International Journal of Business and Management Invention (IJBMI)
ISSN (Online): 2319 – 8028, ISSN (Print): 2319 – 801X
www.ijbmi.org || Volume 15 Issue 6 || June, 2026 || PP—56-75

The Impact of Manufacturing American Vehicles on Air Quality in Pursuit of a Lifecycle Assessment of Emissions in the Transportation Sector

Jim Tanoos

Abstract

Prompted by a surge in respiratory illnesses since the pandemic, air quality has increased in salience. The global transportation sector is a significant contributor to air pollution, and the concept of whole-life carbon emissions has been proposed as a more precise method to gauge its negative impacts, specifically from automobiles. The 2020 Ricardo Report recommended lifecycle assessment (LCA) analysisthat measures both disposal and production of the vehicle in addition to what is discharged from the tailpipe in order to more accurately assess the transport sector's full impact on carbon emissions. This study fills a void in the literature by focusing on hazardous chemicals, specifically benzene and ethylbenzene, emitted from the "birth" phase of the automobile industry's lifecycle to its "grave" phase or the vehicle's disposal. These chemicals are released directly into the air during the production of vehicles in American automobile factories. Big data from the Toxic Release Inventory (TRI) as well as production data from multinational automobile manufacturers BMW, Honda, Subaru, and Toyota, were subjected to cross-sectional analysis utilizing step detection algorithms to identify significant trends.

Date of Submission: 28-05-2026 Date of acceptance: 06-06-2026

I. Introduction

Air quality is increasingly of concern for humans. Smog decreased noticeably and cleaner airincreased during the initial COVID-19 lockdowns when many people stayed at home from work, but these conditions quickly reverted after the lockdowns ended. While urban smog has traditionally been a culprit in poor air quality, enhanced technology and regulatory authority have mitigated some of it since the 1970 Clean Air Act was passed. Nevertheless, industrial activity and other factors continue to contribute to deteriorated air quality. In the United States, alert systems put in place to warn those with respiratory issues about breathing poor air have become commonplace. Laws and literature related to the transportation sector's influence on air quality have traditionally focused on tailpipe emissions, mainly due to the easily-seen grey smog. In 2020, the Ricardo Report recommended a more holistic approach of analyzing whole-life carbon emissions, which more accurately measure the transportation sector's true impact on air quality.

II. Literature Review

Reduced automobile traffic and industrial activity during the COVID-19 lockdowns led to improved air quality due to decreased smog, illustrating the impact of emissions from vehicle tailpipes on pollution levels (Damiani et al., 2024; Singh et al., 2024a). In addition to preventing workers from commuting to work, the lockdown(s) also made factories less likely to operate, thus alleviating the negative impacts on air quality of factory smokestacks during the production process. Ju et al. (2021) and Cardito et al. (2023) studied air quality before and during the COVID-19 era and found a stark improvement during various 2020-2021 lockdowns and an increase in air pollution levels after restrictions were lifted. Khan et al. (2022) examined the levels of specific types of air pollutants in Chicago before and after different periods of work-related restrictions and found that concentration levels for $PM_{2.5}$, NO_2, and CO decreased dramatically during lockdowns. As production activities resumed and more drivers were back on the roads,however, the levels of $PM_{2.5}$, PM_{10}, and NO_2returned to previous levelas(Eker& Secco, 2023; Sarmadi et al., 2021; Zhou et al., 2022).

The deleterious effects of COVID-19 on human respiratory function have prompted new research on the relationship between respiratory health and air quality (Cardito et al., 2023; Mostafa et al., 2024; Niosh, 2024; Princiipi et al., 2023; Saleh &Adley, 2023; Stein &Zar, 2023).Researchers have linked "long-term exposure to [air] pollution and COVID-19 deaths" (Friedman, 2020, para. 1) and found that the majority of health issues that put people at risk for COVID-19 respiratory problems "are the same diseases that are affected by long-term exposure to air-pollution" (Wu et al., 2020, p. 2).

Air pollution has been the subject of scientific study for centuries (Pott, 1775; Carson, 1962; Perkins, 1974; Stern et al., 1984). It has dramatically detrimental effects on human health (Boogaard et al., 2019; Almetwally et al., 2020; Glencross et al., 2020; Cromar et al., 2024), accounting for 11.62% of deaths around the world (Hu et al., 2019).Industrial activities contribute to increased air pollution, with various global sources being responsible (Hime et al., 2018; Power et al., 2018; Rahman et al., 2021), including fossil fuel combustion in motor vehicles, power plants, production facilities such as factories, and residential and commercial heating and cooling systems (Manisalidis et al., 2020; Khonyongwa et al., 2023; Krismanuel and Hairunisa, 2024).In particular, harmful carbon dioxide (CO_2), particulate matter (PM_{10} and $PM_{2.5}$), sulfur dioxide (SO_2), carbon monoxide (CO), ozone (O_3), and nitrogen dioxide (NO_2) directly contribute to air pollution and related respiratory diseases.Researchers have correlated respiratory diseases with poor air quality in China (Dong, 2024), Europe (Brunner, 2024), Japan (Mai, 2024), Latin America (Husaini et al., 2024), Australia (Hertzog et al., 2024), and elsewhere around the world (Alkhanani, 2025; Izuchukwu-Precious, 2025; Raza, 2025).

Regulatory authority on air pollution has existed for some time. In the United States, the 1970 Clean Air Act Amendments (CAAA) set regulations (Isen et al., 2017) with the goal "to protect and enhance the quality of the nation's air resources so as to promote the public health and welfare and the productive capacity of its population" (p. 1707).The US Environmental Protection Agency (EPA) creates regulatory mandates which carry out and enforce CAAA policy, setting air quality standards for hazardous air pollutants that impact respiratory health (Brumberg et al., 2021) and dictating the legal threshold for emissions of six criteria air pollutants (CAPs): ozone (O_3), particulate matter (PM_{10} and $PM_{2.5}$), carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and lead (Pb) (EPA Criteria, 2025). These six substances are of particular concern because "they are pervasive throughout the United States and pose a significant risk to human health, including heart disease, chronic respiratory diseases, birth defects, nerve damage, and cancer" (Thomas & Ong, 2023, p. 18).

Air quality has become such a notable issue that warnings via public alert systems have become commonplace to mitigate "adverse health effects on days when air pollution is high" (Chen et al., 2018, p. 19). The EPA formulates air quality alert thresholds based on pollution severity, and its Air Quality Index (AQI) serves as a guideline for generating warnings. These alerts play a meaningful role in quality-of-life factors in communities across the country by registering hourly or daily measurements of pollutants and communicating those to local citizens (Chen et al., 2018; Azad &Ghandehari, 2022; Sachdev, 2022; Schulte, 2022). More than 4,000 environmental monitoring stations around the country measure the outdoor concentrationsof CAPsbased on the National Ambient Air Quality Standards (NAAQS; EPA Hazardous, 2025). Combined with forecasts created by the National Weather Service (NWS), the EPA, and state agencies, six color-coded categories related to air pollution are determined and available via public alert systems (Otte et al., 2005; United Nations, 2012; Cunha, 2019; Mirabelli et al., 2020).The state of Indiana, for instance, includes a real-time "smogwatch" link in its official website that provides updates for "daily air quality forecasts for ozone and fine particulates, monitoring data for all pollutants and current weather conditions throughout the state" (Indiana Department of Environmental Management, 2025, para. 1-6).

The transportation sector (referred to as "transport" sector in European literature) accounts for over a quarter of global CO_2 emissions (Solaymani, 2019). Much of global literature associated with this industry's effects on air quality has focused on the notorious grey/black smoke emitted from vehicle tailpipes during driving (Yanowitz & McCormick, 2009; Zhang et al., 2015; Anenberg et al., 2019; Giechaskiel et al, 2019; Bej & Chattaraj, 2023). Past regulatory authority has focused on limiting these tailpipe emissions. These regulations have become stricter over time in America, promptingtechnological advances in catalytic converters, engines, and tailpipe filters that limit the black smoke coming out of US vehicles (Regulatory Timeline, 2024).

The 2015 Volkswagen scandal illustrates the emphasis in news and literature on tailpipe emissions as prime culprits of the transport sector's impact on air quality. After scrutinizing the pollution discharged from vehicle tailpipe emissions in America, the EPA determined that the German automaker had violated the Clean Air Act. The company was found to have intentionally cheated (Bovens, 2016; Cavico and Mujtaba, 2016; Rhodes, 2016), leading to a US$30billion penalty. This controversy recommitted organizational focus and regulatory authority enforcement on tailpipe emissions within the entire American transport sector, and attention subsequently turned to tailpipe innovations and new technologies necessary for filtering pollution, which the pandemic further highlighted due to noticeably observable changes in smog. A new stream of literature emerged toexamine the roles of automobile sector stakeholders, consumers, sustainable institutions, and regulatory bodies in limiting tailpipe emissions from running vehicles.

A newer, more accurate methodology to assess the transport sector's true impact on air quality isa lifecycle assessment (LCA, also known as birth-to-grave, cradle-to-grave or whole-life carbon emissions) that includes the creation and disposal of a vehicle as well as its operation.Tan et al. (2011) initially recommended standardizing the accounting concept of "whole-lifecycle automotive manufacturing", amethod of assessing the impact on air quality throughout the entire auto industry, from raw material processing to disposal and/or recycling. Lee (2012) similarly recommended an agreed-upon process to quantify emissions across the automobile supply chain.

The seminal 2020 Ricardo Report endorsed this approach to more accurately measure the carbon footprint of an automobile and outlined the impacts of pollution produced across the entire life of the vehicle. "With the shift to new fuels and powertrain electrification it is more important to use LCA approaches in assessing the relative impacts of different options on a holistic basis" (Ricardo Report, 2020, para. 2). The Ricardo Report discussed the inclusion of emissions not only when an automobile is running but also starting from the extraction of raw materials that form the components and energy for the creation of the automobile through to disposal of the vehicle and/or its parts and recommended that standardized methodologies be developed by governments and global institutions to compare the various automobile life cycle stages,with the goal of providing a global framework for emissions standards.

However, only a few studies have responded to this call.The Low Carbon Vehicle Partnership (2020) attempted to quantify emissions across the lifecycle of a vehicle but conceded that "Life cycle analysis is still in its infancy, with few defined processes and standards" (p. 3). Nevertheless, this report broke new ground in LCA research by estimating that the manufacture of standard (traditional) gasoline-powered vehicles emits 5.6 metric tons of CO_2-equivalent pollution per vehicle (mostly from the steel in the vehicle glider), while the manufacture of a typical hybrid (6.5 metric tons), plug-in hybrid (6.7 metric tons), and battery-electric vehicles (8.8 metric tons) emits higher amounts. Campbell (2022) reported that about 10% of a typical gasoline- or diesel-powered vehicle's LCA CO_2 emissions occur during its production, equating to about 5.6 tons of CO_2, and about 5% occur from the disposal process.

Because sustainability efforts from organizational stakeholders in the multinational automobile industry have often been reactive to regulations and edicts of international institutions (Iguchi, 2015; Selim & Gad el-Rab, 2020), quantifying carbon emissions via whole-life carbon emissions and setting standards in the industry are crucial to future quality of-life issues. In particular, numerous chemicals are emitted by automobile production factories. The sheet metal stamped by robots for the core vehicle bodywork constantly releases airborne particulates during its metalworking process, with welding, cutting, and grinding and the related smoke and fumes being particularly hazardous during this phase. Production processes that solder, screw, and glue on parts with plastics also produce harmful emissions, as well as the paint shops which utilize various hazardous solvents. Smokestack emissions and sulfuric acid are constantly released into the air during the creation of vehicles at factories.

As such, this study will assess the extent to which chemicals and chemical compounds areemitted during the vehicle manufacturing process. In addition, analysis will focus on which ones, if any,were included in theEPA's (1990)188 hazardous air pollutants(EPA Hazardous, 2025) and/or related to the CAPs notably toxic and particularly harmful chemicals and chemical compounds, including (ozone (O_3), particulate matter (PM_{10} and $PM_{2.5}$), carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and lead (Pb). The findings will fill the void in the literature by ascertaining the rates of pollution produced in the manufacture of vehicles in terms of air quality, providing further implications related to the Ricardo Report wherever these automobile factories operate internationally.

