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A comparative analysis of different vehicle configurations

Creating a composite indicator to rank vehicle powertrains along multiple dimensions

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Abstract

A comparative assessment of internal combustion engine vehicles (ICEVs), battery electric vehicles (BEVs), full hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs) and fuel cell electric vehicles (FCVs) is conducted. For each powertrain a reference vehicle is identified in the compact car segment. Five dimensions are selected in order to better understand advantages and disadvantages of the single powertrains, namely: CO2 emissions, NOx emissions, price of vehicle, driving range and noise pollution. A composite indicator including all dimensions simultaneously is created and different weights are assigned to either focus on environmental aspects of the vehicle or dimensions affecting the consumer's choice of purchasing. The results show that in regards to the reference vehicle BEVs and FCVs are the more environmentally-benign options with respect to their emissions in vehicle operation. HEVs on the other hand have the best composite indicator leading the dimensions noise and price reflecting affordability. The life-cycle analysis and well-to-wheel approach are not considered in the assessment.

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1. Introduction

The transport sector worldwide is challenged with serious environmental concerns due to the use of petroleum-based fuels to motorize vehicles, being identified as principal causes for greenhouse gas (GHG) emissions (Sharma & Strezov, 2017). Transportation contributes 24 percent of energy-related global greenhouse gas emissions and this share is growing at a faster rate than other sectors. Reducing emissions is more challenging in this sector because internal combustion technology and petroleum-derived fuels dominate transportation systems, and have been developed and optimised over many decades (International Energy Agency (IEA), 2017). Because of the overwhelming use of petroleum as the fuel of choice, these vehicles do not only reduce petroleum resources, but also release a significant amount of exhaust, which can cause global warming, harm the environment and negatively impact human health. The reduction of carbon dioxide (CO2) emissions is an important element of a global transition to sustainable mobility and is a major challenge for society.

Several reasons lay behind the opportunity of starting the transition from the conventional options towards new, more advanced and cleaner ones including, but not limited to: fluctuation in oil prices, climate change problems and increasing restrictions on emissions brought by regulations and political powers (Torchio & Santarelli, 2010). Alternative fuels such as electricity and hydrogen are often associated with energy savings, sustainable development and environmental conservation, and recent developments show a shift towards alternative fuels (Sharma & Strezov, 2017).

Many advanced vehicle technologies, including battery electric vehicles (BEVs), hybrid electric vehicles (PHEVs and HEVs) and fuel cell vehicles (FCVs) are gaining attention throughout the world due to their capability to improve fuel efficiencies and reduce emissions. It is argued, that transport electrification can contribute to breaking its oil dependency and decreasing its CO2 emissions, as well as emissions of other air pollutants such as nitrogen oxide and particles (European Commission, 2017). The development of strategies that addresses climate change is challenging because of a multitude of different vehicle and fuel technology combinations available today, uncertainty in future costs of advanced vehicle technologies and the importance of connections between the different sectors (Grahn, et al. 2013).

At the Paris climate conference in December 2015, 195 countries adopted the first-ever universal, legally binding global climate deal setting out a global action plan limiting global warming to well below 2°C. The agreement recognises the role of non-party stakeholders including cities, civil society and the private sector and every country commits to determine, plan and regularly report its own contribution in the mitigation of global warming (United Nations (UN), 2015), which President Donald Trump intends to withdraw from

1.1 Research Question

In this thesis, I will focus look at conventional and alternative vehicle technologies (namely BEV, PHEV, HEV and FCV) and their emissions (CO2 and NOx) in usage, as indicators for an environmental focus. Furthermore, I will identify noise pollution, driving range and price of the vehicles as indicators that influence a driver's decision to either buy a conventional or an advanced car. These indicators will be referred to as user preference hereafter. I will create a composite indicator ranking the different reference vehicles along the dimensions. The underlying research questions of this thesis are therefore:

- Is it possible to rank vehicle models using different powertrains along various dimensions?
- Could a composite indicator be created that includes all dimensions simultaneously?

1.2 Outline

The thesis is structured as follows. Chapter 2 gives an overview on the alternative vehicle technologies evaluated in this paper and also provides the general framework for constructing a composite indicator based on the Handbook provided by OECD & Joint Research Centre (2008). Chapter 3 outlines and describes the data used in this thesis for the creation of the composite indicator whereafter Chapter 4 discusses the results obtained by separately analysing the dimension of the composite indicator, the composite indicator itself, and alternating the weights of single dimensions within the composite indicator potentially reflecting the focus either on the environment or user preference. Chapter 5 will be used to discuss the results and any limitations of the aforementioned approach and the and composite indicator itself. Chapter 6 concludes the thesis.

2. Background and Theoretical Framework

In this chapter, I will present the energy flows in conventional and advanced vehicle technologies, also describing the energy source used. Furthermore, I will give a general overview on the methodology of how to create a composite indicator described in the handbook published by OECD. All powertrains described in this section will be used to create the composite indicator in Chapter 3.

