A Comparative Life-Cycle Sustainability Assessment in the Automotive Sector: Internal Combustion vs. All-Electric Vehicles

by Kyra Frederick
kcf29@cornell.edu
B.S Candidate
Department of Biological and Environmental Engineering
Cornell University

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1. EXECUTIVE SUMMARY

All-Electric Vehicles have been growing in popularity with the promise of offering a more sustainable driving experience. However, the question of whether AEVs truly offer an environmental, social or economic advantage still remains.

To address this question, this report will conduct a Life Cycle Sustainability Assessment of both passenger vehicle types, Internal Combustion Vehicles (ICV) and All-Electric Vehicles (AEV), along their life cycle. The LCSA is composed of three sections dedicated to each pillar of sustainability (environmental, social and economic): Environmental Life Cycle Assessment (E-LCA), Life Cycle Costing Analysis (LCC), and Social Life Cycle Assessment (S-LCA). The E-LCA indicates that AEVs cannot definitively be described as having a lesser environmental impact than ICVs. The LCC determines that, for both vehicles, the total life cycle cost is presently greater for AEVs than ICVs. The S-LCA indicates that the statuses of the "transparency" and "health and safety" impact subcategories are satisfied and at risk, respectively with ICVs posing a greater risk to stakeholder health and safety.

More specifically, AEVs will produce lower levels of emissions reactive to ICVs but generate vast amounts of human toxicity potential compared to ICVs due to the battery material requirements. ICVs will continue to have an economic advantage over AEVs despite the driving costs savings associated with electricity use over gasoline use. AEVs will continue to have the social advantage of safety and health due to vehicle design opportunities available to AEVs.

The analysis concludes that the complex reality of passenger vehicle sustainability will remain challenging for the environmentally, economic and socially conscious consumer and automaker when choosing between vehicle alternatives, as neither can be described as having an overall lesser impact.

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2. GOALS AND SCOPE

2.1. Goal

This Life Cycle Sustainability Assessment (LCSA) aims to (1) determine the life cycle sustainability impact of internal combustion vehicles (ICVs) and all-electric vehicles (AEVs) at different life cycle stages, and (2) to compare the relative life cycle sustainability impact of each transportation alternative. The LCSA is intended to be used by consumers in the position of purchasing a passenger vehicle and by decision-makers in the automotive industry interested in improving the life cycle sustainability of their vehicle type. It is important to note the limitations of this LCSA that no formal methods were used in the construction of the LCSA and the analysis was not submitted for peer review.

2.2. Scope

Within this LCSA, the two different vehicle technologies to be analyzed and compared include internal combustion vehicles (ICV) and all-electric vehicles (AEV). The function of both vehicle types, ICV and AEV, is to be used for transportation on roads. System boundaries will be set for ease of analysis. With the exception of the S-LCA, no boundaries will be set with respect to the life cycle stages of each passenger vehicle which means the LCSA will include all life cycle stages from extraction of materials, manufacturing and operation to end of life stage of passenger vehicles. Due to the complexity of the pre-manufacturing supply chain, the S-LCA will only be analyzed for the manufacturing and use life cycle stages of each respective passenger vehicle, excluding the material extraction, and end of life stages of passenger vehicles. It will also only include first-degree social impacts made at the vehicle manufacturer, not second-degree effects such as those from parts manufacturers and distributors. Internal combustion vehicles (ICV) will be analyzed at the average mile per gallon (MPG), namely

25mpg (John, 2019). Where average vehicle values are not available for AEVs, data will be taken from the 2020 highest selling AEV, the Tesla Model 3 (Wagner, 2021). For AEVs, special consideration will be given to the life cycle of the vehicle's battery as this is the primary point of contention in debates concerning the sustainability of AEVs (Lyons, 2018). The battery considered for the AEV will be lithium ion batteries. The full life span of each vehicle is considered to be 150,000 miles (Bult, 2019). The functional unit to be used for consideration throughout the analysis will be one vehicle. This report was prepared from the perspective of a former intern at an all-electric vehicle manufacturer, auto enthusiast, and engineering student at Cornell University for BEE 3299 Sustainable Development.

3. LIFE CYCLE ANALYSIS

3.1. Environmental LCA

In this Environmental LCA, the environmental impact of AEVs and ICVs are evaluated and compared. Subsections of the E-LCA include (1) a Life Cycle Inventory delineating the life cycle stages considered for the vehicles and inputs and outputs associated with each, (2) a Life Cycle Impact assessment describing the midpoint and endpoint impact categories impacted by the inputs and outputs described in section (1), and (3) a concluding Interpretation of (1) and (2). The goals of this section echo that of the overall LCSA but with a focus on the environmental pillar of sustainability.

3.1.1. Phase 2, Life Cycle Inventory

In 2019, electric car sales accounted for 2.6% of global passenger car sales amounting to 2.1 million electric cars and 78.6 million non-electric passenger vehicles (iea, 2020).

Description of Processes to Produce Vehicles:

Passenger vehicle production begins with raw material extraction and processing (Madehow, n.d.). The majority of a vehicle is made up of virgin steel, aluminum and petroleum materials while ICVs have the added material requirement of the rare and difficult to extract lithium used in lithium ion battery production (Daniel, n.d.). The manufacture of passenger vehicles can be broken down into two stages, namely, part construction and vehicle assembly. Before parts are brought together into a vehicle at an automotive factory, parts are made and shipt from thousands of outside suppliers. All shipping, manufacturing and assembly require energy, water, and raw materials and will result in airborne emissions, solid waste and water effluents aside from the final vehicle production. Throughout the vehicle operation phase, ICVs will require gas and AEVs will require electricity to run which, in the case of ICVs, will result in tailpipe emissions and roadside noise. The end of life of a vehicle will generate either solid waste or recyclable materials depending on the material. All metals like steel and aluminum and most plastics can be repurposed (Karagoz, 2020). Even lithium ion batteries are recyclable, though an energy demanding process (Bolt, 2021). According to Automotive Alliance (Shumbat, 2017), in fact, about 86% of a car is recycled at the end of life.