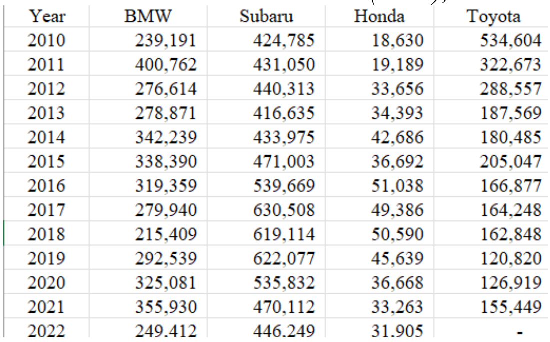
III. Methodology

The EPA publishes an annual Toxic Release Inventory (TRI), a publicly available database containing information on the release of toxic chemicals (T. Antisdel, personal communication, 2017), including those emitted into the air and water/ground. Data from the TRI were mined for the purposes of this study.Data about chemicals released during the production process were analyzed using a cross-sectional analysis, and categories from the TRI were utilized to determine emissions of chemicals including columns 218 (Total On-Site Releases), 243 (Total Transferred Off Site for Disposal), 249 (Total Transferred Off Site for Recycling), and 252 (Total Transferred Off Site for Energy Recovery) (in annual pounds) (see Appendix 1). Total pounds of emissions by factory were mined using columns 109 (Total Fugitive Air Emissions), 113 (Total Stack Air Emissions), 115 (Total Air Emissions), 218 (Total On-Site Releases), 243 (Total Transferred Off Site for Disposal), 249 (Total Transferred Off Site for Recycling), and 252 (Total Transferred Off Site for Energy Recovery) (Swenson, 2023). According to the EPA, total air emissions is the sum of fugitive and stack emissions. Only total air emissions were considered in this study, as the selected facilities had equivalent values for total on-site releases and total air emissions, which means that these chemicals are directly released only to the air. If multiple chemicals are reported, the values are added together to calculate total air emissions (Swenson, 2023).

Total pounds of chemicals emitted during the production process since 2010 were aggregated using all categories of chemical emissions to create "total annual onsite raw emissions" (see Table 1 and Figure 1), with a subsequent inquiry to assess if the total annual onsite raw emissions and/or any specific chemicals or chemical compounds emitted during the production process significantly changed between 2010-2022 (see Appendix 2 for percentage of year-to-year changes). The sample set of multinational automobile organizations manufacturing vehicles in America utilized for the purposes of this analysis were BMW, Honda, Subaru, and Toyota. Subaru had the highest raw emissions but experienced a significant decrease after 2019. BMW had the second-highest emissions, and Honda had the lowest (see Figure 1).

Table 1.

Total Annual Onsite Raw Emissions (in lb.), 2010-2022



Year	BMW	Subaru	Honda	Toyota
2010	239,191	424,785	18,630	534,604
2011	400,762	431,050	19,189	322,673
2012	276,614	440,313	33,656	288,557
2013	278,871	416,635	34,393	187,569
2014	342,239	433,975	42,686	180,485
2015	338,390	471,003	36,692	205,047
2016	319,359	539,669	51,038	166,877
2017	279,940	630,508	49,386	164,248
2018	215,409	619,114	50,590	162,848
2019	292,539	622,077	45,639	120,820
2020	325,081	535,832	36,668	126,919
2021	355,930	470,112	33,263	155,449
2022	249,412	446,249	31,905	-

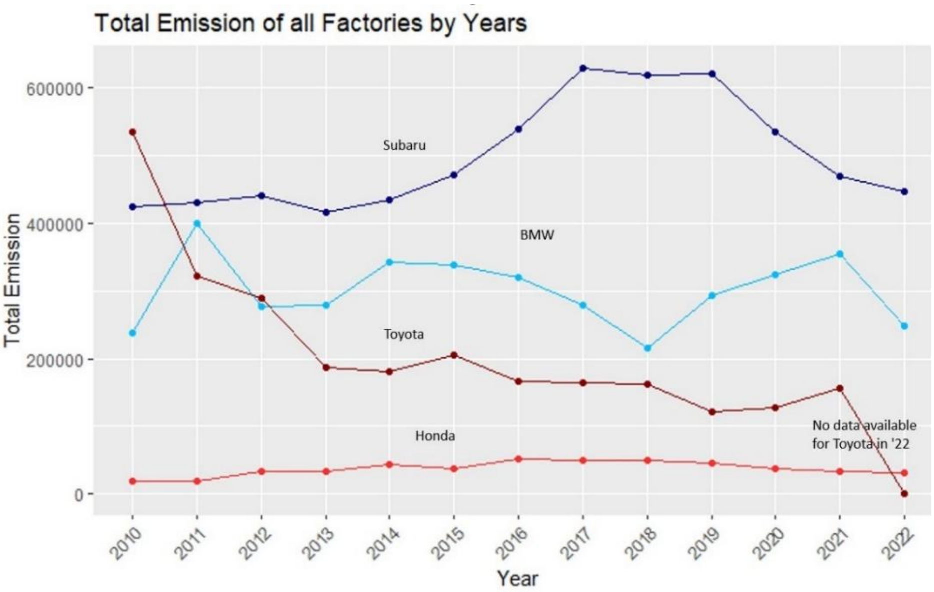


Figure 1. *Total Emissions for BMW, Honda, Subaru, and Toyota, 2010-2022*

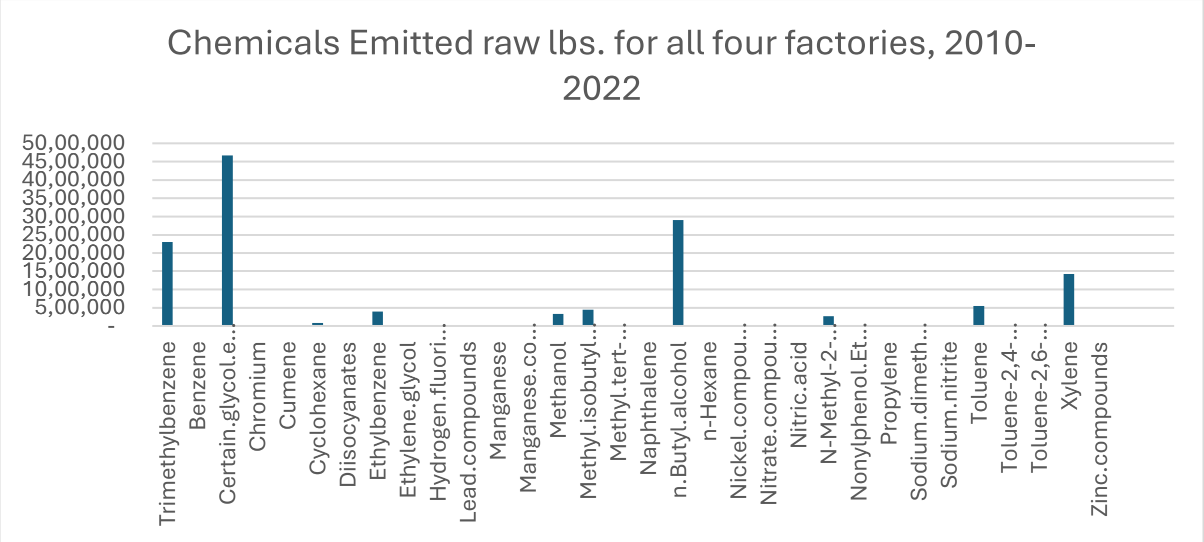
Step detection methodologies were performed to ascertain if any notable alterations in annual emissions occurred. One of the numerous algorithms to determine any changes in the mean via step detection analysis the Cumulative Sum (CUSUM) process, a statistical quality control technique utilized to locate deviations in patterns. It is particularly useful for detecting small or gradual shifts that may not beapparent.If the process is stable, CUSUM values should fluctuate around zero, but if there is a significant shift or drift in the mean over time, the CUSUM values will trend upward or downward, indicating an out-of-control condition, in which a significant change is occurring.As such, the CUSUM values were calculated by utilizing the mean of total emissions for each factory to calculate any potential deviation (see Model 1).

Model 1: *Step Detection Methodologies Utilized for Emissions Changes at BMW, Honda, Subaru, and Toyota, 2010-2022*

$$C_i = \sum_{j=1}^{i}(x_j - \bar{x}) = (x_i - \bar{x}) + \sum_{j=1}^{i-1}(x_j - \bar{x}) = (x_i - \bar{x}) + C_{i-1}$$

Based on the CUSUM process, Subaru's rate of emissions change increased from 2013-2017, then stabilized, and then decreased in 2019. After 2019, emissions went back to lower levels that were similar to their total emissions in 2012. Another noticeable pattern was consistent BMW emissions, with little fluctuation. In addition, although Honda had the smallest amount of annual emissions among the four factories, the CUSUM output revealed that after 2017 there was a dramatic decrease in emissions that was not apparent without the CUSUM chart (see Appendices 3-6). For Toyota, the CUSUM analysis showed that emissions were high in 2010 (the first year of analysis for purposes of this study) but decreased rapidly until 2018 and then leveled off. It was additionally determined that 32 different chemical compounds across the four factories were emitted from 2010-2022. Each of these chemicals and/or chemical compounds was listed in some form onthe 1990 EPA list of 188 hazardous air pollutants (EPA Hazardous, 2025)(see complete list of emitted chemicals from the four factories in Appendices 7-10). In particular, benzene emissions were observed for BMW and Honda throughout the years, but only in 2017 for the Toyota factory, with none being emitted from the Subaru factory (see Appendix 11). Compounds like xylene, toluene, n-butyl alcohol; 1,2,4-trimethylbenzene, ethylbenzene, and certain glycol ethers were emitted by all the factories (see Appendices 12-17). Hydrogen fluoride was observed in the Honda factory in 2013, 2014, and 2017 onwards (see Appendix 18) and chromium was emitted in the Toyota factory (see Appendix 19). The chemicals emitted at the highest rates were 1) certain glycol ethers, 2) n-butyl alcohol, 3) 1,2,4-trimethylbenzene, 4) xylene, and 5) toluene (see Table 2).

Table 2.
Total Raw Chemicals Emitted by All Four factories (in lb.)



Extending the exploratory analysis of chemicals and/or chemical compounds emitted based on the total raw emissions output, the subsequent inquiry was to assess if they changed significantly compared to past emissions. As such, piecewise linear regression analyses were additionally performed to determine when there were ranges in the data where the relationship between the variables changed abruptly.Piecewise linear regression analysis is a preferred method to determine deviations in linear patterns with large datasets.

Through this quantitative approach, multiple linear segments across different ranges of the independent variables (chemicals and/or chemical compounds emitted from a factory in a given year) were assessed, which allowed for a more nuanced understanding of the data compared to single linear model. Output based on this statistical analysis (Table 3) reveals the estimated break points, or years where the patterns of emitted chemicals and/or chemical compounds deviated. For instance, a changein ethylbenzene at the BMW factory occurred in 2017, when it significantly decreased from previous norms then remained consistentin the years immediately afterwards. To confirm these chemical deviations, the Davies Test, a piecewise regression model, was performed for non-constant regression parameters in the linear predictor (Appendix 20).These analyses jointly confirmed significant changes in the emissions patterns of the seven chemicals and/or chemical compounds as shown in Table 3, where the *increases* are differentiated in red font.

Table 3.
Estimate Break Points from Piecewise Regression (Chemicals Emitted)

Chemical	BMW	Honda	Subaru	Toyota
1, 2, 4 Trimethylbenzene	2011, 2015, 2020	2013, 2017	2011, 2014, 2016, 2018 2020	2013, 2015, 2017, 2019

Certain glycol ethers	2016, 2018 2020	2011, 2013, 2018	2014, 2018, 2020	2011, 2013, 2015, 2018, 2020
Ethylbenzene	2012, 2014 2017, 2019	2012, 2015, 2018, 2019	2012, 2014, 2018, 2020	2011, 2013, 2015, 2017, 2019
Ethylene glycol	2011, 2013 2015, 2018 2020	2012, 2014, 2017, 2019	2011, 2013, 2016, 2018, 2020	2013, 2015, 2018
n Butyl alcohol	2014, 2016 2019	2013, 2016, 2018, 2020	2013, 2015, 2017, 2019	2013, 2016, 2018, 2020
Toluene	2011, 2013 2015, 2017 2019	2015, 2017, 2019	2011, 2014, 2016, 2018, 2020	2012, 2014, 2016, 2018, 2020
Xylene mixed isomers	2013, 2015 2017, 2019	2011, 2013, 2015	2012, 2014, 2016, 2018, 2020	2014, 2016, 2020

Even though air quality (especially local air quality) is determined by the levels of chemicals in the air, production sustainability should be normalized by considering emissions in terms of the production of vehicles. As such, this studyintegrated a weighted value (manufacturing rates) in order to provide value to each factory's annual production. As such, all vehicles produced in these facilities for the respective years were considered (see Appendices 21-23).