2.1 Description of powertrain characteristics

Conventional passenger cars use an internal combustion engine to drive the wheels through mechanical transmission. Petrol or Diesel are used as primary energy sources in such vehicle and hereafter denoted as internal combustion engine vehicles (ICEV), and shown in figure 1a.

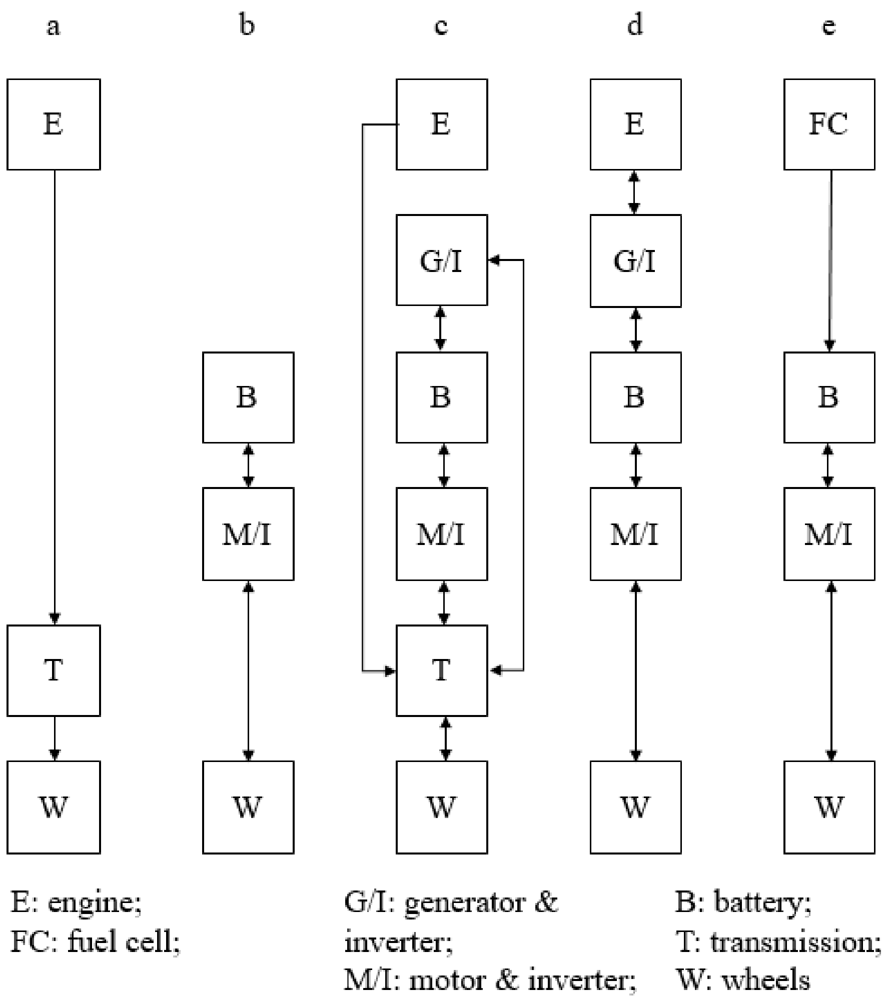
A battery electric vehicle (BEV), depicted in Figure 1b, is set in motion by an electric motor, which is powered by a set of battery packs and can be recharged by the grid. It is arguably the most efficient technology with zero tailpipe emissions - emissions produced through fuel combustion during the vehicle's operation (Gao & Winfield, 2012). However, battery packs are heavy and occupy much vehicle space. Furthermore, recharging time may last for 4-12 hours in common BEVs (Nocera & Cavallaro, 2016).

A hybrid electric vehicle combines a downsized conventional engine, as seen in ICEVs, with a high power battery and electric motor (Heywood, 2010). Figure 2c describes the energy flow of a plug-in hybrid vehicle (PHEV). This configuration allows the driver to either switch entirely to an all-electric mode or use the conventional on-board combustion engine. The vehicle operates as a pure battery electric vehicle until its battery capacity is depleted. The conventional engine kicks in when the battery capacity is depleted and operates an electric generator which extends the driving range of the vehicle (Gao & Winfield, 2012). Figure 2d illustrates a full hybrid vehicle (HEV) configuration not giving the driver the possibility to charge the battery from an external electric supply. However, these vehicles have a split power path that allows the driver to switch between mechanical and electrical power. A large, high-capacity provides battery only operation and is recharged by a generator and/or engine when the battery state-or-charge (SOC) is low (Gao & Winfield, 2012).

Figure 2e shows the configuration of a fuel cell vehicle (FCV) which runs. Fuel cells replace the conventional engine of other vehicle technologies and generate electricity which powers the motor using oxygen from the air and compressed hydrogen stored in tanks on-board. Fuel cell vehicles are considered to be zero-emission vehicles, since they only produce heat and water.