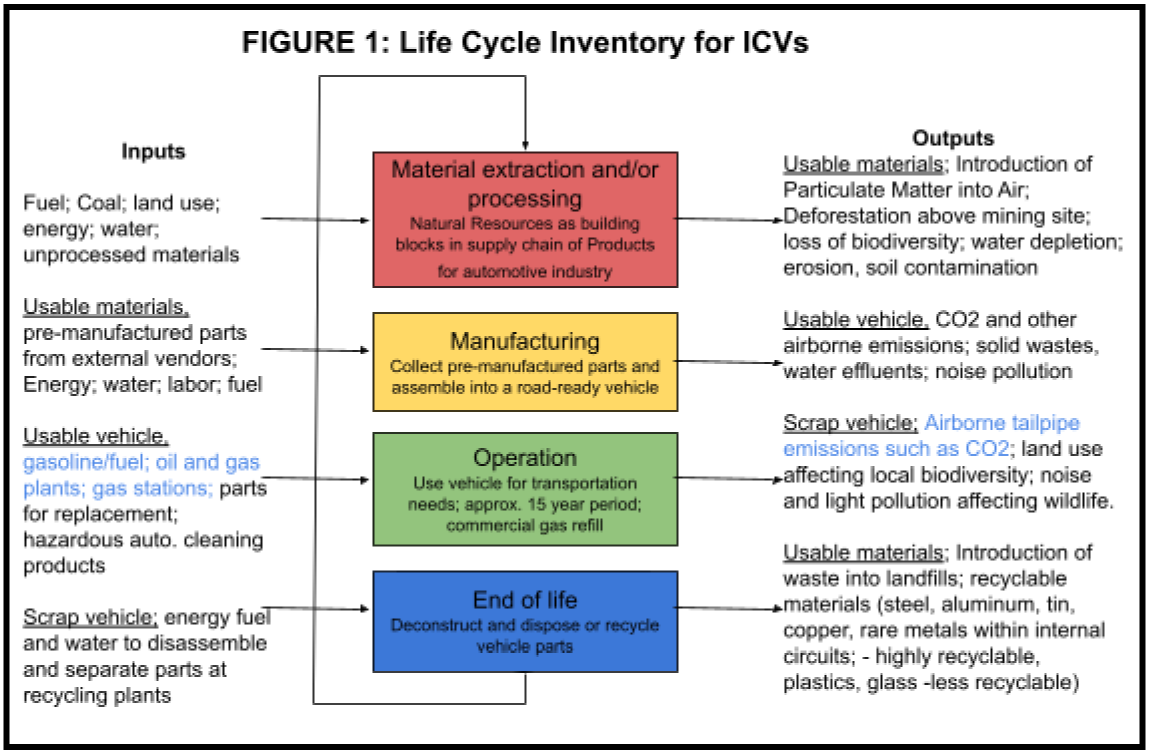

Figure 1: Life Cycle Inventory for ICVs

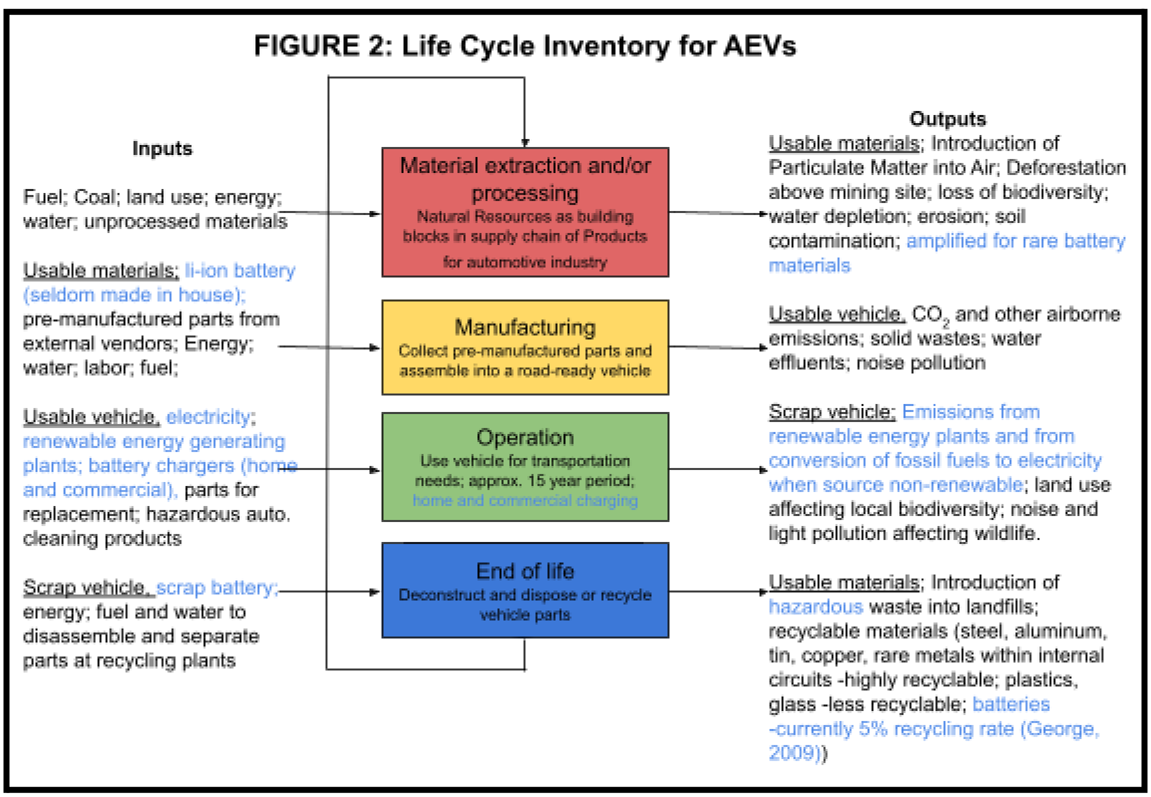

Figure 2: Life Cycle Inventory for AEVs

Figure 1 and 2 show an overview of the four product life-cycle phases of ICV and AEVs, respectively, with individual environmental inputs and outputs. Inputs or Outputs which exist for one vehicle type but not the other, are colored blue. The cradle to grave LCI model only includes inputs and outputs relevant to this environmental LCA, for example, an input in the manufacturing phase surely includes labor hours, however labor hours were excluded as they are extraneous to an environmental life cycle sustainability analysis.

3.1.2. Phase 3, Life cycle impact assessment

In the following section, the elementary flows described in phase 2 (shown in Figure 1 and 2) are assigned midpoint and endpoint impact categories to allow for more meaningful interpretation of the environmental sustainability impact of each system. Input and output terms are underlined and midpoint impacts are assigned numbers below for ease of clarity.

Among the most pressing environmental midpoint impacts of passenger vehicle technologies are (1) resource use, (2)global warming potential, (3) energy consumption, (4) water withdrawal (5) particulate matter formation (6) biodiversity and (7) waste generation. Other midpoint impacts not regarded in this assessment include categories such as acidification or land use.

Inputs associated with material extraction and processing and manufacturing intuitively will increase total (1) resource use, (3) energy consumption and (4) water withdrawal (Shahjadi et al, 2019; Wolff et al. 2020). AEVs impact is greater than ICVs in the (1) resource use category due to the rarity of materials involved in lithium ion battery manufacturing (Dominic, 2010). AEVs are the more (4) water intensive vehicle option while ICVs have the greater (3) energy demand in the material extraction and processing and manufacturing phases (Onat, 2014). Associated outputs of both life cycle phases will include airborne emission which affects (5) particulate matter formation, and (2) increases global warming potential (Onat, 2014; Farjana et al, 2019). Both AEVs and ICVs will have similar effects on these midpoint categories in the material extraction and manufacturing phases due to the similarity of process (Onat, 2014). The (6) biodiversity impact of material extraction outputs stems from land conversion associated with resource extraction (Sonter, 2018) while the (6) biodiversity impact of manufacturing outputs stems from manufacturing waste streams (Latu, 2018). The (6) biodiversity footprints will be greater for ICVs and AEVs again due to the rarity of materials involved in the manufacture of lithium-ion batteries and greater land conversion involved in its extraction (Dominic, 2010). Additionally, vehicle manufacturing generates scrap materials which will affect the midpoint category (7) waste generation. Due to the similarity of manufacturing of ICVs and AEVs, equivalent waste generation is expected in this phase, however, hazardous waste is greater for AEVs than ICVs due to lithium ion battery and renewable energy power plant material requirements (Onat, 2014).

Automotive vehicle operation input of gas and electricity for ICVs and AEVs respectively will also intuitively increase (3) total energy consumption. Outputs of the vehicle operation phase include airborne emissions which affect (5) particulate matter formation and (2) increase global warming potential (Onat, 2014) while outputs such as land use (roads) and noise required to drive passenger vehicles will affect (6) local biodiversity (Bennett, 2017). The vehicle operation phase will contribute the greatest impact to any of the midpoint impact phases as it is the most long lasting phase of each passenger vehicle's life span (Onat, 2014). In the operation phase, all described midpoint categories except (5) particulate matter formation will experience the greatest effects from ICVs. PMF is higher for AEVs due to air emissions from electric power generation (Samaras, 2008).

The end of life stage inputs will affect (3) energy consumption while outputs will affect (7) waste generation (Karagoz, 2020). Waste generation from AEVs is greater than that for ICVs in this stage (Onat, 2014). All associated midpoint impacts will produce endpoint impacts on ecosystem quality, resource depletion, human health and climate change.