Since the different vehicle models within brands had various trim levels (accessories or features such as alert systems, heated seats, larger tires, and sunroofs specific to the model; Belzowski, 2015), model weights (in lb.) were determined by the year of manufacture (Car and Driver, 2024a, 2024b, 2024c; Edmunds, 2024a, 2024b, 2024c; see Figures A1 and A2). Trim levels for Honda vehicles were available in their most recent annual report (Honda, 2023), including for Civic, Civic Hybrid, CR-V, CR-V Hybrid, Insight, and Acura ILX models (see Appendices 24-25). Vehicles produced at the Subaru factory were determined from their own financial and integrated reports (Subaru, 2010, 2015, 2016, 2018, 2020, 2022), including Legacy, Tribeca, Outback, Impreza, and Ascent (see Appendix 26). Precise production data for individual models for the Subaru facility were unavailable for the years 2017-2022 and were thus estimated by using the average weight of each model. The BMW vehicles manufactured were derived from a combination of company news articles, industry publication reports, and official reports (Automotive News, 2012, 2013, 2014, 2017; BMW, 2020, 2022, 2023) and were determined to be X3, X4, X5, X6, X7, XM, X3M, X4M, X5M, and X6M (see Appendix 27). Specific production data for individual models for BMW were unavailable in the years 2017, 2018, and 2020 and as such were estimated based on the average weight of each model. Toyota was omitted from further analysis because accurate vehicle production at their factory in Princeton, IN, was not publicly available. In summary, the weight of each model was identified using all the different weights of trim levels for each model in lb. (see Appendices 28-30), as shown in Model 2 where m represents the number of trims for a specific vehicle model.

$$\text{Model 2: } w_{model} = \frac{w_{trim,1}+w_{trim,2}+\cdots w_{trim,n}}{m}$$

The total production in lb. for each factory was calculated by totaling the lb. of vehicles produced for each model, as shown in Model 3,where $n_{manufacturer,i}$ represents the number of different models produced by each facility, $q_{manufacturer,i}$ represents the quantity of the i-th model produced, and $w_{manufacturer,i}$ represents the weight of the i-th model produced.

$$\text{Model 3: } Total\ production\ (lb.) = \sum_{i=1}^{n_{manufacturer}} (q_{manufacturer,i} * w_{manufacturer,i})$$

For years which did not have production data for specific models, the average weight of the models produced in the facilities was used to find the total production in lb., as shown in Model 4, where $\overline{w}$is the average weight of vehicles produced by models whereby the numerator denotes the total weight of all individual models produced, and n represents the number of models produced in the facilities:

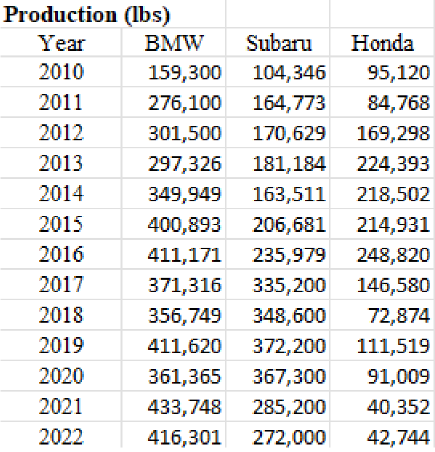
$$\text{Model 4: } \overline{w} = \frac{w_{model,1}+w_{model,2}+w_{model,3}\cdots+w_{model,n}}{n}$$

The total lb. of production for each facility was then found by multiplying the total quantity of vehicles produced and average weight of models (see Appendices 31-33), as shown in Model 5:

Model 5: $Total\ production\ (lb.) = \overline{w} * Q_{total}$

As such, the total lb. of vehicles manufactured by year were determined. Table 4 and Figure 2present the total lb. of production for the three manufacturing facilities.

Table 4.
Total Production (in lb. of total vehicles manufactured)



Production (lbs)			
Year	BMW	Subaru	Honda
2010	159,300	104,346	95,120
2011	276,100	164,773	84,768
2012	301,500	170,629	169,298
2013	297,326	181,184	224,393
2014	349,949	163,511	218,502
2015	400,893	206,681	214,931
2016	411,171	235,979	248,820
2017	371,316	335,200	146,580
2018	356,749	348,600	72,874
2019	411,620	372,200	111,519
2020	361,365	367,300	91,009
2021	433,748	285,200	40,352
2022	416,301	272,000	42,744

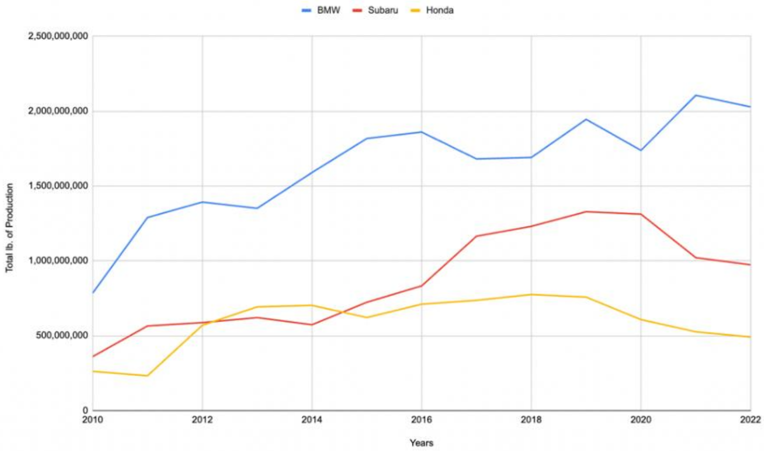


Figure 2.*Total lb. of Production (in total lb. of manufactured vehicles) for BMW, Subaru, and Honda*

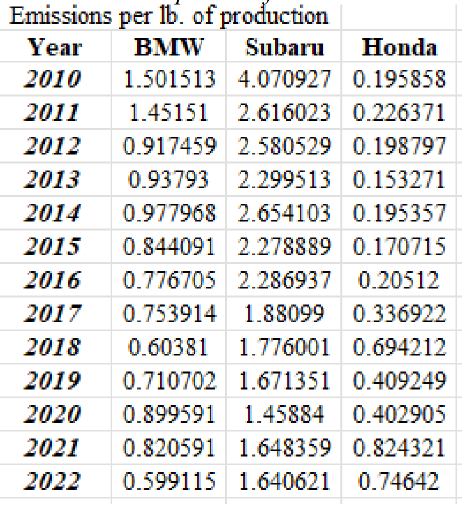
Subsequently, the emissions per lb. of production values were determined by dividing total air emissions lb. by total production lb. for each year, as shown in Model 6.The results offer insight regarding the yieldrelated to sustainable practices for these manufacturing facilities.

Model 6: $Emission\ per\ lb.\ of\ production_{year} = \frac{Total\ air\ emissions\ (lb.)_{year}}{Total\ production\ (lb.)_{year}}$

IV. Results

Table 5and Figure 3 show emissions per lb. of production. As illustrated, Subaru and BMW successfully decreased emissions related to their production of vehicles over time. In particular, 2018 was pivotal, as BMW surpassed Honda in emissions per lb. of production. This raises the question of what mechanisms in their processes changed so that they were producing at more sustainable rates during that timeframe, particularly because BMW increased their total lb. of production during that period. Honda's 2015/2016 period is also noteworthy, as they had been consistent in years prior but became less sustainable in subsequent years.

Table 5.
Emissions per lb. of Production



Emissions per lb. of production

Year	BMW	Subaru	Honda
2010	1.501513	4.070927	0.195858
2011	1.45151	2.616023	0.226371
2012	0.917459	2.580529	0.198797
2013	0.93793	2.299513	0.153271
2014	0.977968	2.654103	0.195357
2015	0.844091	2.278889	0.170715
2016	0.776705	2.286937	0.20512
2017	0.753914	1.88099	0.336922
2018	0.60381	1.776001	0.694212
2019	0.710702	1.671351	0.409249
2020	0.899591	1.45884	0.402905
2021	0.820591	1.648359	0.824321
2022	0.599115	1.640621	0.74642

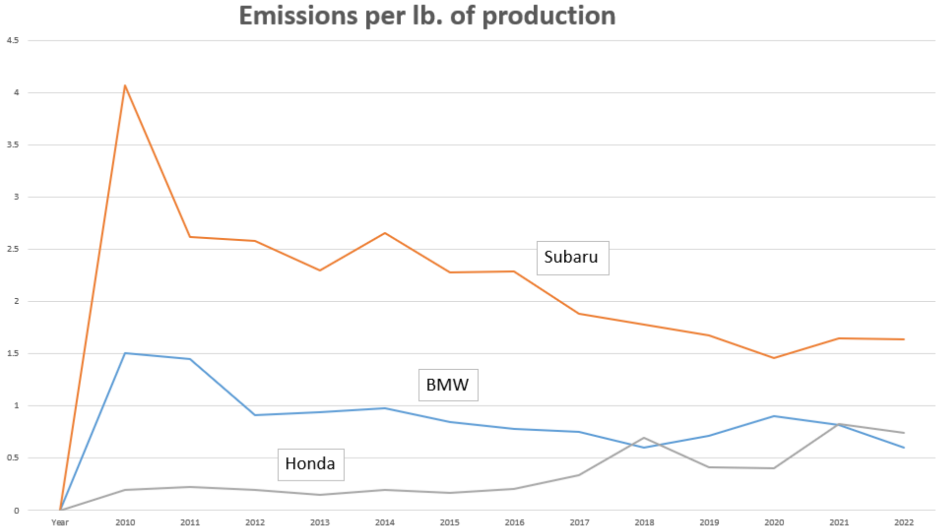


Figure 3. *Emissions per lb. of Production*

Reactions and Implications

Chemicals and chemical compounds emitted from these factories areimportant to consider due to local air quality issues and increasing respiratory health concerns.Since respiratory health and cancer-causing chemicals are unique to air quality analysis, Table 2 (which shows the chemicals and chemical compounds emitted per lb. of production) is especially noteworthy. Since more of certain glycol ethers, n-butyl alcohol, 1,2,4-trimethylbenzene, xylene, and toluene were being emitted than other substances at these factories, further studies on the respiratory impacts of these chemicals and their effect on air quality should be prioritized.

The chemicals and/or chemical compounds the Davies Test found to have increased significantly from prior years (Table 3) require the most scrutiny,as all seven of these chemicalswere listed in some form on the 1990 EPA list of 188 hazardous air pollutants (EPA Hazardous, 2025). These trendsshould be further analyzed to ascertain why the emissions increased and if they were a result of a change in manufacturing processes, type of vehicle being produced, change in regulations, or some other reason. Of those seven chemicals, the most hazardous arexylene, toluene, and ethylbenzene, which all contribute to negative respiratory quality, cause negative health effects with chronic exposure and are particularly volatile organic compounds which especially contribute to smog and cause irritation of the nose and throat, with longtime chronic exposure being carcinogenic.

Future analysis should additionally evaluate the impact of all seven substances on air quality alerts and whether a more specific warning system is warranted if these especially harmful chemicals surpass a certain threshold a given distance from the factory. Local air quality public alert systems will continue to play a role in meaningful warnings to citizens and should be implemented near factories as a courtesy to nearby residents.

For Subaru in particular, changes in their process that contributed to the significant decrease in emissions related to production after 2010 would be of extra benefit to other multinational automobile factories around the world. In general, LCA of vehicle emissions should continue to gain importance, particularly in light of the increased usage of EVs in the years ahead. Ifany factory is better able to manage the impact of more burdensome regulations within the confines of the law, their process should be considered a best practice in the industry and adopted as appropriate.

Tailpipe emissions will continue to be of less importance as the Ricardo Report and LCA become more salient and accepted in the literature as a means of evaluating a sector's emissions record. Since the Ricardo Report espouses a more holistic supply chain approach in assessing the transportation sector's impact in terms of carbon emissions, sectors beyond the automobile industry such as the aerospace, construction,and steel industries should consider similar evaluation metrics to the LCA approach. The mining of materials and energy sources related to a future product and related emissions extraction from the ground, the energy used to power the factories creating that product, and end-of-life disposal should be given attention above and beyond the manufacturing process within the confines of a factory.

In addition, an inquiry about the increased use of additive manufacturing (3D printing) at multinational automobile factories and its impact on emissions decreases might be further considered. 3D printing stands in contrast to the traditional welding of components and is becoming increasingly common as a method to simplify supply chains during the production process (Mejdoub&Elamri, 2024; Khang, 2025; Kohl et al., 2025),especially in automobile factories (Holder et al., 2025).Additive manufacturing is a key technological component of green supply chains because it enables organizations to maintain inventory on demand and create parts on-site, eliminating the inbound cargo of components via shipping and packaging from overseas factories which prompted pandemic-era delays and bottlenecks. This approach increases sustainability and cost control while also fostering sustainability and brand reputation because organizations do not have to speculate what processes were occurring in the early stages of the product's life. Creating parts via 3D printing in-house involves integrating cutting-edge technologies such as techniques for creating spare parts that also avoid the welding process, reducing the amount of scrap and decreasing airborne emissions. It is unclear whether integrating additive manufacturing at any or all of these factories contributed to decreased emissions as found in this study.

