature as seen from equation 2.1. The NPRA Handbook V120 (21) further sets requirements to vertical acceleration related to driving comfort. For design of new main roads and collector/access roads this should not exceed 0,3 m/s^2 or 0,5 m/s^2.

Taken the information above into account, the maximum acceleration value for changes within any plane of the complex road alignment of the case section was assumed to be 0,5 m/s^2 and used further in the driver behavior module.

Visible range

This parameter is an expression for the distance (m) between P_i and $P_{i+visiblerange}$, taken into account when evaluating if the acceleration is to be corrected or not. Setting a visible range of 200 m, as in this study, means that the necessary acceleration from a point P_i is evaluated in terms of achieving the predicted speed at a point 200 m in front of it. Previous points and conditions is not considered when acceleration is evaluated at point (i), only what is in front of the point.

Polynomial function grade

The grade of the function used to calculate new speeds for the corrected acceleration, enters the script as a constant. This can be linear (1), second degree polynomial (2) or third degree polynomial (3). Within this study, the grade is assumed to be one and a linear function only is used.

4 Suggestions for further work

4.1 Possible research objectives

Prediction of speed and energy demand for heavy vehicles

Within the study reported, the speed models were used to evaluate speed for passenger cars. Both speed models will in the future have equations describing heavy vehicles. A similar study to evaluate the speed prediction regarding heavy vehicle can be done.

Estimation of acceleration and deceleration rates

Use of the driver behavior module within this study was limited to assumptions regarding visible range and maximum allowed vehicle acceleration. This require more research and adaption to Norwegian conditions. The two established databases of road geometry and measured speeds along E39: Orkanger – Vinjeøra and E39: Skjennstøbekken – Stokkelva can act as basis for estimation of acceleration and deceleration rates for complex road alignments in rural areas. If these rates later are included in the driver behavior script, the reported results can get further improved.

4.2 Use of the speed prediction models to evaluate design consistency

Correspondence with employees in the NPRA revealed that a future road design is regulated for parts of the case section, the E39: Klettelva - Hestnes. Digital drawings of this future road alignment for the two subsections E39: Klettelva – Otneselva and E39: Otneselva – Hestnes, were kindly provided for use within this study.

By using AutoCAD, the centerlines of the future road alignment were joined together with their original coordinates to one .dwg file. Along this line, points were laid off with 10 m distance using the draw function *Points - measure*. The points with their longitudinal and latitudinal coordinates in addition to the information about profile elevation every 10th meter along the road, was extracted from AutoCAD to Excel files using the command *Data Extraction Wizard*. Information on curvature was read manually from the drawings and combined in Excel with the extracted elevation data and the given information from NPRA regarding changes in speed limit and road width along the future alignment.
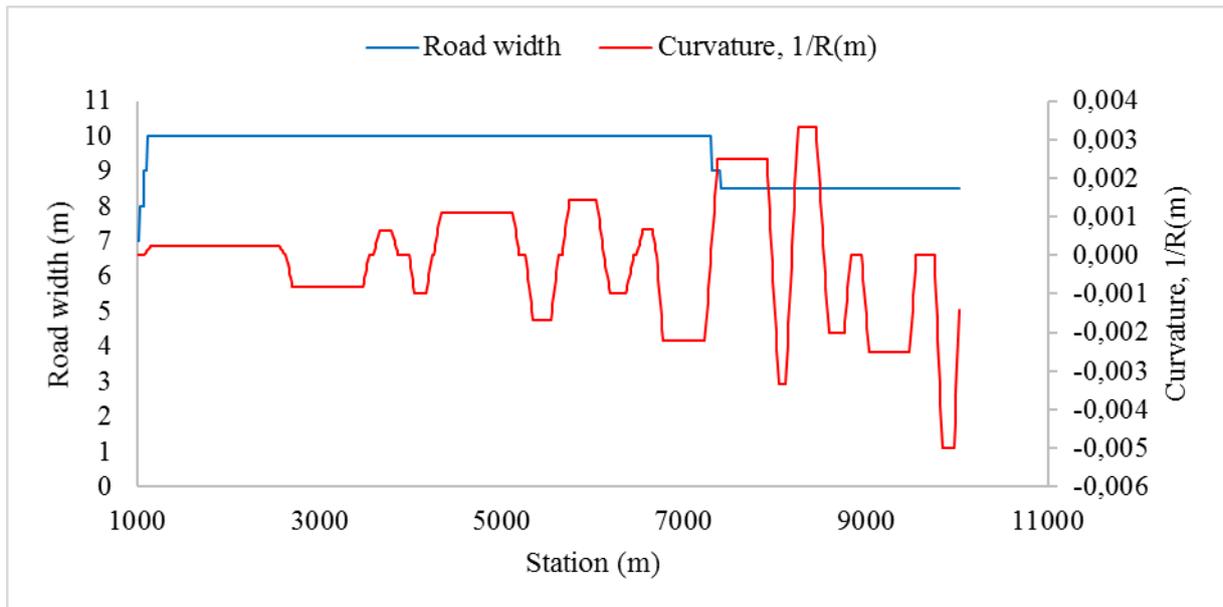
Figure 4.1: Road width and curvature along the future road alignment of E39: Klettelva – Hestnes.
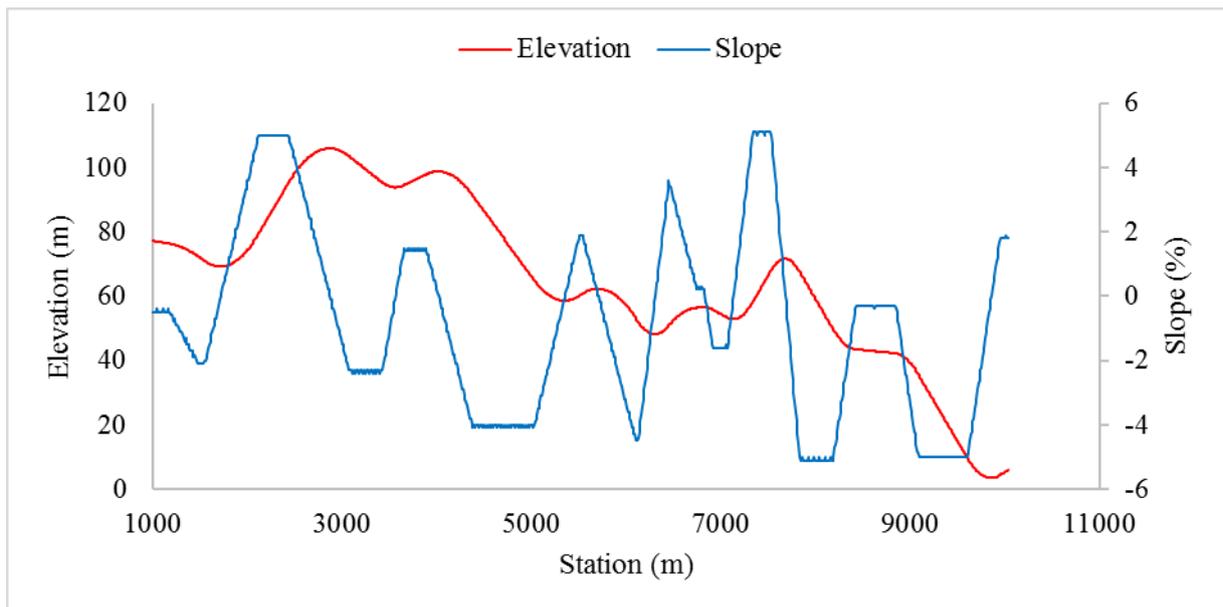
Figure 4.2: Road elevation and slope along the future road alignment of E39: Klettelva – Hestnes.