3.1.3. Phase 4, Interpretation:

For the interpretation it can be concluded that neither ICVs or AEVs can be described as having a lesser environmental life cycle sustainability impact than the other. Both AEVs and ICVs posed advantages within individual categories however a quantitative analysis of each respective impact per functional unit would be required inorder to describe a clear winner with regards to overall sustainability of individual midpoint impacts within the boundaries of this analysis. Notably, a significant barrier to such an analysis would be the need to create a comparative measure for evaluating the difference in severity of each midpoint impact for example, should water depletion be considered more severe than raw material depletion? Focused (not wholistic) suggestions can be made for instance, electricity generation through renewable sources could significantly reduce the impact of AEVs on particulate matter formation and global warming potential (Samaras, 2008). This suggestion will become more suitable as renewable energy generation becomes more available. On the flip side, however, it could be suggested to power AEVs with electricity from non-renewable sources as this would reduce the hazardous waste generation of AEVs due to material requirements of solar charging stations (Onat, 2014). If any conclusion can be drawn from the above environmental LCA it is that the debate about the relative sustainability of AEVs and ICVs could benefit from a more comprehensive environmental LCA of each system. It also highlights the usefulness of life cycle inventory accounting for quantifying the environmental impacts of products. Further study could advance the presented approach through combined consideration of each of the three pillars of sustainability. This study is limited in the conclusions that can be drawn as it will not undergo the critical peer review process where at least three independent experts review the methods and results of the study. For this reason, data and content should be considered as superficial and incomplete. Accepted methods for the LCIA were not used in the construction of this environmental LCA.

RESPONSE TO PEER REVIEW (E-LCA)		
Comments		Responses
1	TA comment: “Good job providing a general diagram, however it doesn’t fully characterize the inputs and outputs for the system, especially because these vary between the two vehicles. I would suggest making two diagrams (one for ICVs and one for AEVs) so that your diagram and narrative support each other. For example, you mention that ICVs will require gas and this will result in tailpipe emissions which AEVs won’t experience so this specific input and output would be important to show on the diagram.”	I appreciate that this point was drawn to my attention. In response, I created two separate diagrams, one for ICVs and one for AEVs (see Figure 1 and 2).
2	Peer comment: “A specific action you could take is to include more detailed info on your graph, particularly in the middle column.”	This was a perceptive comment on something I had not considered for my graph. In response, and after reviewing my peer’’s graphs which included more detailed inputs and outputs and a more developed mid section, I expanded on information in my graphs and mid sections.
3	My comment: I felt it was difficult to compare between my two figures for AEVs and ICVs.	In response, I highlighted which inputs and/or outputs were present for one vehicle type but not the other by coloring them blue to more easily compare between both vehicle types.

3.2. Life Cycle Costing

In this Life Cycle Costing Analysis the economic impact of AEVs and ICVs are evaluated and compared. Subsections of the LCC include (1) an Inventory of Aggregate Costs by life cycle stage categories, (2) a concluding Interpretation of (1). The goals of this section echo that of the overall LCSA but with a focus on the economic pillar of sustainability.

3.2.1. Phase 2&3, Aggregate Costs by Category

The complexity of the Aggregate Costs by Category requires that a detailed method section be included. This phase three is divided by (1) Methods and (2) Description of Results.

3.2.1.1. Methods:

The goal was to attain the total cost put into a vehicle throughout its lifecycle. Inorder to attain this value, costs invested into the vehicle in one life cycle stage were subtracted in the subsequent stage, for example, the cost of producing a passenger vehicle in the manufacturing stage was subtracted in the operation stage from the price of the vehicle inorder to avoid duplication. The result would mean that the remaining cost in the operation stage would equate to the profit awarded to the manufacturer. The same process was conducted within the manufacturing stage for the raw material cost of goods sold. Where appropriate, AEV cost values were calculated by adding costs associated with the battery to the cost calculated for ICVs. For example, the cost of raw material extraction is assumed to be equivalent for AEVs and ICVs outside of the additional battery material requirements for AEVs. Autobodies of both vehicles can be assumed to be of similar cost because the main cost differentiator between both vehicles is the AEVs addition of the battery (Erneuerbare, n.d.; Onat, 2014). The Raw Material COGS was calculated using \$/car or \$/kWh values reported by automotive manufacturers and reduced using the 2020 average profit margin for the raw materials industry at roughly 25% (CSIMarket, 2021). Manufacturing costs were reported using previous research on the manufacturing cost per vehicle and again, the value present in the table was reduced by the Raw Material cost in the previous life cycle stage. Average miles driven per year were assumed to be 13,476 mi/yr (IDriveSafely, n.d.). The full life span of each vehicle is considered to be 150,000 miles (Bult, 2019). AEV values, when without averages, were calculated using data on the highest selling AEV, the Tesla Model 3 (Wagner, 2021). The End of Life section is separated into two parts, the disposal cost and value extracted from recycling. The End of Life Total Cost is reported as a negative value because it reflects the earnings associated with selling/recycling scrap car material. Once average material weights were found, each material type was reduced by the fraction of vehicles recycled (instead of disposed of) and by the fraction of the material which could be retained after recycling. Landfill costs were calculated for both, the fraction of US vehicles which are disposed of (instead of recycled) and the fraction of recycled vehicles that could not be recycled. Recycling rate of batteries was assumed to be 5% (George, 2009) and that of vehicles to be 95% where the recycled materials are assumed to be steel, aluminum, and plastic (Jody, 2006). The recycled fraction of the aluminum is assumed to be 90%, and 95% for all other materials (EPA, n.d.). The fraction of material which could be reused post-recycling is assumed to be a third for batteries (Guardian, 2017) and 86% for vehicles (Shumbat, 2017). The ICV EOL value is greater than the raw material cost because the EOL value includes the profits incurred by the recycler whereas the raw material cost only represents the COGS with the raw material profits being present within the manufacturing raw material cost value. The author of this LCC felt this calculation method to be important to evaluate the cyclical nature of a vehicle life cycle.

While the goal was to attain the total cost over the vehicle's entire lifecycle, the cost to individual stakeholders can be determined by their segregated involvement in respective stages. For example, the automaker’s expenditure is summarized by manufacturing phase data and the consumer expenditure by operation phase data.

Cost category	Vehicle Type ICV ($/vehicle)	AEV ($/vehicle)	Source
Raw Material Extraction/Processing Cost			
Vehicle Material Cost	$1,501		(MasterAutocar, 2018); (CSIMarket, 2021); (Bult, 2019)
Battery Material Cost		$6,150	(ArgusMedia, 2019); (CSIMarket, 2021); (Bult, 2019); (Wikipedia - Tesla Model 3, 2021);
Raw Material cost	**$1,501**	**$7,651**	(ArgusMedia, 2019); (Wikipedia - Tesla Model 3, 2021); (CSIMarket, 2021); (Bult, 2019)
Manufacturing Cost			
Raw Material cost	-$1,501	-$7,651	(Built, 2019); (Ruffo, 2020)
Manufacturing cost	$15,138	$16,529	(Built, 2019); (Ruffo, 2020)
Operating Cost			
Manufacturing cost	-$15,138	-$16,529	(Built, 2019); (Ruffo, 2020)
Driving Cost	$16,470	$1,208	(AAA, n.d); (John, 2019); (ElectricChoice, n.d.); (Wagner, 2021); (Wikipedia - Tesla Model 3, 2021); (Brennan, 2016);(Bult, 2019)
Insurance cost	$17,720	$24,655	(Norman, 2021); (IDriveSafely, n.d.)
Financing cost	$2,785	$4,195	(Bult, 2019); (Kopestinsky, 2021); (Ward, 2020)
Maintenance cost	$5,651	$2,251	(Brennan, 2016); (Bult, 2019)
Savings from Tax credit		-$7,500	(FuelEconomy, n.d.); (IDriveSafely, n.d.)
Total Operating cost	**$64,088**	**$63,880**	
End of Life Cost			
Disposal/ Recycling Cost			
Battery recycling cost		$576	(Guardian, 2017); (Wikipedia - Tesla model 3, 2021); (Bult, 2019); (George, 2009)
Vehicle Scrap recycling cost	-$285		(Cash Auto Salvage, 2019); (Bult, 2019); (Blanco, 2007)
Disposal Cost of non-recyclables within recycled vehicle	$16		(WasteTodayMagazine, 2019); (Autolist, n.d.); (Shumbat, 2017); (Bult, 2019)
Disposal Cost of non-recycled vehicles	$6		(WasteTodayMagazine, 2019); (Autolist, n.d.); (Blanco, 2007); (Bult, 2019)
Total Recycling cost	**-$264**	**$307**	
Reclaimed Value from Recycling			
Value of reclaimed Steel	$540		(Maverick, 2020); (Onat, 2014); (FocusEconomics, 2016); (Blanco, 2007); (Bult, 2019)
Value of reclaimed Plastic	$22		(Maverick, 2020); (Onat, 2014); (Resource-recycling, 2020); (Blanco, 2007); (Bult, 2019)
Value of reclaimed Al	$1,063		(Maverick, 2020); (Onat, 2014); (BusinessInsider, 2021); (Blanco, 2007); (Bult, 2019)
Value of reclaimed Battery		$192	(Guardian, 2017)
Total Reclaimed value	**$1,625**	**$1,817**	
Net EOL Cost/Value	**-$1,889**	**-$1,511**	