Further, changes in federal regulations that impactfacilities equally but prompt different sustainable production trends should be an area of future focus. For instance, for the geopolitically sensitive semiconductor industry, emissions rates should not be assessed based simply on the production of a chip in a factory but also on the emissions and water contamination from mining the lithium used in the battery-backed components that power or protect the semiconductor-based devices and on the disposal of the product.CO_2 emissions that negatively impact air quality, particularly local air quality, will continue to be a concern among scholars and scientists, and it is imperative to consider LCA not only in the automobile sector and its larger transportation sector but in industrial sectorsin order to more accurately assess their full impact on carbon emissions.

References:

[1]. Alkhanani, M. (2025). Assessing the Impact of Air Quality and Socioeconomic Conditions on Respiratory Disease Incidence. *Tropical Medicine and Infectious Disease*, *10*(2), 56.

[2]. Almetwally, A., Bin-Jumah, M., & Allam, A. (2020). Ambient Air Pollution and its Influence on Human Health and Welfare: An overview. *Environmental Science and Pollution Research*, *27*(20), 24815–24830. doi:10.1007/s11356-020-09042-2.

[3]. Anenberg, S., Miller, J., Henze, D., Minjares, R., &Achakulwisut, P. (2019). The Global Burden of Transportation Tailpipe Emissions on Air Pollution-related Mortality in 2010 and 2015. *Environmental Research Letters*, *14*(9), 094012.

[4]. Automotive News. (2012). *2012 North American Production Market Data*. Retrieved from https://www.autonews.com/assets/PDF/CA10327218.PDF.

[5]. Automotive News. (2013). *2013 North American Production Market Data*. Retrieved from https://www.autonews.com/assets/PDF/CA922991219.PDF.

[6]. Automotive News. (2014). *2014 North American Production Market Data*. Retrieved from https://www.autonews.com/assets/PDF/CA922991219.PDF.

[7]. Automotive News. (2017). *2017 North American Production Market Data*. Retrieved from https://www.census.gov/history/pdf/automotivenews2017.pdf.

[8]. Azad, S., &Ghandehari, M. (2022). Emissions of Nitrogen Dioxide in the Northeast U.S. During the 2020 COVID-19 Lockdown. *Journal of Environmental Management*, *312*, Article 114902. doi:10.1016/j.jenvman.2022.114902.

[9]. Bej, D., & Chattaraj, N. (2023). Air Pollution from Vehicle-tailpipe Emissions and Diagnostic Approaches Through Cyber-physical Platform-a review. *Microprocessors and Microsystems*, 104805.

[10]. Belzowski, B. (2015, June). Total Cost of Ownership: A diesel versus gasoline comparison (2012-2013). *University of Michigan Transportation Research Institute.*http://deepblue.lib.umich.edu/bitstream/2027.42/111893/1/103193.pdf.

[11]. BMW. (2020, January 15). *Record Production Year for BMW Manufacturing*. https://www.bmwgroup-werke.com/spartanburg/en/news/2020/record-production-year-for-bmw-manufacturing.html.

[12]. BMW. (2022, January 18). *BMW Manufacturing Sets Production Record in 2021.* https://www.bmwgroup-werke.com/spartanburg/en/news/2022/BMW-Manufacturing-Sets-Production-Record-in-2021.html.

[13]. BMW. (2023a, March 21). *New Study Shows that BMW Manufacturing Remains a Significant Economic Driver in South Carolina*. https://www.press.bmwgroup.com/usa/article/detail/T0411581EN_US/new-study-shows-that-bmw-manufacturing-remains-a-significant-economic-driver-in-south-carolina.

[14]. BMW. (2023b, April 20). *Twenty Year Anniversary: BMW manufacturing's landfill gas-to-energy project continues to power factory*. Retrieved from https://www.bmwgroup-werke.com/spartanburg/en/news/2023/Twenty-Year-Anniversary-Landfill-Gas-to-Energy-Project-Continues-to-Power-Factory.html.

[15]. Boogaard, H., Walker, K., & Cohen, A. (2019). Air Pollution: The emergence of a major global health risk factor. *International Health*, *11*(6), 417–421. doi:10.1093/inthealth/ihz078.

[16]. Bovens, L. (2016). The Ethics of Dieselgate. *Midwest Studies in Philosophy*. Eprints.lse.ac.uk.

[17]. Brumberg, H., Karr, C., Bole, A., Ahdoot, S., Balk, S., Bernstein, A., ... &Trasande, L. (2021). Ambient Air Pollution: Health hazards to children. *Pediatrics*, *147*(6).

[18]. Brunner, J. (2024). Effect of Environmental Pollution on Respiratory Health in Urban Areas of Europe. *European Journal of Health Sciences*, *10*(2), 47-58.

[19]. Campbell, R. (2022). Car Pollution Facts: From production to disposal, what impact do our cars have on the planet? Retrieved from: https://www.autoexpress.co.uk/sustainability/358628/car-pollution-production-disposal-what-impact-do-our-cars-have-planet.

[20]. Car and Driver. (2024a). *BMW.* https://www.caranddriver.com/bmw.

[21]. Car and Driver. (2024b). *Honda.* https://www.caranddriver.com/honda.

[22]. Car and Driver. (2024c). *Subaru.* https://www.caranddriver.com/subaru.

[23]. Cardito, A., Carotenuto, M., Amoruso, A., Libralato, G., & Lofrano, G. (2023). Air Quality Trends and Implications Pre and Post Covid-19 Restrictions. *Science of the Total Environment*, *879*, 162833.

[24]. Carson, R. (1962). *Silent Spring*. Boston, MA: Houghton Mifflin Company.

[25]. Cavico, F., & Mujtaba, B. (2016). Volkswagen Emissions Scandal: A global case study of legal, ethical, and practical consequences and recommendations for sustainable management. *Global Journal of Research in Business & Management Vol*, *4*(2).

[26]. Chen, H., Li, Q., Kaufman, J., Wang, J., Copes, R., Su, Y., &Benmarhnia, T. (2018). Effect of Air Quality Alerts on Human Health: A regression discontinuity analysis in Toronto, Canada. *The Lancet Planetary Health*, *2*(1), E19-E26. doi:10.1016/s2542-5196(17)30185-7.

[27]. Cromar, K., Gladson, L., Gohlke, J., Li, Y., Tong, D., & Ewart, G. (2024). Adverse Health Impacts of Outdoor Air Pollution, Including from Wildland Fires, in the United States: "Health of the Air," 2018–2020. *Annals of the American Thoracic Society*, *21*(1), 76–87. doi:10.1513/annalsats.202305-455oc.

[28]. Cunha, M. (2019). *Wildfire Smoke Effects on Health: Implementing an air quality alertsystem for UCSD* (Capstone paper). Scripps Institution of Oceanography, University of California, San Diego. https://escholarship.org/uc/item/42t2p86p.

[29]. Damiani, A., Irie, H., Belikov, D., Cordero, R., Feron, S., & Ishizaki, N. (2024). Air Quality and Urban Climate Improvements in the World's Most Populated Region During the COVID-19 Pandemic. *Environmental Research Letters*, *19*(3), 034023.

[30]. Dong, S. (2024). The Correlation Between Respiratory Infectious Diseases, Air Pollution, and Meteorological Factors in Jinan, China from 2021 to 2023. *American Journal of Translational Research*, *16*(9), 4577.

[31]. Eker, M., & Secco, E. (2023). Data Analysis of the Air Quality (PM2.5) Before, During and After the COVID-19 Pandemic Lockdowns in Hanoi and Ho Chi Minh City, Vietnam. *WSEAS Transactions on Environment and Development, 19*, 1448–1458.doi:10.37394/232015.2023.19.131.

[32]. Environmental Protection Agency (EPA) Criteria. (2025). Retrieved from https://www.epa.gov/criteria-air-pollutants.

[33]. Environmental Protection Agency (EPA) Hazardous. (2025). Initial List of Hazardous Air Pollutants with Modifications. Retrieved from https://www.epa.gov/haps/initial-list-hazardous-air-pollutants-modifications.

[34]. Friedman, L. (2020, April 7). New Research Links Air Pollution to Higher Coronavirus Death Rates. *The New York Times*.

[35]. Giechaskiel, B., Lähde, T., &Drossinos, Y. (2019). Regulating Particle Number Measurements from the Tailpipe of Light-duty Vehicles: The next step? *Environmental research*, *172*, 1-9.

[36]. Glencross, D., Ho, T., Camiña, N., Hawrylowicz, C., & Pfeffer, P. (2020). Air pollution and its Effects on the Immune System. *Free Radical Biology and Medicine*, *151*, 56–68. doi:10.1016/j.freeradbiomed.2020.01.179.

[37]. Hertzog, L., Morgan, G., Yuen, C., Gopi, K., Pereira, G., Johnston, F., ... & Hanigan, I. (2024). Mortality Burden Attributable to Exceptional PM2. 5 Air Pollution Events in Australian Cities: A health impact assessment. *Heliyon*, *10*(2).

[38]. Hime, N., Marks, G., & Cowie, C. (2018). A Comparison of the Health Effects of Ambient Particulate Matter Air Pollution from Five Emission Sources. *International Journal of Environmental Research and Public Health*, *15*(6), Article 1206. doi:10.3390/ijerph15061206.

[39]. Holder, D., Wulle, F., & Lind, J. (2025). *Advances in Automotive Production Technology.* New York, NY: Springer International Publishing.

[40]. Honda. (2023). *2023 Digital Factbook.* Retrieved from https://hondanews.com/en-US/honda-corporate/releases/release-13f25e90cfe47cd58453f1f710277f1c-honda-2023-digital-factbook.

[41]. Hu, W., Fang, L., Zhang, H., Ni, R., & Pan, G. (2022). Changing Trends in the Air Pollution-related Disease Burden from 1990 to 2019 and its Predicted Level in 25 years. *Environmental Science and Pollution Research*, *30*(1), 1761–1773. doi:10.1007/s11356-022-22318-z.

[42]. Husaini, D., Manzur, K., & Medrano, J. (2024). Indoor and Outdoor Air Pollutants as Emerging Public Health Threat in Latin America and the Caribbean: A systematic review. *Arab Gulf Journal of Scientific Research*, *42*(1), 134-145.

[43]. Iguchi, M. (2015). *Divergence and Convergence of Automobile Fuel Economy Regulations A Comparative Analysis of EU, Japan and the US*. Hanover, PA: Springer International Publishing A&G.

[44]. Indiana Department of Environmental Management. (2025). Smogwatch. https://www.in.gov/idem/airmonitoring/smogwatch/.

[45]. Isen, A., Rossin-Slater, M., & Walker, W. (2017). Every Breath you Take—Every dollar you'll make: The long-term consequences of the Clean Air Act of 1970. *Journal of Political Economy*, *125*(3), 848–902. doi:10.1086/691465.

[46]. Izuchukwu-Precious, O. (2025). Air Pollution and Public Health: Examining the Correlation between PM2.5 Levels and Respiratory diseases in major cities in Nigeria. *Journal of Theory, Mathematics, and Physics, 4*(4), 1-17.

[47]. Ju, M., Oh, J., & Choi, Y. (2021). Changes in Air Pollution Levels After COVID-19 Outbreak in Korea. *Science of the Total Environment*, *750*, Article 141521. doi.org/10.1016/j.scitotenv.2020.141521.

[48]. Khan, S., Dahu, B., & Scott, G. (2022). A Spatio-temporal Study of Changes in Air Quality from Pre-COVID Era to Post-COVID Era in Chicago, USA.*Aerosol and Air Quality Research*, *22*(8), Article 220053. doi.org/10.4209/aaqr.220053.

[49]. Khang, A. (2025). *Driving Green Transportation System Through Artificial.* New York, NY: Springer Publishing.

[50]. Khonyongwa, O., Kumar, S., Kumar, N., Jha, A., Jain, M., & Pandey, S. (2023). Air Pollution Impact on Human Health and its Management: A review. *Macromolecular Symposia*, *407*(1), 1–6. doi.org/10.1002/masy.202100488.

[51]. Kohl., H., Selinger, G., Dietrich, F. (2024). *Decarbonizing Value Chains.* Proceedings of the 20th Global on Sustainable Manufacturing, Ho Chi Minh City, Vietnam.

[52]. Krismanuel, H., &Hairunisa, N. (2024). The Effects of Air Pollution on Respiratory Problems: A literature review. *Poltekita: JurnalIlmu Kesehatan*, *18*(1), 1-15.

[53]. Lee, K. (2012). Carbon Accounting for Supply Chain Management in the Automobile Industry.*Journal of Cleaner Production*, *36*, 83-93.

[54]. Low Carbon Vehicle Partnership. (2020). Lifecycle Emissions from Cars. Retrieved from: BOARD-P-05-00X (zemo.org.uk).

[55]. Mai, K. (2024). Influence of Air Quality on Respiratory Health in Urban Areas in Japan. *Global Journal of Health Sciences*, *9*(2), 49-58.