Data columns describing road elevation (m), calculated slope (%), calculated curvature (m^{-1}), number of lanes, posted speed limit and road width (m) was imported to MATLAB as CSV files and further structed as a database describing the future road alignment. Figure 4.1 show the road width and curvature, and figure 4.2 show the road elevation and slope.

With the future geometry as basis, speed can be predicted as seen in figure 4.3, where the SINTE procedure is used. Such speed profiles can be used to determine if undesirable speed changes occur between geometric features within the future road alignment, and if the overall speed for the road section is in agreement with the roadways intended function.
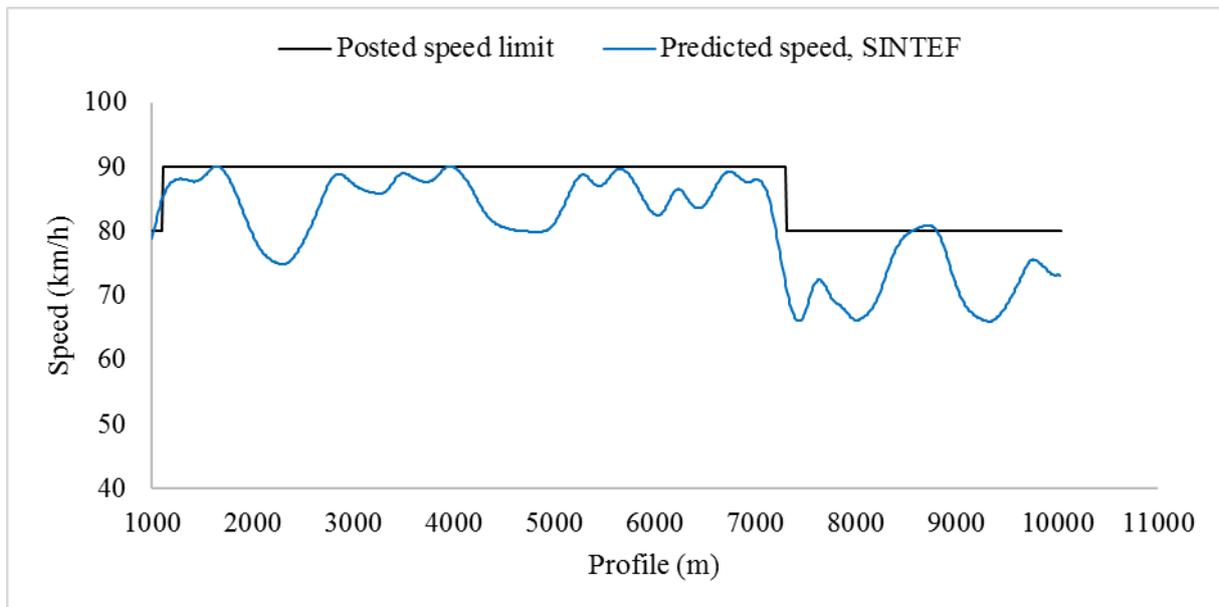
Figure 4.3: Speed profile along the future road alignment, predicted by the SINTEF speed model.

4.3 Use of the speed models to evaluate energy demand

The predicted and smoothed vehicle speed profile, is a good basis for prediction of energy demand along a road section. The first version of the NTNU Energy Module script used to illustrate the use range, calculates vehicle resistances and required energy demand in Joule per kilometer (Joule/km) along the road.

Input parameters

Speed

The speed profiles are taken in as vectors containing speed data in km/h along the road. This is converted to m/s for use within the module.

Station along the road

The station (m) is a corresponding vector to the speed data vector expressing the metering along the road section.

Slope

The slope (%) of the analyzed road is taken in as a vector for use within the module.

Curvature

The curvature, $1/R$ (m^{-1}) of the analyzed road is taken in as a vector and converted to radius (m) for use within the module.

Vehicle mass

If a vehicle mass is not given in as a value to the module, 1600 kg will be used by default.

Frontal area

The frontal area is equal to the cross-section area in front of the vehicle defined by the vehicle height and vehicle width. If a frontal area is not given as a value to the module, 0,6 m^2 will be used by default.