Table 1: Aggregate cost by life cycle stage of passenger vehicle technologies (ICV and AEV) (see appendix A for the full spreadsheet used for calculation). Each table value reflects the cost in $/vehicle lifespan in accordance with the functional unit defined in phase 1 of the LCC.

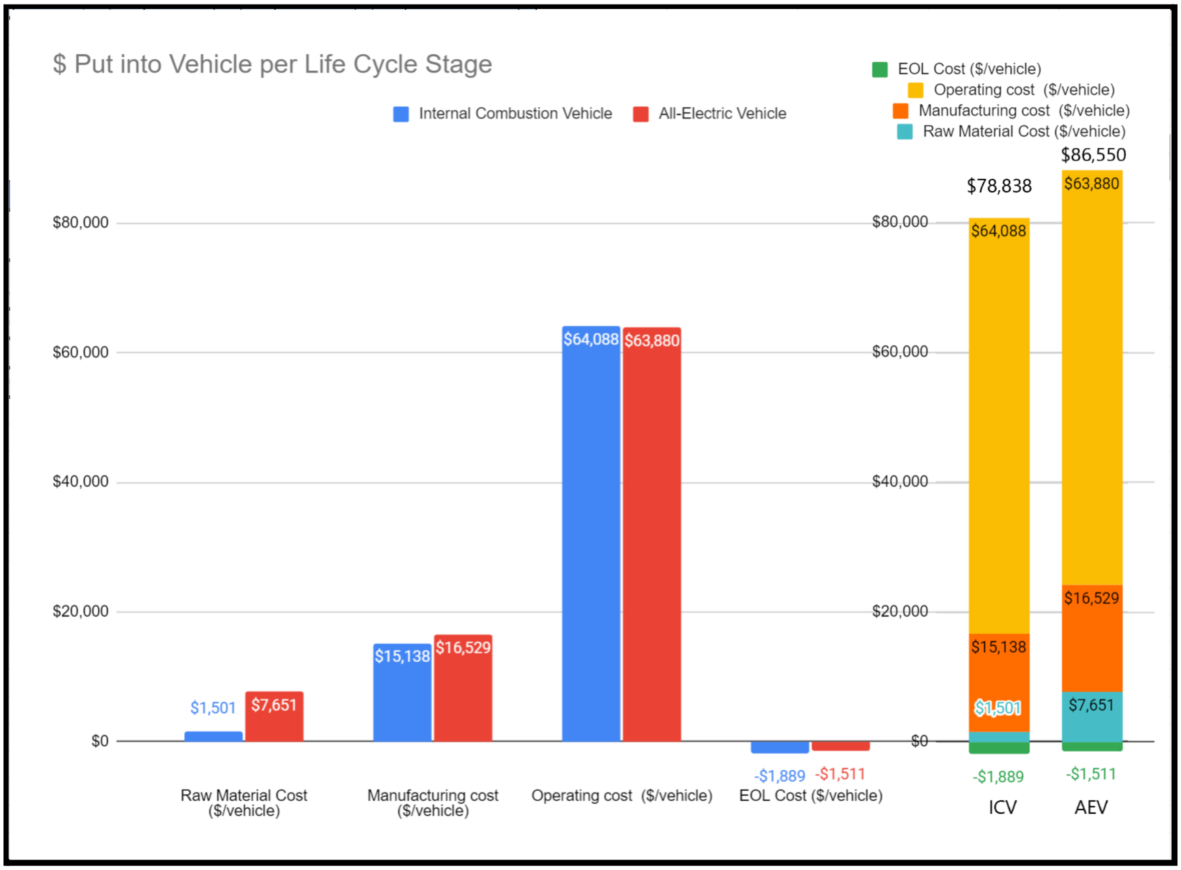

Figure 3: Summary of information presented in Table 1: *Aggregate cost by life cycle stage of passenger vehicle technologies (ICV and AEV)*

3.2.1.2. Results

Figure 3 summarizes the data presented in Table 1. The majority of the costs incurred in a vehicle's lifecycle occur in the operation phase with the second largest being manufacturing cost and then Raw Material Cost. Data values are relatively similar for each phase aside from the Raw Material phase. It should be noted again that while the manufacturing cost appears similar for AEVs and ICVs, the raw material cost was subtracted from these values so the actual cost of manufacturing a vehicle will be of a margin more closely resembling that of the Raw Material cost. This is because the higher cost of electric vehicle manufacturing primarily stems from the material requirements of the battery (Onat, 2014; Ruffo, 2020). The roughly $1500 margin in the manufacturing stage likely stems from the additional cost of assembling the battery powertrain and battery itself. The margins presented in Figure 3 are consistent with those presented in other studies (Onat, 2014; Ruffo, 2020). The operating costs of each vehicle are very similar, however again, the COGS from the manufacturing phase was subtracted from these values. When compared, the maintenance cost and driving (gas vs electricity) cost were significantly lower for AEVs but these benefits were negated by the added insurance cost, financing costs and costs associated with home charging installment. Even the federal tax incentive (FuelEconomy, n.d.) was not high enough to make the AEVs of lesser cost than ICVs throughout its lifespan.

The end of life cost was negative for both AEVs and ICVs which reflects the profit incurred from recycling each scrap vehicle. Notably, a vehicle owner must pay to recycle a lithium ion battery due to the difficulty of recycling materials within it (Bolt, 2021) whereas scrap vehicles (without batteries) can be sold (CashAutoSalvage, 2019). The value of each reclaimed material within the vehicle was highest for the metals followed by battery materials and then the vehicle plastics. The earnings from recycling were greater (or cost was more negative) for ICVs primarily due to the additional charge associated with recycling a battery (Guardian, 2017). The ICV EOL value is greater than the Raw Material cost because the EOL value includes the profits incurred by the recycler whereas the raw material cost only represents the COGS while the raw material profits are present in the manufacturing stage as the raw material cost for the manufacturer. The author of this LCC felt this calculation method to be important to evaluate the cyclical nature of a vehicle life cycle. The reclaimed material value from the battery for the recycler was not great enough to bring the EOL value of AEVs over that of ICVs primarily because only a third of the materials within a scrap battery can be recovered

(Guardian, 2017). The total EOL value of AEVs would be greater if the battery were disposed of even though the materials within the battery have a high purchasing price (ArgusMedia, 2019).

Externality of each vehicle type include air pollution, and traffic congestion and accidentes for which the former will be accounted for in the environmental LCA and the latter in the social LCA.