Figure 1 is based on an illustration from Gao & Winfield, (2012) and adapted according to the vehicles used in this analysis.

Figure 1: Diagram of the energy flows in different types of vehicle configurations: (a) ICEV; (b) BEV; (c) PHEV; (d) HEV; and (e) FCV



2.2 Building a Composite Indicator

The Organisation for Economic Co-operation and Development (OECD) created a Handbook on how constructing composite indicators in collaboration with the Econometrics and Applied Statistics Unit of the Joint Research Centre (JRC) of the European Commission in Ispra, Italy. OECD & JRC (2008) aim to contribute to the understanding of composite indicators in order to be able to illustrate and simplify complex issues. The following chapter is based on recommendations made in and follows the steps described, from its development to presentation and dissemination.

There are several advantages of composite indicators. Firstly, they facilitate communication with the general public. Secondly, they enable users to compare complex and multi-dimensional concepts effectively. Furthermore, composite indicators keep underlying information of various dimensions without making them all visible to the reader.

The Handbook is seen as continuously evolving. The user creating a composite indicator may decide which steps to follow and the sequence of steps to follow.

Step 1. *Theoretical framework*: A concept needs to be defined in order to provide necessary information of what is being measured. A composite indicator is usually built upon various dimensions that need to be described theoretically and empirically.

Step 2. *Data selection*: Dimensions (also referred to as indicators) can be excluded or included after defining the general concept. The quality of available indicators needs to be assessed. It is up to the constructor of the composite indicator to include or exclude dimensions, discussing strengths and weaknesses of each indicator.

Step 3. *Imputation of missing data*: Different methods are available to deal with missing such as (i) case deletion, (ii) single imputation and (iii) multiple imputation. The result after this step is a complete data set without missing values.

Step 4. *Multivariate analysis*: The underlying structure is analysed as individual indicators are sometimes selected in an inconsistent manner increasing the chance for interrelations. Information can therefore be grouped on individual indicators e.g. through principal components analysis, factor analysis and the use of a Cronbach coefficient alpha.

Step 5. *Normalisation*: As different dimension may have different measurement units, a normalisation method needs to be used e.g. ranking, standardisation, min-max, categorical scales and distance to a reference variable.

Step 6. *Weighing and aggregation*: Dependent on the focus area of a composite indicator, weights can be given to different dimensions having a significant effect on the composite indicator itself, and therefore also to the results, implications and interpretation of the composite indicator itself.

Step 7. *Robustness and sensitivity*: Sensitivity analysis can be used to assess the robustness and increase transparency of the composite indicator. Sources of uncertainty can be identified and their impact on the final result can be assessed.

Step 8. *Back to the details*: The composite indicator can be decomposed into its individual parts in order to reveal what is driving the composite indicator results. The relative importance of single dimensions can be shown.

Step 9. *Links to other variables*: In order to increase the explanatory power of the composite indicator, the final result can be linked to existing measures e.g. GDP, inflation, exchange rate (key economic indicators), or climate change and air quality (key environmental indicators).

Step 10. *Presentation and dissemination*: Composite indicators must be able to communicate a story. Tabular approaches or charts can be used to convey a message to the reader.

The intention of this thesis will be to fully leverage the advantages and send clear messages to the reader. Considering that the selection of indicator and weights will be somehow subjectively chosen leading to simplistic conclusions in the aftermath, bears a limitation and bias to the analysis.

Composite indicators are mainly used to provide comparisons between countries in regards to e.g. society, economy, technological development and environment, but does not bind the creation of such indicators solely to countries. It is only stated that the quality of the indicator depends on the fitness for the intended purpose. The International Monetary Fund (IMF) created the so called Data Quality Framework (DQAF) capturing prerequisites of quality e.g. quality of the statistics and assessing the overall quality through five quality dimensions such as (i) assurance of integrity, (ii) methodological soundness, (iii) accuracy and reliability, (iv) serviceability and (v) accessibility (International Monetary Fund (IMF), 2013).

3. Methodology

The following chapter describes the rational for the application of a composite indicator to justify the vehicle segment chosen in the analysis, as well as the reference vehicles analysed and used to create a composite indicator. The dimensions used to build the composite indicator are described in detail. The results and therefore all the presented data will only be shown in Chapter 4.

Please note, that the steps taken in this thesis for the creation of the composite indicator was adapted from the recommended approach. The thesis will first focus on the single dimensions before building the final result.

3.1 Theoretical framework

A composite indicator is formed when individual indicators are aggregated into a single index on the basis of a multidimensional concept. The basis of the thesis and therefore the concept of this underlying model is to rank reference vehicles among single dimensions using different powertrains. My focus on choosing the single dimensions will lay firstly on the environment, such as CO2 emissions and NOx emissions, and secondly on driver's preference to also purchase the car. For the ladder, I've identified noise pollution, driving range of the vehicle and purchase price as dimensions of interest. Subsequently, I will create a composite indicator reflecting the multi-dimensional concept at stake.