Equations and coefficients

Rolling resistance

Necessary force to overcome rolling resistance R_{roll} (N), is evaluated for each point based on a calculated rolling resistance coefficient rr (N/KN).

$$R_{roll} = rr \cdot \frac{\text{Vehicle mass}}{9806,65}$$ Equation 4.1

$$rr = 15 + 0,00003 \cdot (sp - 50)^3$$ Equation 4.2

sp = Average speed between two specific points of the path

Inertial resistance

Necessary inertial forces R_{in} (N) to overcome the gravitational acceleration and start a movement is calculated at each point along the path is.

$$R_{in} = abs(acc) \cdot \frac{\text{Vehicle mass}}{g}$$ Equation 4.3

g = 9,80665 m/s^2

abs(acc) = Absolute value of acceleration between two specific points of the path.

Air resistance

Necessary force to overcome air resistance R_{air} (N) is calculated based on frontal area of the vehicle, air density *rho* set to 1,227 kg/m^3 and an average value of aerodynamic drag coefficient for passenger cars *cd* set to 0,4.

$$R_{air} = \frac{1}{2} \cdot rho \cdot cd \cdot Frontal\ area \cdot sp^2 \qquad \text{Equation 4.4}$$

sp $\quad=\quad$ average speed between two specific points on the path.

Grade resistance

Necessary force to overcome the positive grade or force given by the negative grade along the road R_{grade} (N), is calculated based on the slope at each point.

$$R_{grade} = Vehicle\ mass \cdot \frac{slope(i)}{100 \cdot g} \qquad \text{Equation 4.5}$$

Slope(i) $\;=\;$ Slope at a specific point i on the path.

Horizontal curve resistance

Necessary force to overcome the curve resistance R_{curve} (N) along the road is calculated based on the radius at each point.

$$R_{curve} = \frac{0{,}77 \cdot sp^2 \cdot Vehicle\ mass}{2 \cdot g \cdot Radius(i)} \cdot g \qquad \text{Equation 4.6}$$

Radius(i) $\;=\;$ Radius at a specific point i on the path.

Total resistances and energy

The total resistance R_{tot} is the sum of all resistances calculated above. Energy is calculated as job (Joule).

$$R_{tot} = R_{roll} + R_{in} + R_{air} + R_{grade} + R_{curve} \qquad \text{Equation 4.7}$$

$$Energy = R_{tot} \cdot D \qquad \text{Equation 4.8}$$

D $\qquad=\quad$ Distance between two specific points on the path, calculated based on the station.

Predicted energy profiles along E39: Skjennstøbekken - Stokkelva

As an example of use, figure 4.4 shows predicted energy profiles along the case section of the thesis, based on speed predicted by the EFFEKT speed model and the SINTEF speed model. The accumulated energy demand can be determined from predicted energy profiles by the NTNU Energy Module, and be used as an evaluation criterion when considering environmental impacts in the design stage of the road planning. When comparing possible road alignments relative to each other, the tool can be used to optimize the geometry to achieve a less energy demanding road. An easy link between the NTNU Energy Module and the design tool Nova Point/AutoCAD could therefore be of great interest.

The accumulated energy demand can also be linked to possible energy sources, and distributions of the Norwegian vehicle assembly, to evaluate the emissions from road traffic.
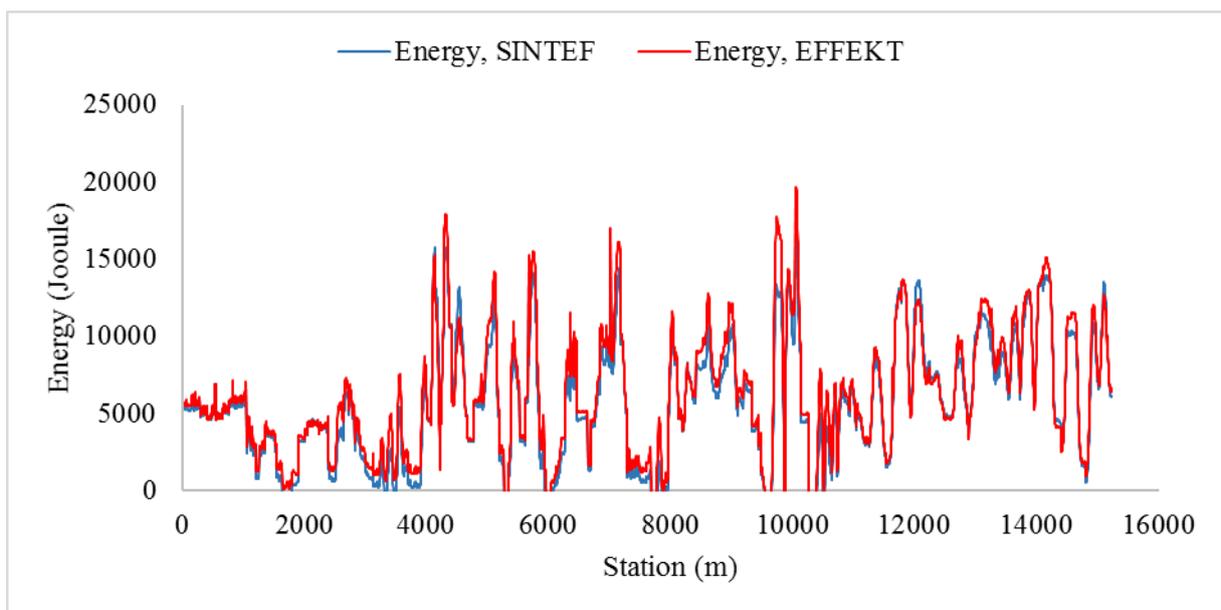
Figure 4.4: Predicted energy profiles based on predicted speed from both the EFFEKT and the SINTEF speed model.

The energy profiles and the accumulated energy demand can also be used to evaluate where electric charging stations should be placed along a road route, and improve the planning process of road networks that aims to serve electrical vehicles. These are expensive installations and their density should also be optimized.