3.2.2. Phase 4, Interpretation:

The data suggests that the total life cycle cost is presently greater for AEVs than ICVs. Both AEVs and ICVs posed advantages within individual categories of life cycle stages for example the costs of operating a vehicle are lower for AEVs but the manufacturing costs are lower for ICVs. Although future projections suggest slight cost reductions for AEVs in the raw material extraction and manufacturing phases (Brennan, 2016) these are likely to remain higher for AEVs due to the rarity of materials involved in lithium ion battery production and cost of electric powertrain assembly (Onat, 2014). Important to the consideration of the overall sustainability of each vehicle type is a comparison between the Raw Material Costs and EOL value. When comparing the AEV and ICV raw material cost and the EOL value of each vehicle's materials, the margin from beginning to end of life leads to the conclusion that AEVs are significantly less cyclical or sustainable from a raw materials standpoint than ICVs. This is because the battery value was reduced by the fraction of batteries currently being recycled in the US, namely 5% and the value that can be extracted from each recycled battery, namely a third (Guardian, 2017). If AEV batteries were recycled at a greater rate, the value of reclaimed material from AEVs would rise significantly, however, the US's waste management system has yet to develop the capacity to recycle such a volume of batteries (Bolt, 2021). The value of material capable of being extracted from a battery is far from being at a rate high enough to lower the overall lifecycle costs of AEVs below that of ICVs (Guardian, 2017). Externalities of each vehicle type include air pollution, and traffic congestion and accidents for which the former will be accounted for in the environmental LCA and the latter in the social LCA. This LCC highlights the importance of life cycle cost accounting for use in the analysis of the overall sustainability of a product, especially when produced in complement with environmental and social assessments. Further study could advance the presented approach through combined consideration of each of the three pillars of sustainability. Although an effort was made to keep in mind the information quality and credibility when selecting sources, a number of data values in Table 1, did not include any form of data verification, for example those on national average material costs. Assumptions made in the creation of Table 1, such as those pertaining to average vehicle lifespan and average annual mileage, unavoidably reduce data reliability. When data values were presented without validation, an effort was made to presume quality by comparing similar values across various sources or by determining which sources were trusted industry standards for attaining cost data such as CSIMarket. Data values were drawn from sources published in different time periods which makes their compilation unlikely to be a true reflection of current values. Most data released on AEVs were calculated/evaluated with a single or limited number of specific AEVs in mind so they do not represent a sample size large enough to produce accurate representations of the average AEV. Even within this report, when average data values were not available, the Tesla Model 3 was used as a benchmark AEV with which to draw conclusions on national average AEV values. At times, data extracted from specific manufacturers were not separated by vehicle type or data was presented as averages for the automotive sector instead of for ICV automobiles making comparison between both vehicle types difficult and of lower data quality. Further discussion of data quality and credibility is included at the end of this report.

RESPONSE TO PEER REVIEW (LCC)		
Comments		Responses
1	TA Comment: No TA comments/suggestions received for L5Pt2 but L5pt1: “it was not clear if you included the perspective from which your LCC was conducted. You spoke about consumers and decision makers, but I took this to be your audience. Make sure to always include every rubric element clearly!”	I appreciate that this was drawn to my attention as I had initially overlooked this rubric element. In response, although there was no goal statement within the E-LCA for the LCSA I felt my analysis could still benefit from a statement of perspective so I included it in my overall LCSA’s goal statement.
2	Peer comment: “You made quite a few assumptions throughout the LCC, so maybe mention how these assumptions could affect the completeness.”	This is an excellent suggestion. In response, I decided to speak about my assumptions in the “discussion of data quality and credibility” section in my LCSA conclusion as well as in my Interpretation section in this LCC.
3	In addition to my peers suggestion to comment on the assumptions I made, I felt there were more limitations I should have mentioned in my interpretation section	In response, I expanded on my discussion of limitations in the LCC’s Interpretation section as well as in the conclusion section.
4	Peer comment: “ In the goal statement you sort of listed two different categories of people, consumers and decision makers in the automotive industry. The cost analysis will not be the same for these two entities, right? So I would suggest narrowing it down to one...”	I understand the sense to want to narrow down my perspective to speak about the costs to one category of involved stakeholder, however as I wanted to get a sense of the total expenditure throughout the entire lifecycle of each vehicle type, narrowing it down to the expense of one stakeholder would be outside the scope of my intended analysis here. However the cost to individual stakeholders can be determined by their segregated involvement in respective stages. For example, the automaker’s expenditure is summarized by the manufacturing phase data and the consumer expenditure by the operation phase data. I will not condense my aggregate cost table as this is

		not my goal but I will add a sentence explaining how a stakeholders expenditure can be determined.

3.3. Social LCA

In this Social LCA, the social impact of AEVs and ICVs are evaluated and compared. Subsections of the E-LCA include (1) an Inventory delineating two impact subcategories with corresponding stakeholder categories, (2) an Impact assessment describing the status of each impact subcategories effect on individual stakeholders listed in (1), and (4) a concluding Interpretation of (1) and (2). The goals of this section echo that of the overall LCSA but with a focus on the social pillar of sustainability. Unlike the E-LCA and LCC, the S-LCA will only be analyzed for the manufacturing and use life cycle stages of each respective passenger vehicle, excluding the material extraction, and end of life stages of passenger vehicles.

3.3.1. Phase 2, Inventory

Listed below are the two impact subcategories and associated stakeholder categories which will be considered in this S-LCA. For each impact subcategory, data sources are described and assessed.

1. Transparency: Consumer; society
2. Safety and Health: Local community; consumer; worker; society

I found qualitative data for the Transparency impact subcategory in the form of Sustainability Reports from 5 popular US-based automakers (Ford, General Motors, Honda, Tesla, Toyota) who distribute both ICV and AEVs. Although transparency is not only about releasing a sustainability report (UNEP, 2013), it is often the most holistic and digestible method of acquiring impact data for an organization. The data is presumed to be reliable for each company because each includes independent/third-party verification statements either within, attached, or linked in the respective reports, except for Tesla, for which the data is confirmed by an internal audit team (Ford, 2021; General Motors, 2019; Honda, 2020; Tesla, 2019; Toyota; 2020). Sustainability reports of the 5 automotive manufacturers include disclosure of environmental, social, and governance (ESG) goals, progress towards achieving the goals, stakeholder list, ESG key performance indicators, and other qualitative efforts being made to reduce the organizational footprint. The sustainability reports also offer information about safety and health (often referred to as ESH, EHS, SHE, or EHSS in the reports) that can be used for the analysis of this S-LCA's second impact subcategory. All large automakers are ISO 45001 certified which is a certification for occupational health and safety management systems and speaks to a high-level commitment to health and safety by all involved automakers. Data included within each sustainability report can be used to determine the extent of transparency offered by each automaker on respective vehicle types to determine whether the automakers provide the transparency necessary for consumers and society to make informed purchasing decisions and understand health risks posed by the automaker's products. On the Safety and Health impact subcategory, data included within the reports can provide information about the safety and health management systems and key performance indicators of each automaker. One limitation is that data included within the report are seldom separated by vehicle type which can make the comparison of both vehicle types more difficult in a later LCSA. Additionally, due to the nature of social data, it is often qualitative, making objective comparison and evaluation more difficult than if the evaluation criteria were quantifiable. The data used in the reports can only represent the social impact of passenger vehicles in the manufacturing and use phases and cannot be used to determine the social impacts in other life cycle stages.