[56]. Manisalidis, I., Stavropoulou, E., Stavropoulos, A., &Bezirtzoglou, E. (2020). Environmental and Health Impacts of Air Pollution: A review. *Frontiers in Public Health*, *8*, 1–13. doi:10.3389/fpubh.2020.00014.

[57]. Mejdoub, Y., &Elamri, A. (2024). *Proceedings of the International Conference on Connected Objects and Artificial Intelligence*. New York, NY: Springer Publishing.

[58]. Mirabelli, M., Ebelt, S., & Damon, S. (2020). Air Quality Index and Air Quality Awareness Among Adults in the United States. *Environmental Research*, *183*, Article 109185. doi:10.1016/j.envres.2020.109185.

[59]. Mostafa, H., Fall, A., Norton, J., Sachithanandham, J., Yunker, M., Abdullah, O., ... & Klein, E. (2024). Respiratory Virus Disease and Outcomes at a Large Academic Medical Center in the United States: A retrospective observational study of the early 2023/2024 respiratory viral season. *Microbiology Spectrum*, *12*(10), e01116-24.

[60]. National Institute for Occupational Safety and Health (NIOSH). (2024, October). About Ventilation and Respiratory Viruses. https://www.cdc.gov/niosh/ventilation/about/index.html.

[61]. Otte, T., Pouliot, G., Pleim, J., Young, J., Schere, K., Wong, D., Lee, P., Tsidulko, M., McQueen, J., Davidson, P., Mathur, R., Chuang, H-Y., DiMego, G., & Seaman, N. (2005). Linking the ETA model with the Community Multiscale Air Quality (CMAQ) modeling system to build a national air quality forecasting system. *Weather and Forecasting*, *20*(3), 367–384. doi:10.1175/WAF855.1.

[62]. Perkins, H. (1974). *Air Pollution, International Edition*. New York, NY: McGraw-Hill Publishing.

[63]. Pott, P. (1775). *Chirurgical Observations: Cancer…* Farmington, Hills, MI: Gale ECCO, Print Editions.

[64]. Power, A., Tennant, R., Jones, R., Tang, Y., Du, J., Worsley, A., & Love, J. (2018). Monitoring Impacts of Urbanisation and Industrialisation on Air Quality in the Anthropocene Using Urban Pond Sediments. *Frontiers in Earth Science*, *6*. doi:10.3389/feart.2018.00131.

[65]. Principi, N., Autore, G., Ramundo, G., & Esposito, S. (2023). Epidemiology of Respiratory Infections During the COVID-19 Pandemic. *Viruses*, *15*(5), 1160.

[66]. Rahman, M., Alam, K., &Velayutham, E. (2021). Is Industrial Pollution Detrimental to Public Health? Evidence from the world's most industrialised countries. *BMC Public Health*, *21*(1), Article 1175. doi.org/10.1186/s12889-021-11217-6.

[67]. Raza, A. (2025). Air Quality Under a Changing Climate: Trends and implications for respiratory diseases. *Journal of Environmental Science and Health*, *1*(1).

[68]. Regulatory Timeline. (2024). Transportation, Air Pollution, and Climate Change. US EPA. Retrieved from https://www.epa.gov/transportation-air-pollution-and-climate-change/timeline-major-accomplishments-transportation-air.

[69]. Rhodes, C. (2016). Democratic business ethics: Volkswagen's emissions scandal and the disruption of corporate sovereignty. *Organization studies*, *37*(10), 1501-1518.

[70]. Ricardo. (2020, September 1). *Ricardo Delivers Major European Report on the Lifecycle Impacts of Road Vehicles*. European Commission. https://www.ricardo.com/en/news-and-insights/press-releases/2020/ricardo-delivers-major-european-report-on-the-lifecycle-impacts-of-road-vehicles.

[71]. Sachdev, P. (2022, June). 10 Worst Smog Cities in America. *WebMD,* Asthma Guide. Retrieved from: https://www.webmd.com/asthma/ss/slideshow-worst-smog-cities;.

[72]. Saleh, S., & Adly, H. (2023). Impact of Ambient Air Pollution Exposure on Long COVID-19 Symptoms: A cohort study within the Saudi Arabian population. *Infectious Disease Reports*, *15*(5), 642-661.

[73]. Sarmadi, M., Rahimi, S., Rezaei, M., Sanaei, D., &Dianatinasab, M. (2021). Air Quality Index Variation Before and After the Onset of COVID-19 Pandemic: A comprehensive study on 87 capital, industrial and polluted cities of the world. *Environmental Sciences Europe*, *33*(1), Article 134. doi:10.1186/s12302-021-00575-y.

[74]. Schulte, K. (2022). 'Real-time' Air Quality Channels: A technology review of emerging environmental alert systems. *Big Data & Society*, *9*(1), 20539517221101346.

[75]. Selim, T., & Gad El-Rab, M. (2020). The Global Auto Industry Self-Driving, Artificial Intelligence, and Autonomous Vehicles. World Economic Forum- Global Agenda Council on Fourth Industrial Revolution.

[76]. Singh, B., Gupta, J., Jain, P., Raish, M., Bin Jardan, Y., & Rahman, S. (2024). Unveiling BTX Dynamics, Source Identification, and Health Implications During COVID-19 Lockdown. *Discover Public Health*, *21*(1), 77.

[77]. Solaymani, S. (2019). CO2 Emissions Patterns in 7 Top Carbon Emitter Economies: The case of transport sector. *Energy*, *168*, 989-1001.

[78]. Stein, R., & Zar, H. (2023). RSV Through the COVID-19 Pandemic: Burden, shifting epidemiology, and implications for the future. *Pediatric Pulmonology*, *58*(6), 1631-1639.

[79]. Stern, A., Turner, B., Boubel, R., Vallero, D., & Fox, D. (1984). *Fundamentals of Air Pollution.* Cambridge, MA: Academic Press.

[80]. Subaru. (2010). *Annual Report 2010.* Retrieved from https://www.subaru.co.jp/en/ir/library/pdf/ar/ar_2010e.pdf.

[81]. Subaru. (2015a). *Annual Report 2015.* Retrieved from https://www.subaru.co.jp/en/ir/library/pdf/ar/ar_2015e.pdf.=

[82]. Subaru. (2015b). *2015 Environmental Report*. Retrieved from https://www.subaru.co.jp/en/csr/report/pdf/2018/14_environment.pdf.

[83]. Subaru. (2016). *Annual report 2016.* Retrieved from https://www.subaru.co.jp/en/ir/library/pdf/ar/ar_2016e.pdf.

[84]. Subaru. (2018). *Consolidated Financial Results for FYE 2018.* Retrieved from https://www.subaru.co.jp/en/ir/library/pdf/fr/2018/2018_4qf_presentation_ts_e.pdf.

[85]. Subaru. (2020). *Consolidated Financial Results for FYE 2020.* Retrieved from https://www.subaru.co.jp/en/ir/library/pdf/fr/2020/2020_4qf_presentation_ts_e.pdf.

[86]. Subaru. (2022). *Consolidated Financial Results for FYE 2022.* Retrieved from https://www.subaru.co.jp/en/ir/library/pdf/fr/2022/2022_4qf_presentation_ts_e.pdf.

[87]. Swenson, S. (August-October, 2023). Email conversations and workshops administered. TRI Program Communications Lead, Stakeholder Engagement Branch, Office of Chemical Safety and Pollution Prevention, US Government.

[88]. Tan, X., Mu, Z., Wang, S., Zhuang, H., Cheng, L., Wang, Y., & Gu, B. (2011). Study on Whole-life Cycle Automotive Manufacturing Industry CO2 Emission Accounting Method and Application in Chongqing. *Procedia Environmental Sciences,5*, 177-172.

[89]. Thomas, W., & Ong, P. (2023). *Environmental Regulations and Industrial Competitiveness: Case studies of toxic industries in Southern California*. New York, NY: Springer Publishing.

[90]. United Nations Environment Programme. (2012). Early Warning Systems a State of the Art Analysis and Future Directions. *Environmental Development*, *4*, 136–171. doi:10.1016/j.envdev.2012.09.004.

[91]. Wu, X., Nethery, R., Sabath, M., Braun, D., & Dominici, F. (2020). Exposure to Air Pollution and COVID-19 Mortality in the United States: A nationwide cross-sectional study. *MedRxiv*, 2020-04.

[92]. Yanowitz, J., & McCormick, R. (2009). Effect of E85 on Tailpipe Emissions from Light-duty Vehicles. *Journal of the Air & Waste Management Association*, *59*(2), 172.

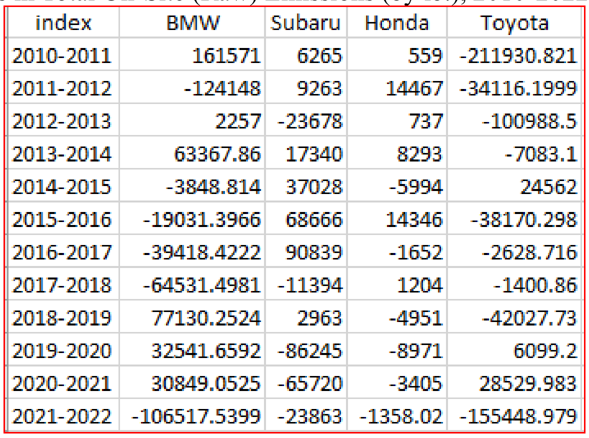
[93]. Zhang, W., Lu, J., Xu, P., & Zhang, Y. (2015). Moving Towards Sustainability: Road grades and on-road emissions of heavy-duty vehicles-a case study. *Sustainability*, *7*(9), 12644-12671.

[94]. Zhou, M., Hu, T., Zhang, W., Wang, Q., Kong, L., Zhou, M., Rao, P., Peng, W., Chen, X., & Song, X. (2022). COVID-19 Pandemic: Impacts on air quality and economy before, during and after lockdown in China in 2020. *Environmental Technology*, *44*(20), 3063–3073. doi.org/10.1080/09593330.2022.2049894.

Appendix 1: Variables Mined from TRI

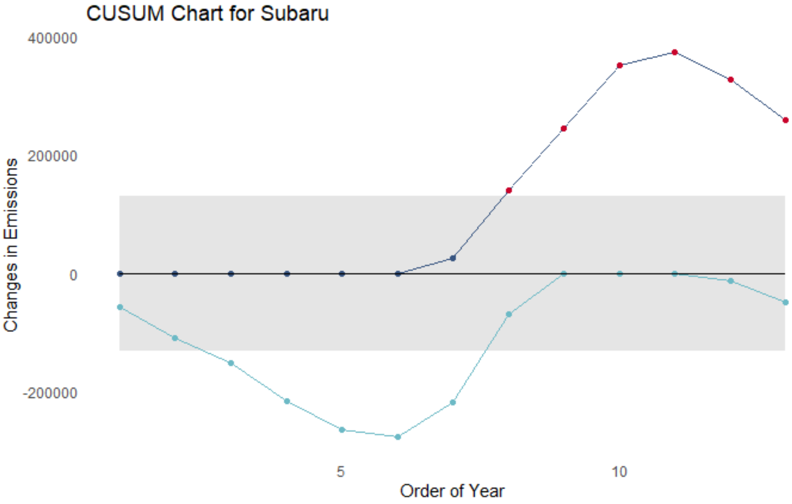
TRI_FACILITY_ID	FACILITY_NAME	STREET_ADDRESS	CITY_NAME	STATE_ABBR	ZIP_CODE	CHEM_NAME	TRI_CHEM_ID	REPORTING_YEAR	TOTAL_ON_OFF_SITE_RELEASE~

Appendix 2: Annual Changes in Total On-Site (Raw) Emissions (by lb.), 2010-2022

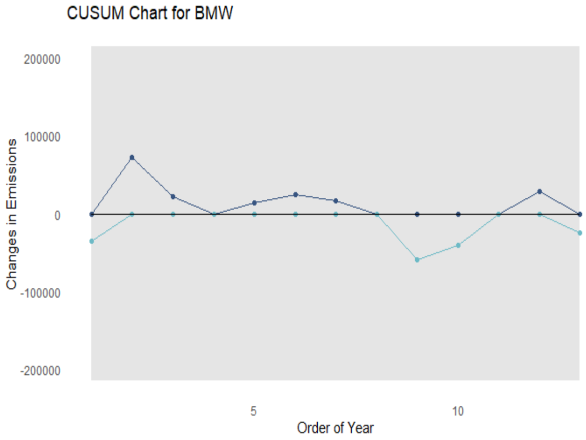


index	BMW	Subaru	Honda	Toyota
2010-2011	161571	6265	559	-211930.821
2011-2012	-124148	9263	14467	-34116.1999
2012-2013	2257	-23678	737	-100988.5
2013-2014	63367.86	17340	8293	-7083.1
2014-2015	-3848.814	37028	-5994	24562
2015-2016	-19031.3966	68666	14346	-38170.298
2016-2017	-39418.4222	90839	-1652	-2628.716
2017-2018	-64531.4981	-11394	1204	-1400.86
2018-2019	77130.2524	2963	-4951	-42027.73
2019-2020	32541.6592	-86245	-8971	6099.2
2020-2021	30849.0525	-65720	-3405	28529.983
2021-2022	-106517.5399	-23863	-1358.02	-155448.979