Dependent on the purpose of a trip, energy profiles could also be interesting knowledge in addition to travel time for a vehicle driver. By making the information regarding energy demand available and understandable, the environmental impacts could easily be evaluated by vehicle drivers when making a decision related to route choices. This can give the environmental conscious driver greater opportunity to choose the least energy demanding route from A to B.

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APPENDIX

MASTER DEGREE THESIS
(TBA4940 Veg)

Spring 2017
for
Maren Bysveen

Vehicle speed prediction models for consideration of energy demand within road design

BACKGROUND

The energy consumption within the transport sector was responsible for 23% of the word's total CO_2 emissions in 2014, and road traffic was found to be the largest contributor both in Norway and Europe. Improvements require a reduction of demand of energy consumption within the transport sector, and a necessity to be able to quantify and evaluate environmental impacts from new and existing road alignments in a realistic and accurate way. The main motivation of this master thesis is to contribute to the development process of an innovative calculation module used to predict vehicle energy demand (Joule/km) along a road section. This is done through an evaluation of the performance of two Norwegian speed prediction models for light vehicles, developed by SINTEF Technology and Society. Both are considered as possible alternatives to be integrated in the future energy module.

TASK

The study aims to compare the traditional regression speed model EFFEKT, developed from average section speeds, to the SINTEF speed model, expressed as an exponential function developed from the average of continuous speed profiles collected with GPS technology. The predicted speed profiles from both speed models are evaluated through linear regression related to the average of measured speeds along one direction of a two – lane rural case road section in Norway. This to answer the following research question:

"How does predicted vehicle speed from the EFFEKT speed model and the SINTEF speed model correlate with measured speed data from the field?"

General about content, work and presentation
The text for the master thesis is meant as a framework for the work of the candidate.
Adjustments might be done as the work progresses. Tentative changes must be done in
cooperation and agreement with the professor in charge at the Department.

In the evaluation thoroughness in the work will be emphasized, as will be documentation
of independence in assessments and conclusions. Furthermore, the presentation (report)
should be well organized and edited; providing clear, precise and orderly descriptions
without being unnecessary voluminous.

The report shall include:
➢ Standard report front page (from DAIM, http://daim.idi.ntnu.no/)
➢ Title page with abstract and keywords. (template on: wiki page for students at CEE
   Departement)
➢ Preface
➢ Summary and acknowledgement. The summary shall include the objectives of the
   work, explain how the work has been conducted, present the main results achieved and
   give the main conclusions of the work.
➢ The main text.
➢ Text of the Thesis (these pages) signed by professor in charge as Attachment 1.

The thesis can as an alternative be made as a scientific article for international publication,
when this is agreed upon by the Professor in charge. Such a report will include the same
points as given above, but where the main text includes both the scientific article and a
process report.

Advice and guidelines for writing of the report is given in "Writing Reports" by Øivind
Arntsen, and in the departments "Råd og retningslinjer for rapportskriving ved prosjekt og
masteroppgave" (In Norwegian) located at wiki page for students at CEE Departement

Submission procedure
Procedures relating to the submission of the thesis are described in DAIM (http://daim.idi.ntnu.no/).
Printing of the thesis is ordered through DAIM directly to Skipnes Printing delivering the
printed paper to the department office 2-4 days later. The department will pay for 3 copies,
of which the institute retains two copies. Additional copies must be paid for by the
candidate/ external partner.

The master thesis will not be registered as delivered until the student has delivered the
submission form (from DAIM) where both the Ark-Bibl in SBI and Public Services
(Building Safety) of SB II has signed the form. The submission form including the
appropriate signatures must be signed by the department office before the form is delivered
Faculty Office.

Documentation collected during the work, with support from the Department, shall be
handed in to the Department together with the report.

O NTNU

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According to the current laws and regulations at NTNU, the report is the property of NTNU. The report and associated results can only be used following approval from NTNU (and external cooperation partner if applicable). The Department has the right to make use of the results from the work as if conducted by a Department employee, as long as other arrangements are not agreed upon beforehand.

Tentative agreement on external supervision, work outside NTNU, economic support etc.
Separate description is to be developed, if and when applicable. See wiki page for students at CEE Departement for agreement forms.

Health, environment and safety (HSE) http://www.ntnu.edu/hse
NTNU emphasizes the safety for the individual employee and student. The individual safety shall be in the forefront and no one shall take unnecessary chances in carrying out the work. In particular, if the student is to participate in field work, visits, field courses, excursions etc. during the Master Thesis work, he/she shall make himself/herself familiar with "Fieldwork HSE Guidelines". NTNU student HSE policy is found here: https://innsida.ntnu.no/hms-for-studenter

If you are doing lab work for your project and master thesis, you have to take an online e-course in lab HSE. To get link, email kontakt@ibm.ntnu.no.

The students do not have a full insurance coverage as a student at NTNU. If you as a student want the same insurance coverage as the employees at the university, you must take out individual travel and personal injury insurance.

Startup and submission deadlines
Startup and submission deadlines are according to information found in DAIM.

Professor in charge: Kelly Pitera

Other supervisors: Giuseppe Marinelli

Department of Civil and Transport Engineering, NTNU
Date: 06.06.2017

_____
Professor in charge (signature)

Subtasks of the thesis	Responsibility
Meetings during preparatory work to define details and understanding of the different speed models with: Petter Arnesen, SINTEF Anders Straume, SINTEF Anders Kroksæter, SINTEF	Maren Bysveen
Establish an excel model for the SINTEF speed model	Maren Bysveen
Establish a MATLAB script for the SINTEF speed model	Giuseppe Marinelli
Establish an excel model of the EFFEKT speed model	Maren Bysveen
Establish a MATLAB script for the EFFEKT speed model	Maren Bysveen
Development of the procedure to extract and process geometric data with speed data. This includes production of MATLAB scripts and ArcGIS toolbox that are used for this purpose.	Giuseppe Marinelli
Establishing database for the E39 section Orkanger – Vinjeøra	Giuseppe Marinelli
First time troubleshooting and feedback on the MATLAB codes, ArcGIS tools and the procedure describing how to establish the database provided by Giuseppe Marinelli.	Maren Bysveen
Establishing database for the E39 section Skjennstøbekken – Stokkelva	Maren Bysveen
Establishing a MATLAB script used to smoothen the horizontal curvature	Giuseppe Marinelli
Establishing a MATLAB script for the driver behavior module	Giuseppe Marinelli
Establishing a MATLAB script for the NTNU Energy module	Giuseppe Marinelli
Processing and presentation of data and study results	Maren Bysveen
Writing of the scientific paper	Maren Bysveen
Writing of the process report	Maren Bysveen