3.3.2. Phase *3, Impact Assessment*

Impact Subcategory	Applicable Stakeholder Category	Status	Assess-ment
Transparency	Consumer	*Satisfied* - data within sustainability reports is publically available and has become an industry standard for passenger vehicle manufacturers (Ford, 2021; General Motors, 2019; Honda, 2020; Tesla, 2019; Toyota; 2020).	
	Society	*Satisfied* - data within sustainability reports is publically available and has become an industry standard for passenger vehicle manufacturers (Ford, 2021; General Motors, 2019; Honda, 2020; Tesla, 2019; Toyota; 2020).	
Safety and Health	Local Community	*At risk* (greater with ICVs than AEVs) (Hineman, 2020)	
	Consumer	*At low risk* (higher risk than AEV owners) (Coverhound, n.d; DesignNews, 2017)	
	Worker	*At risk* (Grimella, 2017)	
	Society	*At risk* (greater with ICVs than AEVs) (Hineman, 2020)	

Table 1: Social impacts of Internal Combustion Vehicles (ICVs)

Impact Subcategory	Applicable Stakeholder Category	Status	Assess-ment
Transparency	Consumer	*Satisfied* - data within sustainability report is publically available and has become an industry standard for passenger vehicle manufacturers	
	Society	*Satisfied* - data within sustainability report is publically available and has become an industry standard for passenger vehicle manufacturers	
Safety and Health	Local Community	*At low risk* (greater with ICVs than AEVs) (Hineman, 2020)	
	Consumer	*At low risk* (lower risk than ICV owners) (Coverhound, n.d; DesignNews, 2013)	
	Worker	*At risk* (Grimella, 2017)	
	Society	*At low risk* (greater with ICVs than AEVs) (Hineman, 2020)	

Table 2: Social impacts of All-Electric Vehicles (AEVs)

The table above describes social impacts by stakeholder category of ICVs (Table 2) and AEVs (Table 2). Depending on the involvement of respective stakeholders, the tables apply to the manufacturing and use life cycle stages of passenger vehicles. Due to the fact that sustainability reports have become somewhat of an industry standard for the passenger vehicle manufacturing industry, and that the reports are publicly available, the status for transparency is marked as satisfied for both ICVs and AEVs for each respective stakeholder group. Of all five sustainability reports released by major US-based automotive manufacturers (Ford, General Motors, Honda, Tesla, Toyota), all, except Tesla, received third party data verification. Tesla's data received verification by an internal Audit Team (Tesla, 2019). For the safety and health impact subcategory, the local community stakeholders are marked as at risk for ICVs and at low risk for AEVs. Tailpipe emissions from ICVs cause air pollution which can affect lung development and lead to asthma and other respiratory diseases (NIH, n.d.). While AEVs do not release tailpipe emissions, AEVs can indirectly contribute to air pollution when the electricity is sourced from non-renewable sources (Onat 2014). For this reason, it is marked as low risk instead of no-risk. Another risk factor for local communities is accidental death. Roughly 6000 pedestrians are killed by vehicles each year in the United States (CDC, 2020). While only a small fraction of the US population (.002%), pedestrian deaths are concentrated in urban areas, making pedestrian safety a greater risk for local communities in cities. For the purpose of this analysis, local communities and society can be considered as the same stakeholder group because roads and vehicles are so integrated into our society that whatever is local to a road also constitutes the entire US society. In fact, if you strip everything off a map except roads, the image looks no different than a regular map (Peters, 2015). Consumers are marked as low risk for both AEVs and ICVs, because vehicle owners only file accident insurance claims once every 17.9 years (Coverhound, n.d). It should be noted that the risk of accidents is lower for AEVs than ICVs primarily because the batteries are located under the vehicle which lowers its center of gravity and reduces the chances of rollover (Design News, 2013). The status of worker's safety and health is at risk for both passenger vehicle types, assuming that both involve similar manufacturing processes and no information could be found about whether battery or powertrain assembly for AEVs posed a significant safety risk. The status was assigned because 4 out of 100 full-time workers suffer some kind of nonfatal occupational accident or illness, twice the amount of the mining or chemical industry (López-Arquillos, 2016).

3.3.3. Phase *4, Interpretation*

When considering only transparency and safety and health, the social impact of both AEVs and ICVs are associated with a number of consequences, with AEVs having a lesser impact than ICVs. Neither AEV or ICV vehicles posed a greater social impact in relation to Transparency. All 5 major US-based automotive manufacturers released sustainability reports and received some form of verification, satisfying the transparency impact subcategory (Ford, 2021; General Motors, 2019; Honda, 2020; Tesla, 2019; Toyota; 2020). ICVs posed a greater risk to the safety and health impact subcategory when considering all relevant stakeholder categories. Differences in safety and health risks of ICVs stem primarily from vehicle design. Lowering the ICVs center of gravity (DesignNews, 2013), or eliminating tailpipe emissions through carbon capture devices (ScienceDaily, 2008) would reduce accident rates and air pollution risk, respectively. Such changes would lead ICVs to pose a safety and health risk more equivalent to that of AEVs. AEVs could lower safety and health impacts by using energy from renewable sources. It should be noted that renewable energy does not have zero effect on air pollution due to the nature of charging stations and solar/wind power plant construction (Onat, 2014). The analysis supports the overall conclusion that passenger vehicles, when analyzed with respect to safety and health, pose a risk to all involved stakeholders. Because this S-LCA was limited by the use of only two impact categories, it should be considered incomplete and no formal conclusion can be drawn of the overall social impact of each vehicle subtype. A comprehensive review of each impact subcategory would be required to make such a conclusion. Data comparing both vehicle types' effects on health and safety is also limited and this S-LCA could benefit from a more direct examination of the health effects of workers involved in different vehicle type's production lines and the health effects of consumers. Due to the selected impact categories, this S-LCA fails to acknowledge the positive social consequences of passenger vehicles on stakeholders which may outweigh the risk and lead to overall positive contributions. If any conclusion can be drawn it is that a life cycle analysis of passenger vehicles could benefit from the inclusion of a more comprehensive S-LCA and that the evaluation of social impacts is possible, even when limited by the subjective or qualitative character of social evaluation criteria. This study is limited in the conclusions that can be drawn as it will not undergo the critical peer review process where at least three independent experts review the methods and results of the study. For this reason, data and content should be considered as superficial and incomplete. Accepted methods for the LCIA were not used in the construction of this S-LCA.

RESPONSE TO PEER REVIEW (S-LCA)		
Comments		Responses
1	TA Comment: No TA comments/suggestions received for L6Pt2 but L6pt1 (Jee-In Lee): “ make sure to indent after the first line of your References.”	This is a great suggestion that I had initially overlooked when completing my reference section. In response, although there was no references section for my S-LCA, I indented my references at the bottom of my overall LCSA.
2	Peer Comment: “one specific action you can take to improve is to add a couple sentences tying it [the S-LCA] back to your goal and scope in the conclusion section.”	I felt this was an excellent suggestion so I included it in my overall conclusion statement at the end of the LCSA.
3	I felt my paragraph describing my tables in Phase 3 was unclear and difficult to understand upon the first read.	I rephrased sentences that I felt lacked clarity.

4	Peer comment (outside of BEE3299): "You should include more than two social impact categories to get a more comprehensive analysis of AEVs and ICVs in this S-LCA"	I wholeheartedly agree that my analysis would benefit from the inclusion of more impact categories for this S-LCA, however it is outside of the present scope of this project and of my analysis because the assignment asks us to include only two. Future studies of the social life cycle sustainability of passenger vehicles could significantly benefit from a more thorough analysis of all impact subcategories. From my findings, such an analysis does not exist yet for passenger vehicles.

4. CONCLUSION

This LCSA's comparative assessment of environmental, economic and social impacts for AEVs and ICVs, produced in 2021, concludes that neither AEVs or ICVs is the more sustainable vehicle alternative. This conclusion was determined following the completion of an E-LCA, LCC and S-LCA, which indicated that (1) neither vehicle type can be described as having a lower environmental impact, (2) AEVs have a greater total life cycle cost and (3) ICVs pose a greater risk to stakeholder safety and health with both vehicle alternatives satisfying the transparency impact subcategory.

It should be noted that this LCSA was focused on determining which vehicle alternative was "more" sustainable but neither product is sustainable. Because each vehicle type requires the use of non-renewable resources to manufacture and operate, and that both, unavoidably, result in a negative effect on the environment and human health, neither can be described as entirely sustainable.