3.2 Data selection

The subsequent chapters will outline variables and describe dimensions chosen in the analysis. The reference vehicles will serve as identifier of a specific powertrain technology.

3.2.1 Vehicle segment and reference vehicles

According to the International Council on Clean Transportation, new passenger car registrations in Europe increased to 14.6 million vehicles in 2016 (ICCT, 2017). The largest increase in vehicle sales took place in the sport utility vehicle (SUV) segment. This was expected and seen already over the past couple of years. Nevertheless, compact cars still represent the largest segment of passenger cars in Europe (Carsalesbase, 2018). The United

States Environmental Protection Agency categorises passenger cars in regards to their total passenger and cargo volume: a compact car has a total passenger and cargo volume of 2850 – 3100 litre (US EPA, 2018).

Table 1 shows the reference vehicles chosen for the analysis. All vehicles are compact cars.

Table 1: Presentation of reference vehicles and vehicle powertrain definition

Abbreviation	Reference Vehicle	Powertrain Definition
$ICEV_{Gasoline}$	Volkswagen Golf TSI	Internal combustion engine vehicle Energy carrier: gasoline
$ICEV_{Diesel}$	Volkswagen Golf TDI	Internal combustion engine vehicle Energy carrier: diesel
BEV	Volkswagen e-Golf	Battery electric vehicle Energy carrier: electricity
$PHEV_{Gasoline}$	Volkswagen GTE	Plug-in-hybrid vehicle Energy carrier: gasoline and electricity
$HEV_{Gasoline}$	Toyota Prius VVT-i	Full hybrid vehicle Energy carrier: gasoline
FCV	Toyota Mirai	Fuel cell vehicle Energy carrier: hydrogen

Almost 1.5 million of new car registrations in in Europe in 2016 are Volkswagen vehicles, representing a market share of eleven percent (ICCT, 2017). Volkswagen overtook Toyota in 2017 as the world’s biggest car manufacturer and is leading the ranking since then (Baccardax, 2018). Nevertheless, Volkswagen did neither commercially market a full hybrid electric nor a fuel cell electric vehicle yet. Toyota on the other side pioneered with its Toyota Prius Hybrid in 1997 as the world’s first mass market hybrid. Furthermore, it manufactured a hydrogen fuel cell vehicle, unveiled it in 2014 and is selling it since 2016 commercially.

3.2.2 CO2 emissions

Air pollution caused by transport already today presents a major health problem in European cities. Road transport is a major source of CO2 emissions, a global pollutant and once emitted it affects the entire ecosystem (European Environment Agency (EEA), 2017). Reducing emissions in the transport sector is still costly as it heavily relies on fossil fuels, and alternative clean technologies have a higher cost.

Tailpipe emissions are usually calculated in grams per kilometre travelled (g/km). Until September 1st 2017 they were measured in the New European Driving Cycle (NEDC), the test cycle for vehicles in the EU. Since than it is being phased out by the new Worldwide Harmonized Light Vehicle Test Procedure (WLTP) introducing more realistic testing conditions and hence avoiding and better identifying manipulative behaviour of car manufacturers (WLTP, 2018) as it has been seen in the past.

CO2 emissions are then published officially by the manufacturer. Published values, retrieved from the NEDC or WLTP, may differ from real on-the-road driving.

3.2.3 NOx emissions

Nitrogen oxides (NOx) is a so called ambient or local pollutant, and represent a family of seven compounds. Automobiles are a major contributor to NOx emissions, as it is produced from the reaction of nitrogen and oxygen gases in the air during combustion. Increasing evidence suggests that NOx has a direct negative effect on the respiratory system. It also reacts to form smog and acid rain (Icopal Noxite, 2015).

Nitrogen oxides tailpipe emissions are published officially by the manufacturer.

3.2.4 Price

The price of a car is an important factor for a soon-to-be car owner whether to purchase a car. Unfortunately, I was not able to gather pre-tax prices of all the reference vehicles. I have therefore decided to base this indicator on new passenger car in Norway prices provided by Bil Norge (2018).

3.2.5 Driving range

Driving range describes the distance travelled of a vehicle before it needs to be refuelled. More specifically, before ICEVs and other vehicle configurations need to be refuelled with petrol or diesel, or before the batteries of BEVs and PHEVs need to be recharged by the grid. The measurement unit used in this thesis is kilometres and reflects the range a reference vehicle can travel with the assumption it has been fully recharged and fuelled at the starting point.

It is assumed that the higher the range, the more preferred will the reference vehicle be for the driver. A driver can travel further without the need to stop and charge or refuel the vehicle, saving travel time for longer distances. Refuelling time is not considered in this analysis.

Whereas the driving range was published by the manufacturer for most of the reference vehicles, including the BEV, FCV and the HEVs, it had to be calculated for the ICEVs. Official combined fuel consumption values were divided by the fuel tank volume and multiplied by 100 in order to get estimates for the driving range.