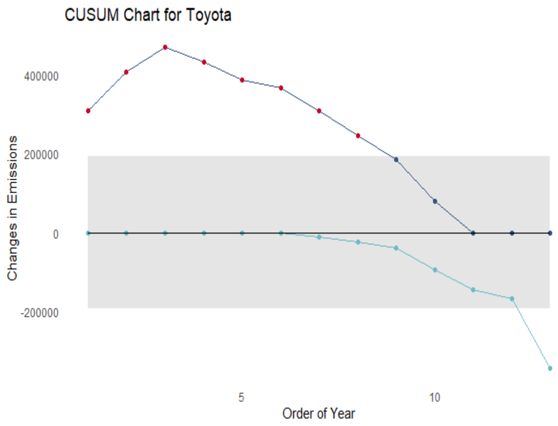
Appendix 3: CUSUM Chart Depicting Subaru Raw Emissions Patterns



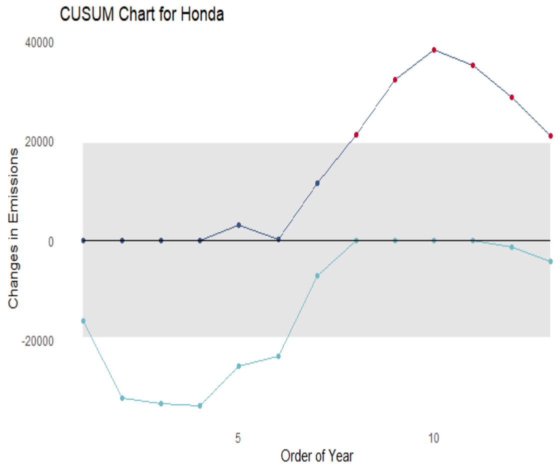
Appendix 4: CUSUM Chart Depicting BMW Raw Emissions Patterns



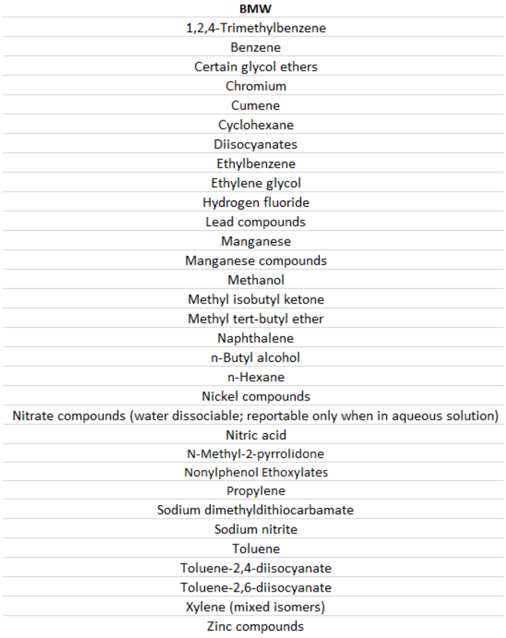
Appendix 5: CUSUM Chart Depicting Toyota Raw Emissions Patterns



Appendix 6: CUSUM Chart Depicting Honda Raw Emissions Patterns



Appendix 7: Emitted Chemicals from the BMW Factory

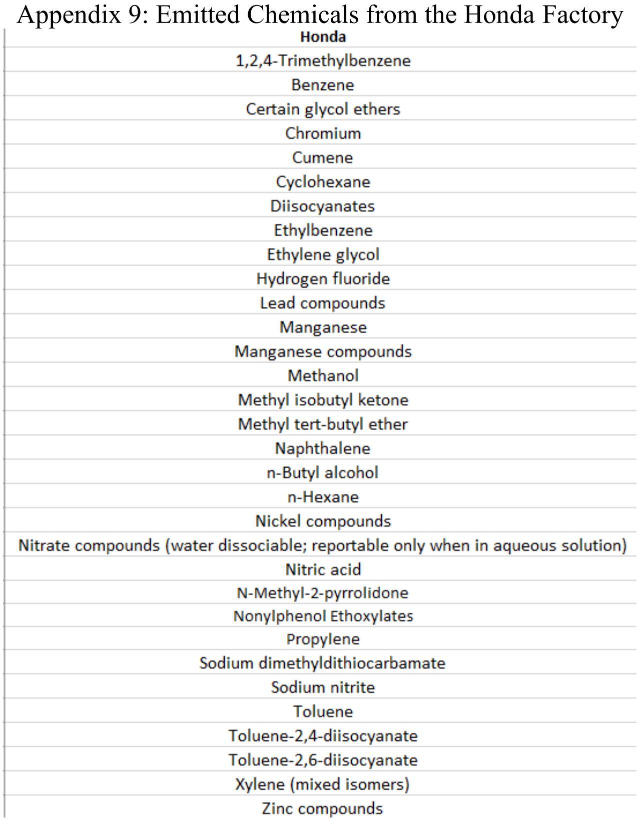


BMW
1,2,4-Trimethylbenzene
Benzene
Certain glycol ethers
Chromium
Cumene
Cyclohexane
Diisocyanates
Ethylbenzene
Ethylene glycol
Hydrogen fluoride
Lead compounds
Manganese
Manganese compounds
Methanol
Methyl isobutyl ketone
Methyl tert-butyl ether
Naphthalene
n-Butyl alcohol
n-Hexane
Nickel compounds
Nitrate compounds (water dissociable; reportable only when in aqueous solution)
Nitric acid
N-Methyl-2-pyrrolidone
Nonylphenol Ethoxylates
Propylene
Sodium dimethyldithiocarbamate
Sodium nitrite
Toluene
Toluene-2,4-diisocyanate
Toluene-2,6-diisocyanate
Xylene (mixed isomers)
Zinc compounds

Appendix 8: Emitted Chemicals from the Subaru Factory

Subaru
1,2,4-Trimethylbenzene
Benzene
Certain glycol ethers
Chromium
Cumene
Cyclohexane
Diisocyanates
Ethylbenzene
Ethylene glycol
Hydrogen fluoride
Lead compounds
Manganese
Manganese compounds
Methanol
Methyl isobutyl ketone
Methyl tert-butyl ether
Naphthalene
n-Butyl alcohol
n-Hexane
Nickel compounds
Nitrate compounds (water dissociable; reportable only when in aqueous solution)
Nitric acid
N-Methyl-2-pyrrolidone
Nonylphenol Ethoxylates
Propylene
Sodium dimethyldithiocarbamate
Sodium nitrite
Toluene
Toluene-2,4-diisocyanate
Toluene-2,6-diisocyanate
Xylene (mixed isomers)
Zinc compounds

Appendix 9: Emitted Chemicals from the Honda Factory

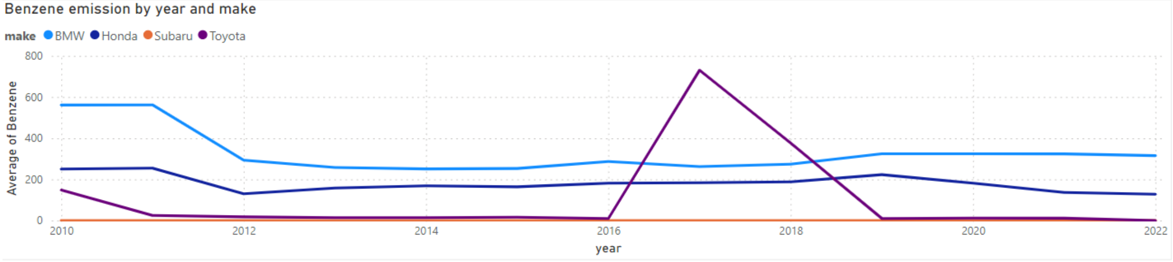


Honda
1,2,4-Trimethylbenzene
Benzene
Certain glycol ethers
Chromium
Cumene
Cyclohexane
Diisocyanates
Ethylbenzene
Ethylene glycol
Hydrogen fluoride
Lead compounds
Manganese
Manganese compounds
Methanol
Methyl isobutyl ketone
Methyl tert-butyl ether
Naphthalene
n-Butyl alcohol
n-Hexane
Nickel compounds
Nitrate compounds (water dissociable; reportable only when in aqueous solution)
Nitric acid
N-Methyl-2-pyrrolidone
Nonylphenol Ethoxylates
Propylene
Sodium dimethyldithiocarbamate
Sodium nitrite
Toluene
Toluene-2,4-diisocyanate
Toluene-2,6-diisocyanate
Xylene (mixed isomers)
Zinc compounds

Appendix 10: Emitted Chemicals from the Toyota Factory

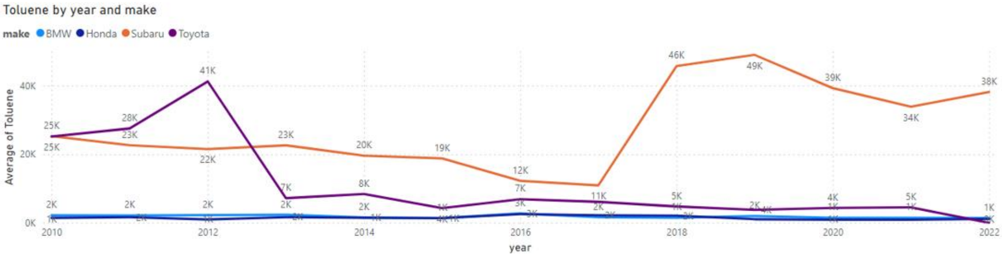
Toyota
1,2,4-Trimethylbenzene
Benzene
Certain glycol ethers
Chromium
Cumene
Cyclohexane
Diisocyanates
Ethylbenzene
Ethylene glycol
Hydrogen fluoride
Lead compounds
Manganese
Manganese compounds
Methanol
Methyl isobutyl ketone
Methyl tert-butyl ether
Naphthalene
n-Butyl alcohol
n-Hexane
Nickel compounds
Nitrate compounds (water dissociable; reportable only when in aqueous solution)
Nitric acid
N-Methyl-2-pyrrolidone
Nonylphenol Ethoxylates
Propylene
Sodium dimethyldithiocarbamate
Sodium nitrite
Toluene
Toluene-2,4-diisocyanate
Toluene-2,6-diisocyanate
Xylene (mixed isomers)
Zinc compounds

Appendix 11: Benzene (raw emissions by lb.)

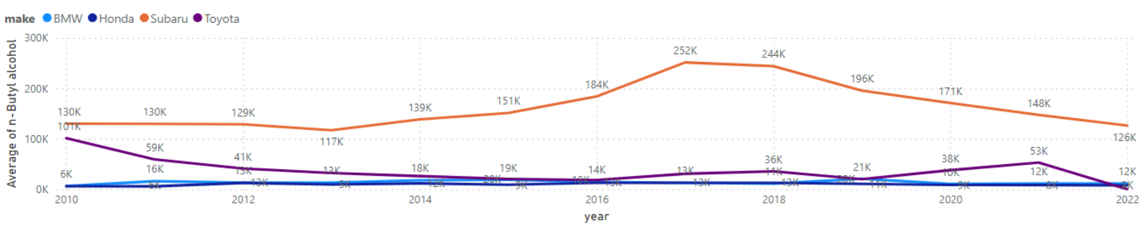


Appendix 12. Xylene (raw emissions by lb.)

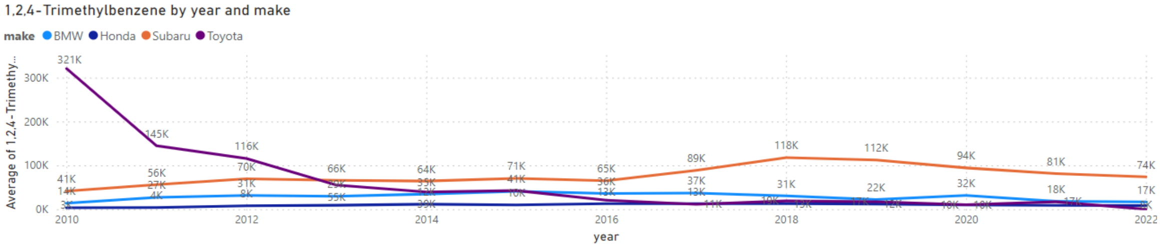
Appendix 13. Toluene (raw emissions by lb.)