Of particular importance is the use/operation life cycle stage which contributes the greatest impact to any of the three pillars because it is the most long lasting phase of each passenger vehicle's lifespan (Onat, 2014). The Operation phase has the greatest environmental impact, social impact and total cost of any of the other lifecycle stages. Although the case for the operation stage, impact is not always aligned with the duration of cycle, for example, the EOL AEV environmental effect is greater than that of the material extraction phase if materials go unrecycled, although shorter in duration.

Tradeoffs to any pillar are unlikely to alter this LCSA's ultimate conclusion. AEVs will improve such that total life cycle cost will decline with improvements in battery manufacturing, an increase in global battery recycling capacity and driving range improvements (Brennan, 2016), however costs are unlikely to fall below those of ICVs, even with improvements for AEVs, due to the rarity of materials required in lithium-ion battery manufacturing and the complexity involved in the battery powertrain assembly (Onat, 2014; Ruffo, 2020).

AEVs are also projected to experience a decrease in global warming potential (GWP) with driving range improvements and a decline in emissions from power generation associated with the changing US energy mix (Brennan, 2016). This GWP differential relative to ICVs will occur despite higher fuel economy requirements for ICVs, which lower ICV GWP. A slight decline in human toxicity potential (HTP), one of AEV's greatest environmental risk factors, is also expected with an increase in global battery recycling capacity and greater public awareness of the importance of recycling batteries (Bolt, 2021). If a quantitative grading system could be developed to assign relative weights to environmental impacts, the slight HTP reduction and respective GWP reduction for both vehicle types is unlikely to result in a clear winner as to who will have a lesser environmental effect.

Notedly, any environmental improvement for both ICVs and ACVs, such as driving range improvements, will inevitably raise the total manufacturing cost for each vehicle. The converse is also true where any attempt to reduce costs, for example in automotive manufacturing, could result in greater GWP and overall environmental impact. Cost reduction measures may also pose negative ramifications on social impact categories such as safety and health for relevant stakeholders (Brennan, 2016). One notable example is that, at present, the cost to recycle a battery is greater than the cost to dispose of it (Bolt, 2021) . In this example, if cost is prioritized, hazardous waste would be introduced into the environment and pose a risk to human health. If the environment is prioritized, total expenditure would rise. Ultimately, improvements in individual categories come with a cost whether it be paid in GWP, dollars or safety and health. AEVS and ICVS stage complex environmental, economic and social tradeoffs in which benefits in one sustainability pillar are linked to consequences in another pillar.

I restate the above argument to make my final point - **any tradeoff made in one pillar for either vehicle alternative, will result in consequences to another pillar**. Now consider that AEVs and ICVs are both vehicles. AEVs are ICVs with a special focus given to the environmental pillar, which, as predicted, results in consequences to total cost and human health. Keeping in mind that AEVs are only ICVs after making tradeoffs to one of the pillars, it makes sense why no clear winner can be chosen with respect to the overall sustainability of each vehicle type. Costs, environmental, economic or social can be transferred but they cannot be removed.

The complex reality of passenger vehicle sustainability will remain challenging for the environmentally, economic and socially conscious consumer and automaker, as neither can be described as having an overall lesser impact. Consumers and automakers must consider all future trade offs with a holistic cradle-to-cradle lens when weighing the impacts of alternative passenger vehicle technology.

4.1. Discussion of data quality and credibility

Although an effort was made to keep in mind the information quality and credibility when selecting sources, a number of data values, particularly those used in compilation of the Aggregate Cost by Category Inventory, did not include any form of data verification. When data values were presented without validation, an effort was made to presume quality by comparing similar values across various sources. It is the responsibility of any third party to, in use of this report, conduct proper due diligence in verifying this report's contents. The multitude of assumptions made in the creation of Table 1, such as those pertaining to average vehicle lifespan and average annual mileage, unavoidably reduce data reliability. Data values were drawn from sources published in different time periods which makes their compilation unlikely to be a true reflection of current values. Most data released on AEVs were calculated/evaluated with a single or limited number of specific AEVs in mind so they do not represent a sample size large enough to produce accurate representations of the average AEV. Even within this report, when average data values were not available, the Tesla Model 3 was used as a benchmark AEV with which to draw conclusions on national average AEV values. At times, data extracted from specific manufacturers were not separated by vehicle type or data was presented as averages for the automotive sector instead of for ICV automobiles making comparison between both vehicle types difficult and of lower data quality. In various sections of this report, AEVs were assumed to be of the same build as ICVs with the main differentiator being the AEV's addition of the battery leading to a differential of inaccuracy between AEV and ICV analyses. Due to the different assumptions and boundaries set within reports, a large discrepancy exists between sustainability data across published reports, particularly in the environmental section leading to an inherent reduction of data quality in this LCSA. An effort was made to presume quality through comparison across various sources and finding a level of consistency. Unlike the E-LCA and LCC, the S-LCA was only conducted for the use and manufacturing fases, excluding those in the extraction and EOL phases leading to a reduction in completeness with respect to the E-LCA and LCC. Because the S-LCA was limited by the use of only two impact categories, it should be considered incomplete and no formal conclusion can be drawn of the overall social impact of each vehicle subtype. Due to the selected impact categories, this S-LCA fails to acknowledge the positive social consequences of passenger vehicles on stakeholders which may outweigh the risk and lead to overall positive contributions. Quality issues such as these within the S-LCA were accounted for throughout this paper by (1) explicitly stating data limitations in the Interpretation of each of the three analyses and (2) by making some form of attempt to reduce data quality risk. Accepted methods for the LCIA were not used in the construction of this environmental LCA. This study is also limited in the conclusions that can be drawn as it will not undergo the critical peer review process where at least three independent experts review the methods and results of the study. For the above reasons, data and content should be considered as superficial and incomplete.

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Appendix A

Cost category	Vehicle Type ICV	Vehicle Type AEV	Notes	Source
Raw Material Extraction/Processing Cost				
Vehicle Mtrl. cost $/vehicle	$2,000.00		Cost for the purchaser/manufacturer	(MasterAutocar, 2018)
Gross Margin Raw Mtl Industry	0.2494			(CSIMarket, 2021)
Raw Mtrl COGS $/vehicle	$1,501.20		Selling price-COGS)/Selling Price. Solve for COGS	
Average mi/lifespan	150,000			(Bult, 2019)
Vehicle Material Cost $/mi	**$0.0100**			(MasterAutocar, 2018); (CSIMarket, 2021); (Bult, 2019)
Battery Raw Matl. Cost $/kWh		$75.00	Cost for the purchaser/manufacturer	(ArgusMedia, 2019)
KWh/battery		82.00	Based on #1 sold EV2020: Tesla Mdl 3	(Wikipedia - Tesla Model 3, 2021)
BatteryRaw Matl. Cost $/unit		$6,150.00		
Gross Margin Raw Mtl Industry		0.2494	Based on average 2020 industry gross margin percentage	(CSIMarket, 2021)
Raw material COGS $/battery		$6,150.000	(Selling price-COGS)/Selling Price. Solve for COGS	
Average mi/lifespan		150,000	(Bult, 2019)	(Bult, 2019)
Battery materials Cost $/mi		**$0.0410**		(ArgusMedia, 2019); (CSIMarket, 2021); (Bult, 2019); (Wikipedia - Tesla Model 3, 2021);
Raw Material cost $/mi	**$0.0100**	**$0.0510**		(ArgusMedia, 2019); (Wikipedia - Tesla Model 3, 2021); (CSIMarket, 2021); (Bult, 2019)
Manufacturing Cost				
Raw Material cost $/mi	**-$0.0100**	**-$0.0510**	raw material cost subtracted to avoid duplication of values between stages	(Built, 2019); (Ruffo, 2020)
Manufacturing cost $/lifespan	$16,638.86	$24,180.21	The E-drive adds $2400 to the production expenses, and the battery pack – at $9500	(Ruffo, 2020)
Average mi/lifespan	150,000.00		(Bult, 2019)	
Manufacturing cost $/mi	**$0.1009**	**$0.1102**		(Built, 2019); (Ruffo, 2020)
Operating Cost				
Manufacturing cost $/mi	**-$0.1009**	**-$0.1102**	manufacturing cost subtracted to avoid duplication of values between stages	(Built, 2019); (Ruffo, 2020)
Average Vehicle $/lifespan	$36,600.00	$55,600.00		(Coren, 2019)
Average mi/lifespan	150,000			(Bult, 2019)
Average Vehicle cost ($/mi)	**$0.2440**	**$0.3707**	*battery replacement cost is factored into maintenance cost and therefore not included in this calculation. EV charging station cost included within driving cost	(Coren, 2019); (Bult, 2019)
Gas cost $/gal	$2.7450	-		(AAA, n.d)
Average mpg	25	-		(John, 2019)
electricity cost ($/kwh)	-	$0.1320		(ElectricChoice, n.d.)
kWh/100mil	-	24	Based on #1 sold EV2020: Tesla Mdl 3	(Wagner, 2021) (Wikipedia - Tesla Model 3, 2021)
Average home EV charging $	-	$1,200.00		(Brennan, 2016)
Average mi/lifespan	-	150,000		(Bult, 2019)