Meeting with Petter Arnesen, SINTEF 27.02.17

During the meeting, the established excel model for the SINTEF speed model was discussed, in addition to my interpretation of the SINTEF procedure. Petter answered to questions regarding the procedure, especially related to:

1. The input variable slope: The meeting revealed that the SINTEF speed model takes in slope as percentage. I was further advised to calculate relative slope within 25 m sections or use a floating average
2. The input variable horizontal curvature: Should be included in the speed model as $1/R(m)$.
3. The model coefficient $C(x)$: Traffic corrected coefficient $C_k(x)$ represents speeds in a free flow situation. This is to be used within this study.
4. Speed model appearance: The speed model does not take previous and future geometric properties into account when modeling speed at a certain point, and further have to be smoothened in some way.

Meeting with Anders Straume and Anders Korkseth, SINTEF 09.03.17

During the meeting, the established excel model for the EFFEKT speed model was discussed, in addition to my interpretation of the EFFEKT procedure. Anders and Anders answered to questions regarding the procedure, especially related to:

1. The dividing of the road link into sub sections: Correction factors for curvature and slope and vehicle speed can be predicted for points and the average speed can further be assigned to subsections.

Appendix 4 – The EFFEKT speed model script

<div align="right">Developer: Maren Bysveen</div>

```matlab
function [speedprofile,acc,smat] =
SM_EFFEKT_v5(STATION,PSL,NL,RW,SLOPE,HCURV)
%Calculates speed along sub sections of the road


%% Section 1: preparing input variables
BV = RW;
S = SLOPE;  %Calculated from heights of points before added as an input
for a=1:length(HCURV)
    if isnan(HCURV(a))== 0 && HCURV(a) == 0 % if it is a tangent and not
NaN
        R(a,1) = 1000; % R is very big
    elseif isnan(HCURV(a)) == 0 && HCURV(a) ~= 0 % if curve and not Nan
        R(a,1) = abs(1/HCURV(a));
    else
        R(a,1) =NaN;
    end
end
L = length(PSL);
%% Preparing subsections
%Subdivision of the road links
%Criterion 1 – speed limit
%Criterion 2 – change in slope sign


k=1;
for i = 1:L %from the beginning to the end of the road
    if i==L %if we are at the end of the road, we save the last section
        smat(k,1)=smat(k-1,2); %the starting point of current section is
the final points of previous section
        smat(k,2)=i; %storing position of last points of section
        lengthvect=smat(:,3);
        smat(k,3) = STATION(i)-sum(lengthvect(1:k-1)); %Need to store every
subsection in a matrix to get access to the lengths and dedicate a HKFi and
SFi
        k=k+1;
    elseif PSL(i)~= PSL(i+1) || sign((S(i))*S(i+1))==-1 || NL(i)~= NL(i+1)
%if PSL change or if SLOPE change or if NL change
        if k==1 %if we are at the first section
            smat(k,1)=1; %first section begin with 1st point
            smat(k,2)=i; %storing position of last points of section
            smat(k,3)= STATION(i); %I store the station as it is, since
it's first section
            k=k+1;
        else
            smat(k,1)=smat(k-1,2); %the starting point of current section
is the final points of previous section
            smat(k,2)=i; %storing position of last points of section
            lengthvect=smat(:,3);
            smat(k,3) = STATION(i)-sum(lengthvect(1:k-1)); %Need to store
every subsection in a vector to get access to the lengths and dedicate a
HKFi and SFi
            k=k+1;
        end
    end
end
```