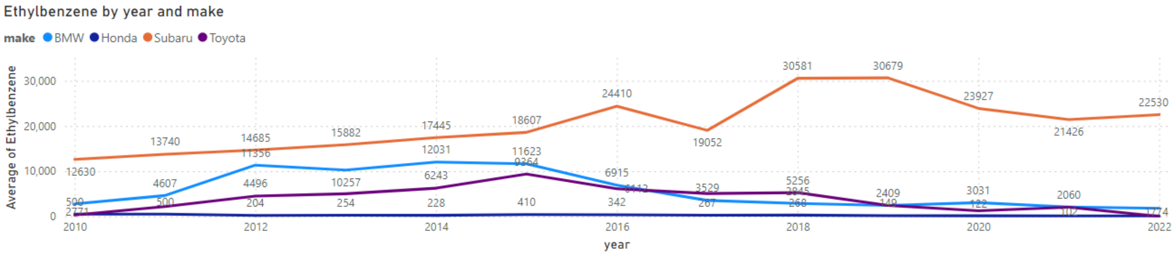
Appendix 14 Butyl Alcohol (raw emissions by lb.)



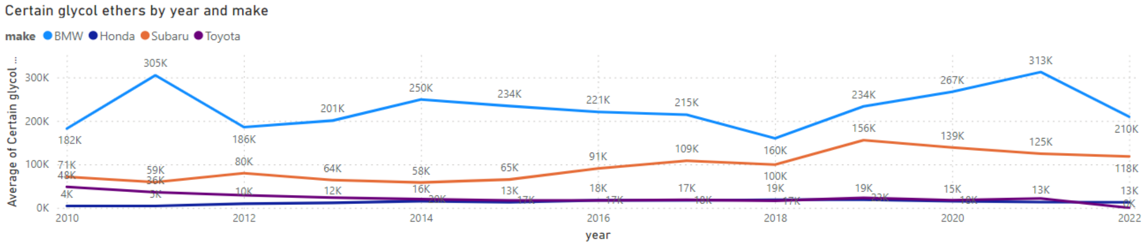
Appendix 15: 1, 2, 4 Trimethylbenzene (raw emissions by lb.)



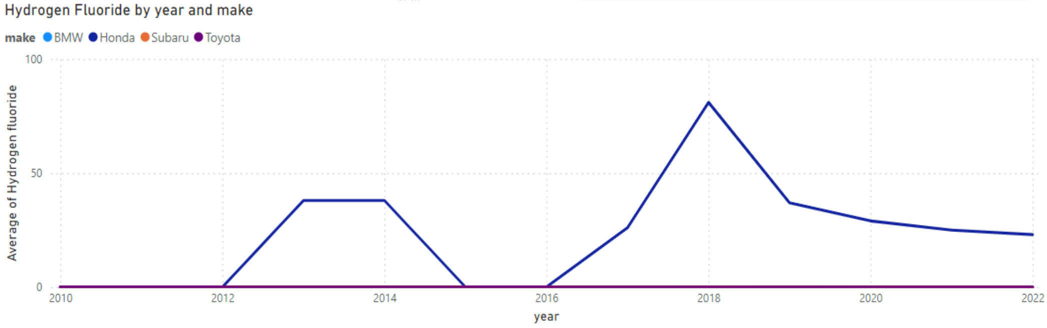
Appendix 16: Ethylbenzene (raw emissions by lb.)



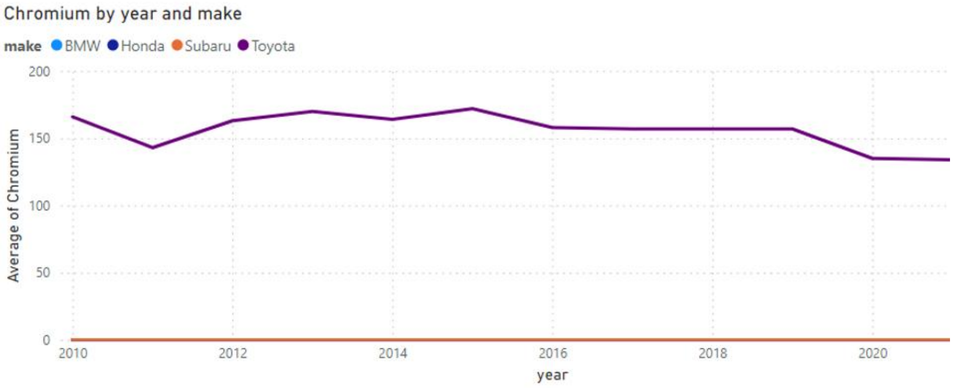
Appendix 17:Certain Glycol Ethers (raw emissions by lb.)



Appendix 18: Hydrogen Fluoride (raw emissions by lb.)



Appendix 19: Chromium via Toyota (raw emissions by lb.)

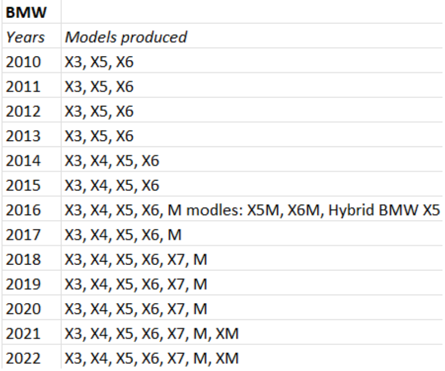


Appendix 20: *Davies' Test from Piecewise Regression (Chemicals Emitted)*

Chemical	BWM	Subaru	Honda	Toyota
1, 2, 4 Trimethylbenzene	0.001	0.019	1.9 e-5	1 e–5
Certain glycol ethers	1	0.656	5.7 e-5	0.094
Ethylbenzene	0.004	0.036	0.516	1.1 e-5

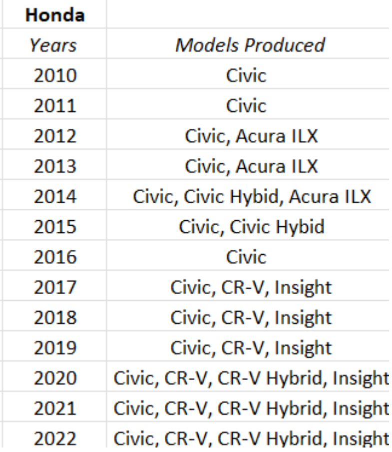
Ethylene glycol	0.006	6.6 e–5	0.444	5.1 e-5
n Butyl alcohol	0.104	0.007	0.022	0.02
Toluene	1	0.366	0.09	0.316
Xylene mixed isomers	0.060	0.005	0.6598	0.637

Appendix 21: BMW Models Manufactured



BMW	
Years	*Models produced*
2010	X3, X5, X6
2011	X3, X5, X6
2012	X3, X5, X6
2013	X3, X5, X6
2014	X3, X4, X5, X6
2015	X3, X4, X5, X6
2016	X3, X4, X5, X6, M modles: X5M, X6M, Hybrid BMW X5
2017	X3, X4, X5, X6, M
2018	X3, X4, X5, X6, X7, M
2019	X3, X4, X5, X6, X7, M
2020	X3, X4, X5, X6, X7, M
2021	X3, X4, X5, X6, X7, M, XM
2022	X3, X4, X5, X6, X7, M, XM

Appendix 22: Honda Models Manufactured

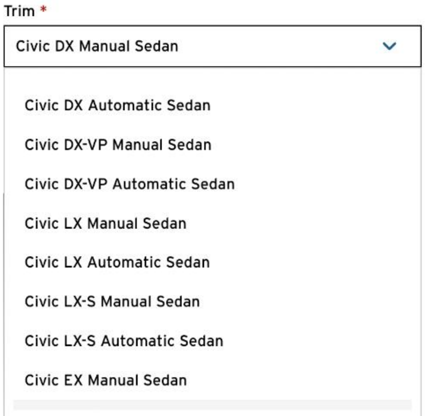


Honda	
Years	*Models Produced*
2010	Civic
2011	Civic
2012	Civic, Acura ILX
2013	Civic, Acura ILX
2014	Civic, Civic Hybid, Acura ILX
2015	Civic, Civic Hybid
2016	Civic
2017	Civic, CR-V, Insight
2018	Civic, CR-V, Insight
2019	Civic, CR-V, Insight
2020	Civic, CR-V, CR-V Hybrid, Insight
2021	Civic, CR-V, CR-V Hybrid, Insight
2022	Civic, CR-V, CR-V Hybrid, Insight

Appendix 23: Subaru Models Manufactured:

Subaru	
Years	*Models produced*
2010	Legacy, Tribeca
2011	Legacy, Tribeca
2012	Legacy, Tribeca
2013	Legacy, Tribeca
2014	Legacy, Tribeca
2015	Legacy
2016	Legacy
2017	Legacy, Outback, Impreza
2018	Ascent, Legacy, Outback, Impreza
2019	Ascent, Legacy, Outback, Impreza
2020	Ascent, Legacy, Outback, Impreza
2021	Ascent, Legacy, Outback, Impreza
2022	Ascent, Legacy, Outback, Impreza

Appendix 24: Honda Civic 2011 Models Manufactured



Trim *

Civic DX Manual Sedan

Civic DX Automatic Sedan

Civic DX-VP Manual Sedan

Civic DX-VP Automatic Sedan

Civic LX Manual Sedan

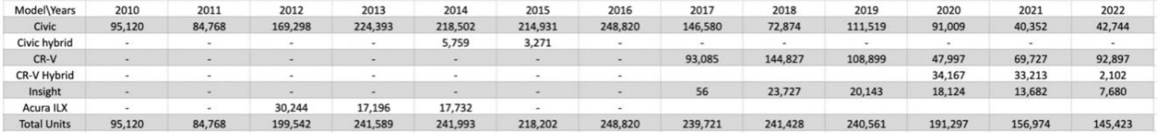
Civic LX Automatic Sedan

Civic LX-S Manual Sedan

Civic LX-S Automatic Sedan

Civic EX Manual Sedan

Appendix 25: Honda Production Units

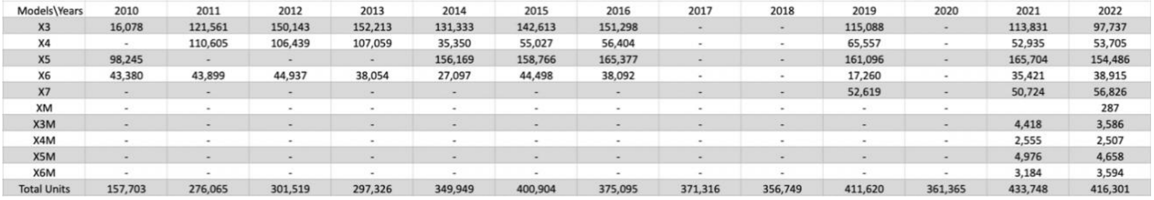


Model\Years	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Civic	95,120	84,768	169,298	224,393	218,502	214,931	248,820	146,580	72,874	111,519	91,009	40,352	42,744
Civic hybrid	-	-	-	-	5,759	3,271	-	-	-	-	-	-	-
CR-V	-	-	-	-	-	-	-	93,085	144,827	108,899	47,997	69,727	92,897
CR-V Hybrid	-	-	-	-	-	-	-				34,167	33,213	2,102
Insight	-	-	-	-	-	-	-	56	23,727	20,143	18,124	13,682	7,680
Acura ILX	-	-	30,244	17,196	17,732	-	-						
Total Units	95,120	84,768	199,542	241,589	241,993	218,202	248,820	239,721	241,428	240,561	191,297	156,974	145,423

Appendix 26: Subaru Production Units

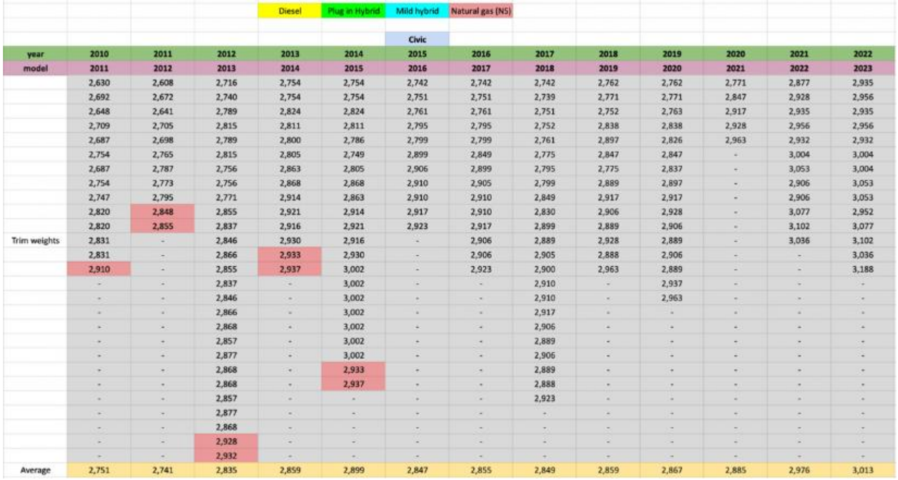
Models\Years	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Legacy	100,149	159,215	164,968	177,471	161,204	206,681	235,979	-	-	-	-	-	-
Tribeca	4,197	5,558	5,661	3,713	2,307	0	0	-	-	-	-	-	-
Outback	-	-	-	-	-	-	-	-	-	-	-	-	-
Impreza	-	-	-	-	-	-	-	-	-	-	-	-	-
Ascent	-	-	-	-	-	-	-	-	-	-	-	-	-
Total Units	104,346	164,773	170,629	181,184	163,511	206,681	235,979	335,200	348,600	372,200	367,300	285,200	272,000