3.2.6 Noise

Road transport generates substantial noise (or "unwanted sound"), affecting sleep, causing annoyance and increasing the risk of cardiovascular diseases and psychological disorders, with at least 10,000 premature deaths in Europe every year (EEA, 2018).

The unit for measurement for the sound level is decibel (dB). It is assumed in this thesis that the lower the noise pollution of a vehicle is, the more preferred the vehicle is for a driver to be bought. The thesis evaluates the ranks the external rolling noise of the reference vehicles.

3.3 Normalisation

Based on the Handbook published by OECD & Joint Research Centre (2008) and the normalisation methods presented, ranking is chosen.

$$I_q = Rank(x_q)$$
$$x_q = value\ for\ indicator\ q$$

3.4 Weighting and aggregation

Weights of the different factors and inputs can have an important effect on the overall resulting composite indicator. The constructor is able to influence the quality, as well as the implications denoted by the composite indicator by giving different weights to the dimensions. Higher weights could be assigned to more reliable data in order to guide the reader and make the importance of a single dimension visible.

The dimensions described in the chapters 3.2.2 to 3.2.6 can be grouped into two sub-groups either having a focus on the environment or on the user preference influencing the decision to buy a car or not. Therefore, three different composite indicators will be presented in the next chapter:

1. Composite indicator with equal weights along all dimensions: each dimension will be weighted equally, which means that the rankings are multiplied by factor 0.2
2. Composite indicator focusing on environmental aspects: the dimensions related to CO2 emissions and NOx emissions will receive a higher weight, implying a stronger focus and preference of users on the environmental friendliness of the vehicle. The two indicators will be multiplied by factor 0.4. As a result, 80 percent of the focus lies on the emission of the reference vehicle
3. Composite indicator focusing on user preferences: Similarly to the aforementioned composite indicator, 80 percent of the focus will be put on the residual dimensions of our analysis, namely: price, driving range and noise. It is therefore assumed, that the consumer wants a vehicle that is affordable and has an extended driving range.

3.5 Presentation

Results are presented in a tabular format.

4. Results

The following chapter is divided into two parts. The reference vehicles will be ranked along each dimension in the first part, visible in column 3 of each table. The second part will then create three different composite indicators whereas (i) weights are distributed equally among the dimensions, (ii) more weights are put onto emission indicators reflecting a stronger environmental focus, and (iii) more weights are put onto the residual three dimensions defined as user preferences.

4.1 Separate Indicator Analysis

4.1.1 CO2 emissions

Table 2: Ranking of vehicle configuration along the dimension CO2 emissions

Vehicle Configuration	CO_2 [g/km][a)]	Ranking [1-6]
BEV	0	1
FCV	0	1
$PHEV_{Gasoline}$	38	3
$HEV_{Gasoline}$	82	4
$ICEV_{Gasoline}$	114	5
$ICEV_{Diesel}$	119	6

[a)] Based on data retrieved from (Bil Norge, 2018), (Sinclair Group, 2018) and (Volkswagen AG - United Kingdom, 2018)

Table 2 shows CO2 emissions in gram per kilometre driven of all vehicle configurations included in this paper. According to this presentation, internal combustion engine vehicles are the most pollutant vehicle configurations in vehicle operation. BEVs and FCVs have zero-emissions and can therefore be denoted as zero-emission vehicles. PHEVs perform better than HEVs due to their all-electric ability, reducing their emissions to zero as long as the battery pack is not depleted.

It can be seen, that a reduction of CO2 emissions is favoured by the use of electricity as powertrain in vehicle operation.

4.1.2 NOx emissions

Table 3: Ranking of vehicle configurations along the dimension NOx emissions

Vehicle Configuration	**NO_X [mg/km] [a)]**	**Ranking [1-6]**
BEV	0	1
FCV	0	1
$PHEV_{Gasoline}$	5	3
$HEV_{Gasoline}$	27	4
$ICEV_{Gasoline}$	27	4
$ICEV_{Diesel}$	52	6

[a)] Based on data retrieved from (Next Green Car, 2018)

Similarly to the aforementioned dimension of CO2 emissions, BEVs and FCVs lead the ranking in table 3 and show zero emissions. FCVs output is neither CO2 nor NOx, but water and heat. The internal combustion engine vehicle using Diesel as energy carrier is the most polluting on an ambient level due to the composition of the fuel itself. Therefore, we also see HEVs and ICEVs using petrol as their energy carrier in a slightly better position.