Appendix 4 – The EFFEKT speed model script

```matlab
%% Calculate road width at a subsection and store it in smat column 4
for a=1:length(smat)
    smat(a,4)=(mean(BV(smat(a,1):smat(a,2)))+0.18)/1.1;
end


%% Calculate HKF for each section and store it in smat column 5
for a = 1:length(smat)
    SECT_PSL=PSL(smat(a,1):smat(a,2)); %extracting PSL values for all
points inside the current section
    SECT_ST=STATION(smat(a,1):smat(a,2)); %extracting STATION values for
all points inside the current section
    SECT_R=R(smat(a,1):smat(a,2)); %extracting curvature values for all
points inside the current section
    for c=1:length(SECT_R)
        if isnan(SECT_R(c))==1
            SECT_ST(c,2)=0;
        else
            if c==1
                SECT_ST(c,2)=0;
            else
                SECT_ST(c,2)=SECT_ST(c,1)-SECT_ST(c-1,1);
            end
        end
    end
    for b = 2:length(SECT_R)
        if SECT_PSL(b) <= 80 && SECT_R(b) < 380 && isnan(SECT_R(b))==0
            HKF(b,1)=1.245-(3.945*(SECT_R(b).^-0.468));
        elseif SECT_PSL(b) <= 80 && SECT_R(b) >= 380 && isnan(SECT_R(b))==0
            HKF(b,1)=1;
        elseif SECT_PSL(b) == 90 && SECT_R(b) < 200 && isnan(SECT_R(b))==0
            HKF(b,1)=0.841;
        elseif SECT_PSL(b) == 90 && SECT_R(b) >= 450 && isnan(SECT_R(b))==0
            HKF(b,1) = 1;
        elseif SECT_PSL(b) == 100 || SECT_PSL(b) == 110 &&
isnan(SECT_R(b))==0
            HKF(b,1) = 1;
        elseif isnan(SECT_R(b))==1
            HKF(b,1) = 0;
        else
            HKF(b,1)=0.7143 + (0.000635*SECT_R(b));
        end
        HKF(b,2)=SECT_ST(b)-SECT_ST(b-1); %storing length for each point
inside the section
    end
    smat(a,5)=dot(HKF(:,1),HKF(:,2))/sum(SECT_ST(:,2)); %evaluating HKF for
the whole section
    clear HKF
end


%% Calculate SF for each section and store it in smat column 6
for a = 1:length(smat)
    SECT_S=S(smat(a,1):smat(a,2)); %extracting slope values for all points
inside the current section
    SECT_PSL=PSL(smat(a,1):smat(a,2)); %extracting PSL values for all
points inside the current section
    SECT_ST=STATION(smat(a,1):smat(a,2)); %extracting STATION values for
all points inside the current section
    for b = 2:length(SECT_S)
        if SECT_PSL(b) <= 80 && SECT_S(b) >= 3 && isnan(SECT_S(b))==0
            SF(b,1)=1.086-(0.029*SECT_S(b));
        elseif SECT_PSL(b) <= 80 && SECT_S(b) < 3 && isnan(SECT_S(b))==0
```

```matlab
        SF(b,1)=1;
        elseif SECT_PSL(b) == 90 && SECT_S(b) >= 2 && isnan(SECT_S(b))==0
            SF(b,1)=1.0773-(0.0386*SECT_S(b));
        elseif SECT_PSL(b) == 90 && SECT_S(b) < 2 && isnan(SECT_S(b))==0
            SF(b,1) = 1;
        elseif SECT_PSL(b) == 100 || SECT_PSL(b) == 110 &&
isnan(SECT_S(b))==0
            SF(b,1) = 1;
        elseif isnan(SECT_S(b))==1
            SF(b,1) = 0;
        end
        SF(b,2)=SECT_ST(b)-SECT_ST(b-1); %storing length for each point
inside the section
    end
    smat(a,6)=dot(SF(:,1),SF(:,2))/smat(a,3); %evaluating SF for the whole
section
    if smat(a,6) > smat(a,5) %Correcting SF to 1 if SF>HKF at a subsection
        smat(a,6) = 1;
    end
    clear SF
end


%% Calculate speed for each section, correct for maximum speed values and
store it in smat column 7
for a = 1:length(smat)
    SECT_NL=NL(smat(a,1)+1); %extracting lane values for all points inside
the current section
    SECT_PSL=PSL(smat(a,1)+1); %extracting PSL values for all points inside
the current section
    if SECT_PSL<= 80 && SECT_NL== 1
        speed = smat(a,6)*((196.8*smat(a,5))+(11.5*smat(a,4))-109.9);
        if SECT_PSL == 80 %correct speed value if greater then the
following
            smat(a,7) = speed;
        elseif SECT_PSL == 70 && speed >= 59
            smat(a,7) = 59;
        elseif SECT_PSL == 60 && speed >= 54
            smat(a,7) = 54;
        elseif SECT_PSL == 50 && speed >= 45
            smat(a,7) = 45;
        elseif SECT_PSL == 40 && speed >= 40
            smat(a,7) = 40;
        elseif SECT_PSL == 30 && speed >= 30
            smat(a,7) = 30;
        else
            smat(a,7) = speed;
        end
    elseif SECT_PSL <= 80 && SECT_NL == 2
        speed = (143.1*smat(a,5))+(80.4*smat(a,6))+(1.75*smat(a,4))-155.6;
        if SECT_PSL == 80 %correct speed value if greater then the
following
            smat(a,7) = speed;
        elseif SECT_PSL == 70 && speed >= 68.7
            smat(a,7) = 68.7;
        elseif SECT_PSL == 60 && speed >= 62.1
            smat(a,7) = 62.1;
        elseif SECT_PSL == 50 && speed >= 51.0
            smat(a,7) = 51.0;
        elseif SECT_PSL == 40 && speed >= 40
            smat(a,7) = 40;
        elseif SECT_PSL == 30 && speed >= 30
```

```matlab
            smat(a,7) = 30;
        else
            smat(a,7) = speed;
        end
    elseif SECT_PSL <= 80 && SECT_NL == 4 || SECT_NL == 6
        speed = 87.3*smat(a,5)*smat(a,6);
        if SECT_PSL == 80 %correct speed value if greater then the
following
            smat(a,7) = speed;
        elseif SECT_PSL == 70 && speed >= 71.4
            smat(a,7) = 71.4;
        elseif SECT_PSL == 60 && speed >= 66.6
            smat(a,7) = 66.6;
        elseif SECT_PSL == 50 && speed >= 54.0
            smat(a,7) = 54.0;
        end
    elseif SECT_PSL == 90 && SECT_NL == 2
        smat(a,7) = 91.9*smat(a,5)*smat(a,6);
    elseif SECT_PSL == 90 && SECT_NL == 4 || SECT_NL == 6
        smat(a,7) = 96.2*smat(a,5)*smat(a,6);
    elseif SECT_PSL == 100 && SECT_NL == 4 || SECT_NL == 6
        smat(a,7) = 103.7;
    elseif SECT_PSL == 110 && SECT_NL == 4 || SECT_NL == 6
        smat(a,7) = 107.2;
    end
end
smat; %just for check

%% Assign a speed value to every point within a sub section
for a=1:L
    flag=0;
    ST=STATION(a);
    for b=1:length(smat)
        ST1=STATION(smat(b,1));
        ST2=STATION(smat(b,2));
        if ST>ST1 && ST<=ST2
            speedprofile(a,1)=smat(b,7);
            flag=1;
        elseif a==1 && flag==0
            speedprofile(a,1)=smat(b,7);
            flag=1;
        end
    end
end

%% Evaluating acceleration for each point
for i=1:L-1
    acc(i,1)=((speedprofile(i+1)/3.6)^2-
(speedprofile(i)/3.6)^2)/(2*(STATION(i+1)-STATION(i)));
 end
acc(length(acc)+1,1)=acc(length(acc),1);
%% Plot
subplot(2,1,1)
plot(STATION,speedprofile),
subplot(2,1,2)
plot(STATION,acc);
```