Appendix 27: BMW Production Units



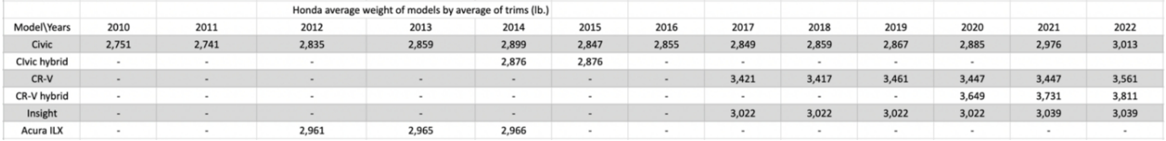
Models\Years	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
X3	16,078	121,561	150,143	152,213	131,333	142,613	151,298	-	-	115,088	-	113,831	97,737
X4	-	110,605	106,439	107,059	35,350	55,027	56,404	-	-	65,557	-	52,935	53,705
X5	98,245	-	-	-	156,169	158,766	165,377	-	-	161,096	-	165,704	154,486
X6	43,380	43,899	44,937	38,054	27,097	44,498	38,092	-	-	17,260	-	35,421	38,915
X7	-	-	-	-	-	-	-	-	-	52,619	-	50,724	56,826
XM	-	-	-	-	-	-	-	-	-	-	-		287
X3M	-	-	-	-	-	-	-	-	-	-	-	4,418	3,586
X4M	-	-	-	-	-	-	-	-	-	-	-	2,555	2,507
X5M	-	-	-	-	-	-	-	-	-	-	-	4,976	4,658
X6M	-	-	-	-	-	-	-	-	-	-	-	3,184	3,594
Total Units	157,703	276,065	301,519	297,326	349,949	400,904	375,095	371,316	356,749	411,620	361,365	433,748	416,301

Appendix 28: Honda Civic 2011 Average Weight Using All Trims (lb.)



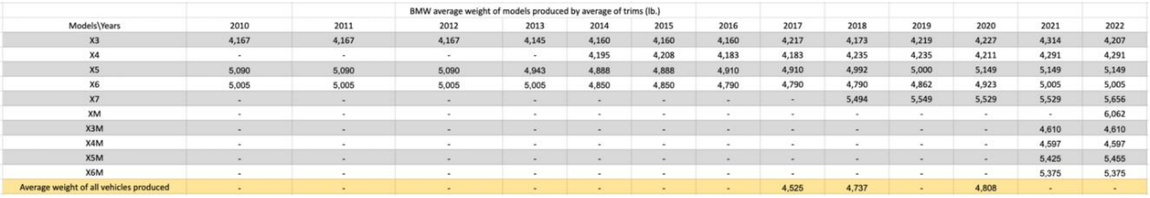
				Diesel	Plug in Hybrid	Mild hybrid	Natural gas (NS)						
						Civic							
year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
model	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
	2,630	2,608	2,716	2,754	2,754	2,742	2,742	2,742	2,762	2,762	2,771	2,877	2,935
	2,692	2,672	2,740	2,754	2,754	2,751	2,751	2,739	2,771	2,771	2,847	2,928	2,956
	2,648	2,641	2,789	2,824	2,824	2,761	2,761	2,751	2,752	2,763	2,917	2,935	2,935
	2,709	2,705	2,815	2,811	2,811	2,795	2,795	2,752	2,838	2,838	2,928	2,956	2,956
	2,687	2,698	2,789	2,800	2,786	2,799	2,799	2,761	2,897	2,826	2,963	2,932	2,932
	2,754	2,765	2,815	2,805	2,749	2,899	2,849	2,775	2,847	2,847	-	3,004	3,004
	2,687	2,787	2,756	2,863	2,805	2,906	2,899	2,795	2,775	2,837	-	3,053	3,004
	2,754	2,773	2,756	2,868	2,868	2,910	2,905	2,799	2,889	2,897	-	2,906	3,053
	2,747	2,795	2,771	2,914	2,863	2,910	2,910	2,849	2,917	2,917	-	2,906	3,053
	2,820	2,848	2,855	2,921	2,914	2,917	2,910	2,830	2,906	2,928	-	3,077	2,952
	2,820	2,855	2,837	2,916	2,921	2,923	2,917	2,899	2,889	2,906	-	3,102	3,077
Trim weights	2,831	-	2,846	2,930	2,916	-	2,906	2,889	2,928	2,889	-	3,036	3,102
	2,831	-	2,866	2,933	2,930	-	2,906	2,905	2,888	2,906	-	-	3,036
	2,910	-	2,855	2,937	3,002	-	2,923	2,900	2,963	2,889	-	-	3,188
	-	-	2,837	-	3,002	-	-	2,910	-	2,937	-	-	-
	-	-	2,846	-	3,002	-	-	2,910	-	2,963	-	-	-
	-	-	2,866	-	3,002	-	-	2,917	-	-	-	-	-
	-	-	2,868	-	3,002	-	-	2,906	-	-	-	-	-
	-	-	2,857	-	3,002	-	-	2,889	-	-	-	-	-
	-	-	2,877	-	3,002	-	-	2,906	-	-	-	-	-
	-	-	2,868	-	2,933	-	-	2,889	-	-	-	-	-
	-	-	2,868	-	2,937	-	-	2,888	-	-	-	-	-
	-	-	2,857	-	-	-	-	2,923	-	-	-	-	-
	-	-	2,877	-	-	-	-	-	-	-	-	-	-
	-	-	2,868	-	-	-	-	-	-	-	-	-	-
	-	-	2,928	-	-	-	-	-	-	-	-	-	-
	-	-	2,932	-	-	-	-	-	-	-	-	-	-
Average	2,751	2,741	2,835	2,859	2,899	2,847	2,855	2,849	2,859	2,867	2,885	2,976	3,013

Appendix 29: Honda Civic 2011 Average Weight of Models by Average of Trims (lb.)



			Honda average weight of models by average of trims (lb.)										
Model\Years	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Civic	2,751	2,741	2,835	2,859	2,899	2,847	2,855	2,849	2,859	2,867	2,885	2,976	3,013
Clvic hybrid	-	-	-		2,876	2,876	-	-	-	-	-		
CR-V	-	-	-	-	-	-	-	3,421	3,417	3,461	3,447	3,447	3,561
CR-V hybrid	-	-	-	-	-	-	-	-	-	-	3,649	3,731	3,811
Insight	-	-	-	-	-	-	-	3,022	3,022	3,022	3,022	3,039	3,039
Acura ILX	-	-	2,961	2,965	2,966	-	-	-	-	-	-	-	-

Appendix 30: BMW Average Weight of Models Produced by Average of Trims (lb.)



			BMW average weight of models produced by average of trims (lb.)										
Models\Years	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
X3	4,167	4,167	4,167	4,145	4,160	4,160	4,160	4,217	4,173	4,219	4,227	4,314	4,207
X4	-	-	-	-	4,195	4,208	4,183	4,183	4,235	4,235	4,211	4,291	4,291
X5	5,090	5,090	5,090	4,943	4,888	4,888	4,910	4,910	4,992	5,000	5,149	5,149	5,149
X6	5,005	5,005	5,005	5,005	4,850	4,850	4,790	4,790	4,790	4,862	4,923	5,005	5,005
X7	-	-	-	-	-	-	-	-	5,494	5,549	5,529	5,529	5,656
XM	-	-	-	-	-	-	-	-	-	-	-	-	6,062
X3M	-	-	-	-	-	-	-	-	-	-	-	4,610	4,610
X4M	-	-	-	-	-	-	-	-	-	-	-	4,597	4,597
X5M	-	-	-	-	-	-	-	-	-	-	-	5,425	5,455
X6M	-	-	-	-	-	-	-	-	-	-	-	5,375	5,375
Average weight of all vehicles produced	-	-	-	-	-	-	-	4,525	4,737	-	4,808	-	-

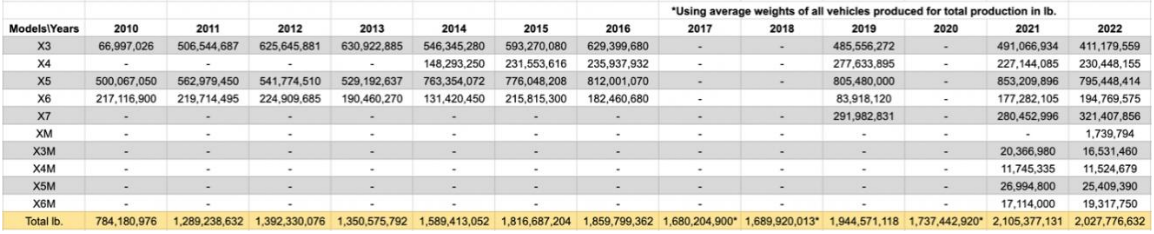
Appendix 31: Honda Total Production (lb.)

Model\Years	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Civic	261,675,120	232,349,088	479,959,830	641,539,587	633,437,298	611,908,557	710,381,100	417,606,420	208,346,766	319,724,973	262,560,965	120,087,552	128,787,672
Clvic hybrid	-	-	-	-	16,562,884	9,407,396	-	-	-	-	-	-	-
CR-V	-	-	-	-	-	-	-	318,443,785	494,873,859	376,899,439	165,445,659	240,348,969	330,806,217
CR-V hybrid	-	-	-	-	-	-	-	-	-	-	124,675,383	123,917,703	8,010,722
Insight	-	-	-	-	-	-	-	169,232	71,702,994	60,872,146	54,770,728	41,579,598	23,339,520
Acura ILX	-	-	89,552,484	50,986,140	52,593,112	-	-	-	-	-	-	-	-
Total lb.	261,675,120	232,349,088	569,512,314	692,525,727	702,593,294	621,315,953	710,381,100	736,053,227	774,923,619	757,496,558	607,452,735	525,933,822	490,944,131

Appendix 32: Subaru Total Production (lb.)

								*Using average weights of all vehicles produced for total production in lb.					
Models\Years	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Legacy	342,609,729	541,649,430	564,025,592	605,353,581	563,730,388	723,176,819	832,533,912	-	-	-	-	-	-
Tribeca	17,614,809	23,421,412	23,345,964	15,312,412	9,514,068	-	-	-	-	-	-	-	-
Outback	-	-	-	-	-	-	-	-	-	-	-	-	-
Impreza	-	-	-	-	-	-	-	-	-	-	-	-	-
Ascent	-	-	-	-	-	-	-	-	-	-	-	-	-
Total lb.	360,224,538	565,070,842	587,371,556	620,665,993	573,244,456	723,176,819	832,533,912	1,164,149,600*	1,230,209,400*	1,328,009,600*	1,311,628,300*	1,021,016,000*	973,216,000*

Appendix 33: BMW Total Production (lb.)



								*Using average weights of all vehicles produced for total production in lb.					
Models\Years	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
X3	66,997,026	506,544,687	625,645,881	630,922,885	546,345,280	593,270,080	629,399,680	-	-	485,556,272	-	491,066,934	411,179,559
X4	-	-	-	-	148,293,250	231,553,616	235,937,932	-	-	277,633,895	-	227,144,085	230,448,155
X5	500,067,050	562,979,450	541,774,510	529,192,637	763,354,072	776,048,208	812,001,070	-	-	805,480,000	-	853,209,896	795,448,414
X6	217,116,900	219,714,495	224,909,685	190,460,270	131,420,450	215,815,300	182,460,680	-		83,918,120	-	177,282,105	194,769,575
X7	-	-	-	-	-	-	-	-	-	291,982,831	-	280,452,996	321,407,856
XM	-	-	-	-	-	-	-	-	-	-	-	-	1,739,794
X3M	-	-	-	-	-	-	-	-	-	-	-	20,366,980	16,531,460
X4M	-	-	-	-	-	-	-	-	-	-	-	11,745,335	11,524,679
X5M	-	-	-	-	-	-	-	-	-	-	-	26,994,800	25,409,390
X6M	-	-	-	-	-	-	-	-	-	-	-	17,114,000	19,317,750
Total lb.	784,180,976	1,289,238,632	1,392,330,076	1,350,575,792	1,589,413,052	1,816,687,204	1,859,799,362	1,680,204,900*	1,689,920,013*	1,944,571,118	1,737,442,920*	2,105,377,131	2,027,776,632