Driving Cost ($/mi)	**$0.1098**	**$0.0081**	Ev average driving cost includes the initial cost of installation being Average Installation cost/lifespan /mi/lifespan	(AAA, n.d); (John, 2019); (ElectricChoice, n.d.); (Wagner, 2021); (Wikipedia - Tesla Model 3, 2021); (Brennan, 2016);(Bult, 2019)
insurance $/yr	$1,592.00	$2,215.00		(Norman, 2021)
Average miles/yr	13,476.00			(IDriveSafely, n.d.)
Insurance cost ($/mi)	**$0.1181**	**$0.1644**		(Norman, 2021); (IDriveSafely, n.d.)
Loan Total Cost ($/lifespan)	$38,226.00	$58,029.00	69month financing period at 3.11% interest rate	(Ward, 2020)
Loan Amount ($/lifespan)	$34,950.00	$53,093.44	For EV: EV Cost Veh *Loan Amount/ICV Veh Cost	(Ward, 2020)
Financing cost ($/lifespan)	$3,276.00	$4,935.56	Loan- loan amount(B&C6)	
Average mi/lifespan	150,000.00			(Bult, 2019)
Fraction US veh. financed	0.85			(Kopestinsky, 2021)
Financing cost	**$0.0186**	**$0.0280**	Total loan added cost is the financing cost/average vehicle lifespan (mi/lifespan) multiplied by the fraction of US vehicles financed by loans	(Bult, 2019); (Kopestinsky, 2021); (Ward, 2020)
Maintenance cost/lifespan	$5,651.00	$2,251.00		(Brennan, 2016)
Average mi/lifespan	150,000			(Bult, 2019)
Maintenance cost ($/mi)	**$0.0377**	**$0.0150**		(Brennan, 2016); (Bult, 2019)
Tax credit ($/lifespan)	-	-$7,500.00	Dollars presented as negative because this is a saving	(FuelEconomy, n.d.)
Average mi/lifespan	150,000			(IDriveSafely, n.d.)
Savings from Tax credit ($/mi)	**$0.0000**	**-$0.0500**		(FuelEconomy, n.d.); (IDriveSafely, n.d.)
Total Operating cost $/mi	**$0.4273**	**$0.4259**		
End of LIfe cost				
			Disposal/ Recycling Cost	
Battery recycling $/kg		$1.20		(Guardian, 2017)
Battery weight kg/battery		480.00	Based on #1 sold EV2020: Tesla Mdl 3	(Wikipedia - Tesla model 3, 2021)
Average mi/lifespan	-	150,000	(Bult, 2019)	(Bult, 2019)
Recycling rate of battery		**0.0500**	Value multiplied by recycling rate of batteries	(George, 2009)
Battery recycling cost ($/mi)		**$0.0038**		(Guardian, 2017); (Wikipedia - Tesla model 3, 2021); (Bult, 2019); (George, 2009)
Average Scrap car value $/car	-$300.00		Value does not include battery for either vehicle and is reported as a negative because this is a cost acquired from sale.	(CashAutoSalvage, 2019)
Average mi/ car lifespan	150,000			(Bult, 2019)
Recycling rate of vehicle	0.95			(Blanco, 2007)
Vehicle Scrap recycling cost ($/mi)	**-$0.0019**			(CashAutoSalvage, 2019); (Bult, 2019); (Blanco, 2007)
Landfill $/lb	$0.0277			(WasteTodayMagazine, 2019)
Average car weight lb	4000			(Autolist, n.d.)
Fraction of Vehicle disposable	0.14			(Shumbat, 2017)
Average mi/ car lifespan	150,000			(Bult, 2019)

Disposal Cost of non-recyclables within recycled vehicle ($/mi)	**$0.0001**			(WasteTodayMagazine, 2019); (Autolist, n.d.); (Shumbat, 2017); (Bult, 2019)
Landfill $/lb	$0.0277			(WasteTodayMagazine, 2019)
Average car weight lb	4000			(Autolist, n.d.)
Recycling rate of US vehicles	0.05			(Blanco, 2007)
Average mi/ car lifespan	150,000			(Bult, 2019)
Disposal Cost of non-recycled vehicles ($/mi)	**$0.0000**			(WasteTodayMagazine, 2019); (Autolist, n.d.); (Blanco, 2007); (Bult, 2019)
Total Recycling cost $/mi	**-$0.0018**	**$0.0020**		(Guardian, 2017); (Wikipedia - Tesla model 3 2021); (CashAutoSalvage, 2019); (Blanco, 2007); (George, 2009); (WasteTodayMagazine, 2019); (Autolist, n.d.); (Shumbat, 2017); (Bult, 2019)
Reclaimed Value from Recycling				
Steel kg/car	900			(Maverick, 2020)
Recycled fraction Steel	0.95			(Onat, 2014)
Steel ($/kg)	$0.6653			(FocusEconomics, 2016)
Recycling rate of US vehicles	0.95			(Blanco, 2007)
Average mi/ car lifespan	150,000			(Bult, 2019)
Value of reclaimed Steel $/mi	**$0.0036**			(Maverick, 2020); (Onat, 2014); (FocusEconomics, 2016); (Blanco, 2007); (Bult, 2019)
Plastic kg/car	151			(Maverick, 2020)
Recycled fraction Plastic	0.9			(Onat, 2014)
Plastic ($/kg)	$0.1722			(Resource-recycling, 2020)
Recycling rate of vehicle	0.95			(Blanco, 2007)
Average mi/ car lifespan	150,000			(Bult, 2019)
Value of reclaimed Plastic $/mi	**$0.0001**			(Maverick, 2020); (Onat, 2014); (Resource-recycling, 2020); (Blanco, 2007); (Bult, 2019)
Aluminum kg/car	565			(Maverick, 2020)
Recycled fraction Al	0.9			(Onat, 2014)
Aluminum $/kg	$2.2000			(BusinessInsider, 2021)
Recycling rate of vehicle	0.95			(Blanco, 2007)
Average mi/ car lifespan	150,000			(Bult, 2019)
Value of reclaimed Al $/mi	**$0.0071**			(Maverick, 2020); (Onat, 2014); (BusinessInsider, 2021); (Blanco, 2007); (Bult, 2019)
Value of reclaimed Battery materials $/mi		**$0.0013**	Based on estimate that only a third of the value can be extracted from recycled LI batteries	(Guardian, 2017)
Total Reclaimed value $/mi	**$0.0108**	**$0.0121**		(FocusEconomics, 2016); (Blanco, 2007); (Bult, 2019); (Maverick, 2020); (Onat, 2014); (Resource-recycling, 2020) (BusinessInsider, 2021)
Net EOL Cost/Value $/mi	**-$0.0126**	**-$0.0101**	Recycling Cost - Reclaimed Value. Negative value indicates a total savings from End of Life stage of product	