Developer: Giuseppe Marinelli

```matlab
function [speedprofile,acc] = SM_sintef_v2 (STATION,PSL,NL,RW,SLOPE,HCURV)
% Calculates speed at points along the road

%% preparing INPUT VECTORS to feed the SM_SINTEF.

xd  = RW; % Road width (paved surface)

% generating the sliding averaged slope requested by SINTEF speed model

fw=25; %setting the width of the sliding average (for SINTEF=25m)

for a=2:length(SLOPE)
    %cycle for covering half fw meters before and after the point (tot fw)
    Pstat=STATION(a); %saving the station of current point
    TEMP_SLOPE=SLOPE(a)*(STATION(a)-STATION(a-1)); %saving the slope at
current point
    i=1;
    flag=1;
    while flag==1
        if a+i<length(SLOPE) %if the points are not finished and
            if abs(STATION(a+i)-Pstat)<(fw/2) %if we are within half fw
forward
                TEMP_SLOPE=TEMP_SLOPE+(SLOPE(a+i)*(STATION(a+i)-
STATION(a+i-1))); %I add the slope weighted with the corresponding length
                i=i+1;
            else
                flag=0; %I stop the while because over half fw
            end
        else
            flag=0; %I stop the while because out of point range
        end
    end
    k=1; %reset counter to 1
    flag=1; %reset the flag to 1
    while flag==1
        if a-k>1 %if we do not hit the begin of the poins list
            if abs(STATION(a-k)-Pstat)<(fw/2) %and if we are within half fw
backward
                TEMP_SLOPE=TEMP_SLOPE+(SLOPE(a-k)*(STATION(a-k)-STATION(a-
k-1))); %I add the slope weighted with the corresponding length
                k=k+1;
            else
                flag=0; %I stop the while because over half fw
            end
        else
            flag=0; %I stop the while because out of point range
        end
    end
    AVG_SLOPE(a,1)=TEMP_SLOPE/(STATION(a+i-1)-STATION((a-k+1))); %getting
the average slope
end
AVG_SLOPE(1,1)=AVG_SLOPE(2,1);

for a=1:length(AVG_SLOPE)
    if AVG_SLOPE(a)>0 %Taking slope with right sign
        xs(a) = abs(AVG_SLOPE(a)); % Taking as uphill in absolute value
```

```matlab
            xf(a) = 0;
        else
            xs(a) = 0;
            xf(a) = abs(AVG_SLOPE(a)); % Taking as downhill in absolute value
        end
end
xs=xs';
xf=xf';
xk  = abs(HCURV); % Taking road curvature in absolute value



%% Applying the SINTEF Speed Model
for a=1:length(PSL)
% equations come from Hjelkrem, 2016 (Internal documentation)
    if NL(a)==2
        if  PSL(a)==50 || PSL(a)==60
            if      PSL(a)==50
                C  = 51.8;
                Ck = 52;
            elseif PSL(a)==60
                C  = 60.6;
                Ck = 61;
            end
            beta_D    =  0;
            beta_S    = -0.0171;
            beta_F    = -0.0153;
            beta_K    = -1.983;
            beta_DS   =  0;
            beta_DF   =  0;
            beta_DK   =  0;
            beta_SK   =  0;
            beta_FK   =  0;
            beta_DSK  =  0;
            beta_DFK  =  0;
            beta_KK   = -334.9;
        elseif PSL(a)==70 ||  PSL(a)==80 ||  PSL(a)==90
            if      PSL(a)==70
                C        = 69.3;
                Ck       = 71;
            elseif PSL(a)==80
                C        = 77;
                Ck       = 82;
            else
                C        = 85.8;
                Ck       = 90;
            end
            beta_D    =  0.0182;
            beta_S    = -0.0296;
            beta_F    = -0.0214;
            beta_K    = -2.383;
            beta_DS   =  0;
            beta_DF   =  0;
            beta_DK   =  0;
            beta_SK   = -3.825;
            beta_FK   = -3.517;
            beta_DSK  =  0;
            beta_DFK  =  0;
            beta_KK   = -485.3;
        end
    elseif NL(a)==4
        if  PSL(a)==70 || PSL(a)==80 || PSL(a)==90 || PSL(a)==100
```

```matlab
        if      PSL(a)==70
            C        = 74.8;
            Ck       = 76;
        elseif PSL(a)==80
            C        = 76.5;
            Ck       = 85;
        elseif PSL(a)==90
            C        = 92;
            Ck       = 96;
        elseif PSL(a)==100
            C        = 99.6;
            Ck       = 103;
        end
        beta_D    =  0.0076;
        beta_S    = -0.0111;
        beta_F    = -0.0368;
        beta_K    =  0;
      end
    end

    %% Application of the speed model and speed storage
    if NL(a)==2
        U=beta_D   * (xd(a)-8) + ...
          beta_S   * xs(a) + ...
          beta_F   * xf(a) + ...
          beta_K   * xk(a) + ...
          beta_DS  * (xd(a)-8) * xs(a) + ...
          beta_DF  * (xd(a)-8) * xf(a) + ...
          beta_DK  * (xd(a)-8) * xk(a)+ ...
          beta_SK  * xs(a) * xk(a) + ...
          beta_FK  * xf(a) * xk(a) + ...
          beta_DSK * (xd(a)-8) * xs(a) * xk(a) + ...
          beta_DFK * (xd(a)-8) * xf(a) * xk(a) + ...
          beta_KK  * xk(a)^2;
    elseif NL(a)==4
        U=beta_D   * (xd(a)-19) + ...
          beta_S   * xs(a) + ...
          beta_F   * xf(a) + ...
          beta_K   * xk(a);
    end
    fart=Ck*exp(U);
    speedprofile(a,1) = fart;
end

%% calculating vehicle acceleration and plotting

for i=1:length(PSL)-1
    acc(i,1)=((speedprofile(i+1)/3.6)^2-
(speedprofile(i)/3.6)^2)/(2*(STATION(i+1)-STATION(i)));
end
acc(length(acc)+1,1)=acc(length(acc));

subplot(2,1,1)
plot(STATION,speedprofile),
subplot(2,1,2)
plot(STATION,acc);
end
```