4.1.3 Price

Table 4: Ranking of vehicle configurations along the dimension price

Vehicle Configuration	**Price [NOK] [a)]**	**Ranking [1-6]**
$HEV_{Gasoline}$	308200	1
BEV	318300	2
$PHEV_{Gasoline}$	360500	3
$ICEV_{Gasoline}$	365300	4
$ICEV_{Diesel}$	403600	5
FCV	559000	6

[a)] Based on data retrieved from (Bil Norge, 2018)

Table 4 uses Norwegian retail prices of the reference vehicles. According to the data, an FCV is the most expensive vehicle configuration in this analysis. Reasons for such an elevated retail price might be associated to the safety concerns, high costs and low liability of fuel cells. HEVs, BEVs and PHEVs are leading in the ranking, which can be directly attributed to incentives given by the Norwegian government on electric and hybrid cars. According to an article from the New York Times, 52 percent of new cars sold in the country last year ran on advanced forms of fuel (Tsang & Libell, 2018).

4.1.4 Driving Range

Table 5: Ranking of vehicle configurations along the dimension driving range

Vehicle Configuration	Range [km] [a)]	Ranking [1-6]
$ICEV_{Diesel}$	1085	1
$HEV_{Gasoline}$	1045	2
$ICEV_{Gasoline}$	1000	3
FCV	502	4
BEV	300	5
$PHEV_{Gasoline}$	50*	6

[a)] Based on data retrieved from (ADAC, 2018), (Peter Cooper Group, 2018), (Toyota Motor Corporation, 2018), (Volkswagen AG - Austria, 2018) and (Volkswagen AG - Mazedonia, 2016)

*939 km would be the consolidated distance using gasoline and electricity

Internal combustion engines and HEVs are leading this dimension according to table 3. All three vehicle configurations have a driving range of above 1000 km. The reference vehicle for FCVs, the Toyota Mirai, is one of the first commercially marketed fuel cell electric vehicles and comes in 4th in the ranking with an impressive 500 km range, leaving BEVs and PHEVs behind. PHEVs are last in this ranking, as only all-electric range is considered in the analysis. According to the manufacturer, 939 km can be reached in optimal conditions in the NEDC (Volkswagen AG - Mazedonia, 2016), which would push the PHEV up to the 4th rank. However, only the all-electric range is considered in the creation of the composite indicators at the end of this chapter.

4.1.5 Noise

Table 6: Ranking of vehicle configurations along the dimension noise

Vehicle Configuration	**Noise [dB] [a)]**	**Ranking [1-6]**
$HEV_{Gasoline}$	67	1
$ICEV_{Diesel}$	69	2
FCV	69	2
BEV	69,5*	4
$PHEV_{Gasoline}$	71	5
$ICEV_{Gasoline}$	72	6

[a)] Based on (Auto Umweltliste, 2017), (Peter Cooper Group, 2018), (Toyota Motor Corporation - Europe, 2017) and (Volkswagen AG - Austria, 2018)

*Average taken between 68 and 71 dB

Noise pollution might be one of the most interesting dimensions in this analysis. The HEV is leading in the ranking with the lowest value of sound level with 67 dB, followed by the Diesel car and the FCV. The loudest vehicle among all vehicle configurations is the internal combustion engine that is powered by gasoline with 72 dB. Having solely a difference of 5 dB, a closer look is taken to the measure of decibel to better understand the dimension. According to IAC Acoustics (2018) 60 dB can be compared to the sound level of a conversation in a restaurant, being half as loud as 70 dB. 80 dB reflects the sound level of a garbage disposal truck and possibly damages your hearing if exposed for 8 hours in a row. An increment in the measure decibel therefore leads to an exponential increase in the soundlevel.

4.2 Creation of composite indicators

4.2.1 Unweighted average

Table 7: Composite indicator, assigning equal weight to all dimensions

Vehicle Configuration			**Ranking**			**Unweighted average**
	CO_2 emissions (w = 0,2)	NO_X emissions (w = 0,2)	Norwegian retail price (w = 0,2)	Driving range (w = 0,2)	Noise pollution (w = 0,2)	(Rank)
HEV$_{\text{Gasoline}}$	4	4	1	2	1	2.40 (1)
BEV	1	1	2	5	4	2.60 (2)
FCV	1	1	6	4	2	2.80 (3)
ICEV$_{\text{Diesel}}$	6	6	5	1	2	4.00 (4)
PHEV$_{\text{Gasoline}}$	3	3	3	6	5	4.00 (4)
ICEV$_{\text{Gasoline}}$	5	4	4	3	6	4.40 (6)

Table 7 shows that the HEV reference vehicle is leading the ranking when creating a composite indicator including all dimensions simultaneously. Even though the HEV only turns out to be 4^{th} in the overall analysis in the dimensions of CO2 emissions and NOx emissions, it was able to become first in the ranking due to the better performance in the remaining three dimensions, scoring best on price and noise pollution. The FCV turns out to be in the top three due to its environmental performance. Unfortunately, the price to purchase the vehicle impeded the reference vehicle to be better positioned in the ranking. The PHEV comes in 4^{th} in the overall ranking due to the all-electric driving range considered in this analysis, sharing the position with the Diesel reference vehicle. The result would look much different using the total driving range suggested by the manufacturer also using the on board internal combustion engine. The Diesel car outperformed the conventional petrol car due to the much better rankings in the dimensions related to noise pollution and driving range.