Developer: Giuseppe Marinelli

```matlab
function [ACHSP, ACHACC] = acc_smoother (STATION,SPEED,ACC,VISRANGE,GRAD)
% This function gives back the achieved speed profile, based on the
% desired speed profile provided by the Speed Model, based on a maximum
% established acceleration ACC and a visibility range DIST.
% STATION= vector of station of points;
% SPEED  = vector of speeds, expressed in km/h
% ACC    = max acceleration, expressed in m/s^2
% VISRANGE  = visibility range, expressed in m
% GRAD = polynomial function grade, expressed as pure number


%% Setting up the right measurements units
SPEED=SPEED/3.6; %generating speeds in m/s from km/h


%% Smoothing process


ACHSP(1)=SPEED(1); %setting initial speed as the starting one


for a=1:length(STATION)-1 %for each point of the track
    if isnan(ACHSP(a))==1 && a<(length(STATION)/2) %if the desired speed at
the current point is NaN and we are at the beginning of the road
        ACHSP(a+1,1)=SPEED(a+1); %skipping current point
        ACHACC(a,1)=NaN;
    elseif isnan(SPEED(a+1))==1 && a>(length(STATION)/2) %if the next speed
at the current point is NaN and we are at the end of the road
        ACHSP(a+1,1)=SPEED(a+1); %skipping current point
        ACHACC(a,1)=NaN;
    else
        %% research and identification of points inside the visible range
from current position (a)
        STa=STATION(a); %storing station of current point on track (a)
        SPa=ACHSP(a); %storing speed of current point on track (a)
        flag=1; %"raising up" the flag to start looping for identify the
points inside the visible range
        b=1; %initializing counter b
        while flag==1 %up to when the flag is "up"
            if a+b+1>length(STATION) || isnan(SPEED(a+b+1))==1 %if we are
at the end of the trip or we have "NaN" speeds
                VISPTS_ST=STATION(a+1:a+b); %storing stations of visible
points (from a+1 to a+b) on track
                VISPTS_SP=SPEED(a+1:a+b); %storing speeds of visible points
(from a+1 to a+b) on track
                flag=0; %visible range identified: stopping while cycle and
"lowering" flag :)
            else
                DISTb=STATION(a+b+1)-STa; %evaluating distance between
(a+b+1)point and current point (a)
                if DISTb>VISRANGE %if (b+1)point is "out of visible range"
--> found last point (b) inside visible range!
                    VISPTS_ST=STATION(a+1:a+b); %storing stations of
visible points (from a+1 to a+b) on track
                    VISPTS_SP=SPEED(a+1:a+b); %storing speeds of visible
points (from a+1 to a+b) on track
                    flag=0; %visible range identified: stopping while cycle
and "lowering" flag :)
                else
```

```matlab
                b=b+1; %not yet reached the limit of visible range!
Keep searching!
            end
          end
        end
        %% smoothing with GRAD degree polynomial function of following
speeds
        if length(VISPTS_ST)>GRAD %if I have enough points to fit a
polynomial function
            P=polzero([0;(VISPTS_ST-STa)],[0;(VISPTS_SP-SPa)],GRAD);
%evaluating the GRAD degree polinomial function coefficients
            smoothSP=polyval(P,[0;(VISPTS_ST-STa)]); %evaluating the
"smoothed" speeds given by the polynomial function
        else
            ACHSP(a+1,1)=NaN; %skipping current point
            ACHACC(a,1)=NaN;
        end

        %% next acceleration evaluation
        nextSP=smoothSP(2)+SPa; %calculating the desired speed for next
point (a+1) "smoothed" by the polinomial function
        nextACC=(nextSP^2-SPa^2)/(2*(VISPTS_ST(1)-STa)); %calculating the
necessary acceleration to reach the next point (a+1) speed "smoothed" by
the polinomial function
        %% decision
        if length(VISPTS_ST)>GRAD  %if I had not enough points to fit a
polynomial function
            if nextACC>0.5 || nextACC<(-0.5) %if the desired acceleration
is too big (dec/acc), I apply the limit acceleration ACC
                if nextACC>0 % if I am supposed to accelerate
                    ACHSP(a+1,1)=sqrt(2*ACC*(VISPTS_ST(1)-STa)+SPa^2); %
applying ACC to accelerate the vehicle and storing new speed
                    ACHACC(a,1)=ACC; %storing the applied acceleration
                else  % if I am supposed to decelerate
                    ACHSP(a+1,1)=sqrt(2*(-ACC)*(VISPTS_ST(1)-STa)+SPa^2); %
applying ACC to decelerate the vehicle and storing new speed
                    ACHACC(a,1)=-ACC; %storing the applied acceleration
                end
            else % if the desired acceleration is acceptable, I apply it
with its sign
                ACHSP(a+1,1)=sqrt(2*nextACC*(VISPTS_ST(1)-STa)+SPa^2);
                ACHACC(a,1)=nextACC; %storing the applied acceleration
            end
        end
        %% plotting of local results for check
%         close
%         plot([STa;VISPTS_ST],[SPa;VISPTS_SP],'.b')
%         hold on
%         plot([STa;VISPTS_ST],smoothSP+SPa,'r')
%         plot(VISPTS_ST(1),nextSP,'om')
%         plot(VISPTS_ST(1),ACHSP(a+1),'xk')
    end
end
ACHACC=[ACHACC;NaN];
ACHSP=ACHSP*3.6; %converting back speeds from m/s to km/h
end
```