It can be seen that, this composite indicator by nature is more focused on user preferences than environmental aspects when introducing equal weights over all dimensions. This can be explained, because the total number of dimensions evaluating emissions and therefore environmental aspects is lower than the residual amount of dimensions.

4.2.2 Environmental focus

Table 8: Composite indicator, assigning 80 percent of the weight in equal parts to dimensions focusing on the environment

Vehicle Configuration	**Ranking**					**Environ-mental focus**
	CO_2 emissions (w = 0,4)	NO_X emissions (w = 0,4)	Norwegian retail price (w = 0,066)	Driving range (w = 0,066)	Noise pollution (w = 0,066)	(Rank)
BEV	1	1	2	5	4	1.53 (1)
FCV	1	1	6	4	2	1.60 (2)
PHEV$_{Gasoline}$	3	3	3	6	5	3.33 (3)
HEV$_{Gasoline}$	4	4	1	2	1	3.47 (4)
ICEV$_{Gasoline}$	5	4	4	3	6	4.47 (5)
ICEV$_{Diesel}$	6	6	5	1	2	5.33 (6)

The composite indicator depicted in the last column of table 8 depicts a different result. Various weights are applied to the single dimensions. In order to increase the environmental focus of the final composite indicator, the weights for CO2 emissions and NOx emissions have been increased. In total, the focus on the environment now lies on 80 percent, whereas only 20 percent focus will be given to the other three dimensions, minimizing it to 6.66 percent for each dimension.

BEV, FCV and PHEV take the first three positions in the ranking, and it can be seen, that these positions are almost identical to the ones from the respective dimensions. The only difference is, that the FCV falls in the ranking by one position whereas it previously shared the first place with the BEV. This is due to elevated price of the reference vehicle. Furthermore, also position four to six do not see a change. The HEV is not able to surpass the PHEV considering his rankings in price, driving range and pollution, as the environmental aspect is too strong in this analysis.

Please note again that these weights are subjectively set in order to potential of composite indicators and the importance of weighting and aggregation.

4.2.3 Focus on user preference

Table 9: Composite indicator, assigning 80 percent of the weight in equal parts to dimensions focusing on user preference

Vehicle Configuration	Ranking					Focus on user preference
	CO_2 emissions (w = 0,1)	NO_X emissions (w = 0,1)	Norwegian retail price (w = 0,266)	Driving range (w = 0,266)	Noise pollution (w = 0,266)	(Rank)
$HEV_{Gasoline}$	4	4	1	2	1	1.87 (1)
BEV	1	1	2	5	4	3.13 (2)
$ICEV_{Diesel}$	6	6	5	1	2	3.33 (3)
FCV	1	1	6	4	2	3.40 (4)
$PHEV_{Gasoline}$	3	3	3	6	5	4.33 (5)
$ICEV_{Gasoline}$	5	4	4	3	6	4.37 (6)

Table 9 shows the opposite scenario to the aforementioned and described results in Chapter 4.2.2. 80 percent of the weight is now associated to the dimensions price, driving range and noise pollution, leaving only 20 percent of the focus on environmental aspects in the vehicle operation. The HEV jumps on top of the ranking with a comfortable distance to the following vehicle configurations. The Diesel car was able to jump on to position three, surpassing the FCV and closing the gap to the BEV reference vehicle, due to the reduced focus on environmental aspects and high ranks in driving range and noise pollution.

5. Limitations

It has been shown, that it is possible to create a composite indicator along various dimensions and including different, not correlating concepts such as environmental focus and user preferences. However, improvements could still be made.

The created composite indicator is based on five dimensions. Arguably, these dimensions do not reflect the whole picture and do not represent the dimensions along which the final consumer is purchasing a car or not. Important key indicators such as refueling time or infrastructure availability were disregarded due to either unavailability of reliable sources and data or due to the complexity of assessing such indicators and incorporating them in the final composite indicator. Furthermore, automation technologies such as Adaptive Cruise Control, Autonomous driving or Lane Keeping Assistance are not accounted for considering user preferences.

Furthermore, the dimensions chosen show lack information or are known to be inaccurate. CO2 tailpipe emissions and NOx emissions are known to be manipulated values in the NEDC. Sufficient data from the WLTP is not available yet and both test procedures co-exist at the time this thesis is being written. In addition, emissions change according to the area (local, rural), level of service and road gradients (Morrison, et. al 2018). The price for a reference vehicle is given in Norwegian Kroner, and already includes road taxes and insurance schemes from Norway. A more adequate and reliable measure for the price would have been the pre-tax manufacturer price, which was not available for all the reference vehicles in this analysis. Driving range represents the distance traveled with the vehicle assuming driving behavior, road conditions and temperatures that do not reflect real time driving. Further research needs to be done.

However, the model is able to provide a clear message to the reader by analyzing a multi-dimensional concept through one value. CO2 emissions, NOx emissions, noise pollution, purchase price and driving range are important measures for nowadays more environmentally aware consumers in the market. The Diesel scandal and its aftermath is still influencing consumer behavior and led to a significant decrease in new Diesel passenger car registration in the past years.

Unfortunately, the creation of a composite indicator bears substantial risks regarding to accuracy and reliability. Selection of indicators, selection of data sources and weighing and aggregation of dimensions and are dependent on the craftsmanship of the modeler. The modeler therefore has the power to guide the reader into a desired direction which may leads to inappropriate policies in a political and administrative context.

Most importantly, considering the indicators focusing on an environmental impact the model is only evaluating the vehicle operation and can therefore be considered as a simplistic tank-to-wheel (TTW) analysis, the second of the two stages in the fuel cycle. The analysis disregards the upstream production of the vehicle fuel which includes resource exploitation and transportation, fuel production, transmission, distribution and storage (Peng, et. al, 2017).

5.1 Life-cycle Analysis and Well-to-Wheel Approach

According to Mierlo et. al. (2017) a life-cycle analysis (LCA) is a standardized methodology for the assessment of environmental performance of any product throughout the whole life-cycle. It takes into account all the emissions from different product stages including fuel production, vehicle production, vehicle operation and vehicle disposal. The so called well-to-wheels (WTW) approach is a subclass of life-cycle assessments only including direct and indirect consumptions related to fuel production and vehicle operations (Orsi, et. al, 2016).

Electric vehicles, including fuel cell electric vehicles, have been marketed as zero-emission vehicles. This can also be seen in our analysis above, bringing the BEV and FCV on top of the ranking. The claim is not accurate if emissions are included that are released from electricity generation, and therefore considering the WTW approach. The emissions can be reduced when electricity is generated from renewable sources, such as wind and solar, or nuclear. For countries, other than Norway, substantial greenhouse gas emissions can be associated in a well-to-wheel approach to electric vehicles.

In regards to LCA, it can be stated that considerable resources (energy and materials) are consumed and emissions generated during their production (Sullivan et. al, 2010). Battery technology needs to be researched, lithium and other rare earths need to be extracted and assembled to battery packs we are familiar with in electric vehicles and after the life of a vehicle, the battery packs need to be properly disposed and recycled (Mierlo et. al, 2017).

6. Conclusions

The purpose of this thesis has been to compare various powertrain technologies in use today through various dimensions and to create a composite indicator including these dimensions. CO2 emissions, NOx emissions, Norwegian retail price, driving range and noise pollution have been identified as dimensions and reference vehicles have been compared against these dimensions. Ranking was used as normalisation method in order to make the dimensions comparable. The data was available online under no cost.

The composite indicators created show different results depending on the weights that are assigned to the dimensions. Dimensions were able to be assigned to two sub-categories, namely environmental focus and user preference. In the analysis three different composite indicators were created. Firstly, equal weights were assigned to the all dimensions, and therefore setting an equal importance to the dimensions. The full HEV reference vehicle, Toyota Prius VVT-i, came in first in the final ranking, performing best in noise pollution and price, as well as having decent ranking for CO2 and NOx emissions, even though coming behind the BEV, FCV and PHEV in the respective dimensions. Secondly, the focus was shifted to environmentally benign powertrain technologies assigning 80 percent of the weight to CO2 emissions and NOx emissions. Such a shift in focus meant that the BEV reference vehicle, Volkswagen e-Golf, and the FCV reference vehicle, Toyota Mirai, ranked first and second respectively. Both cars are considered to be zero-emission vehicles in vehicle operation. Lastly, 80 percent of the weights were given to dimensions reflecting user preferences, such as price, driving range and noise pollution. It is assumed, that the lower the price, the lower the noise pollution and the higher the driving range of a reference vehicle is, the higher the user preference will be. The Toyota Prius VVT-i, ranked first again, basically due to the mentioned reason in the first composite indicator. Most notably, the Diesel Car, Volkswagen Golf TDI, takes the third rank, even though it turned last in the CO2 emissions and NOx emissions dimensions.

Composite indicators are a powerful tool being able to enable users to compare and understand complex dimensions effectively. The constructor of the composite indicator can influence the reliability and meaningfulness of the indicator in every step. This composite indicator can be taken as starting point for further researchers, including other dimensions such as infrastructure availability, total cost of operations, particle matter emissions, refuelling time, safety and many more. Furthermore, it can be expanded by adding more reference vehicles, more vehicle segments or more powertrain technologies to the analysis.

However, this thesis does not take a LCA into account and only assesses the TTW stage of a WTW approach into account. Energy resource extraction, energy carrier production and distribution, battery manufacturing and disposal, vehicle manufacturing and materials production have therefore not been analysed. Further research could expand the focus of this composite indicator to the well-to-tank (WTT) stage or even be part of a LCA.

7. References

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