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Autogeddon or autoheaven: Environmental and social effects of the automotive industry from launch to present

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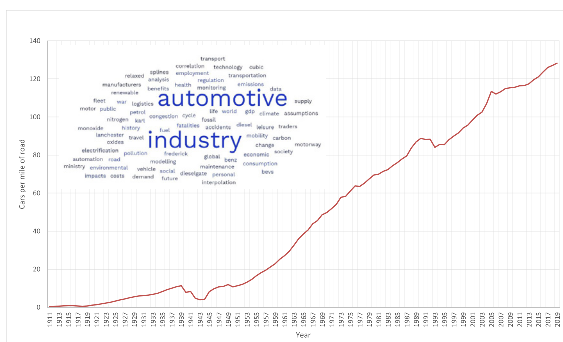
HIGHLIGHTS

- Original datasets relating to the UK automotive sector reconstructed 1900–2020
- Significant emissions resulted from early industry; successful remediation late C20
- Ratios of fatalities to cars show social ingraining & rapid response to legislation
- World War 2 a landmark for auto industry, creating capacity for mass production
- Future developments require renewable energy & overcoming resource scarcity, etc

GRAPHICAL ABSTRACT



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ABSTRACT

The automotive industry is one of the most significant and increasing sources of pollution worldwide. Previous studies examining its impacts focus on the post-1950 era as data available before this period is scarce. This study carefully reconstructs six datasets from the early 20th century to 2019 for the UK: annual number of motor cars, road lengths, road fatalities, NOx and CO emissions, and fuel consumption. Interpolation was prudently used to fill gaps in the data sets. Results highlight changing health, social and environmental effects throughout the growth of the automotive sector. Ratios of fatalities to cars indicate social ingraining of the car and rapid response to legislation. Significant emissions resulted from the early industry. Successful remediation of emissions occurred in the late 20th century. All variables studied were interrelated, but expansion of road networks particularly contributed to a range of both positive and (unintended) negative consequences. World War 2 appears to have been a landmark for the automotive industry, producing capacity for mass production, personal mobility and research and therefore a struggle between impacts and social policies. We have demonstrated that technological developments and regulatory interventions relating to the motor industry, alongside events that have catalysed societal change, have been crucial in terms of subsequently providing benefits to society whilst also acting to mitigate (but not prevent) the adverse and frequently devastating impacts of motor vehicles on human health and the environment. A periodic, regular, overarching, independent review (~ every 5 years) of the collective positive and negative impacts of the motor vehicle industry and appropriate interventions are essential to maintain and improve social benefits and public and environmental health, as well as supporting delivery of the United Nations' Sustainable Development Goals by 2030 and beyond.

1. Introduction

The birth of the automotive industry is typically recognised from when Karl Benz received the patent for his invention of the automotive powered by an internal combustion engine in 1886. His invention was continually

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improved via important contributions from notable figures such as Frederick W. Lanchester, one of the most influential engineers of the late 19th century and early 20th centuries. Lanchester invented and patented a Pendulum Governor to control engine speeds as well as designing a new petrol engine that had a revolutionary epicyclic gearbox that allowed two forward moving speeds and reversing capability (Platt, 1968).

There were soon numerous small companies making expensive hand-made cars for the wealthy, including Daimler, De Dion-Bouton, Renault, Humber, Wolseley, Napier, Alldays and Onions, Star and Vauxhall (Saul, 1962). However, it was not until the American industrialist and business magnate, Henry Ford, introduced the assembly line technique of mass production to his manufacturing plants that cars were transformed from an unaffordable luxury to a legitimate travel option for the middle class. Mass production dramatically cut production costs allowing cars to become more affordable, proliferating personal mobility and making the Ford Model T by far the most popular car in the early 20th century (Thomas, 1969).

Nowadays there are an estimated 1.4 billion cars on the road globally, with over 32 million in the UK alone. They have played a crucial role in increasing mobility for billions, increasing nations' gross domestic product (GDP), and generating substantial employment in both upstream and downstream industries. However, a relatively small number of countries are known for engineering and manufacturing automobiles because of the inherent infrastructure and skills requirements, so the majority of countries import automobiles. Cars have become the world's second most exported product (>£640 billion in 2020), even surpassing oil export revenues, and so are a product of prodigious economic importance (Saberi, 2018). Motor transport had greater economic and social impacts on the United Kingdom (UK) than any other industry during the inter-war periods (Dyos and Aldcroft, 1969). Nearly all forms of internal transport - railways, trams, canals, coastal shipping and horse-drawn vehicles - suffered from road competition (Dudley, 1957). Facilitation and consequent employment and investment opportunities counteracted many of these drawbacks, which alleviated some pressures of those years (Dyos and Aldcroft, 1969). Major landmarks, including important legislation and safety advances in automotive history, are compiled in Table 1. It is clear that post-World War 2, sector developments became more comprehensive.

Due to the sheer scale of the automotive industry, there are very significant costs and benefits to car use. At the level of an individual, the financial costs include the burdens associated with purchasing a vehicle, interest payments, repairs and maintenance, depreciation, fuel and oil, parking fees, taxes, insurance, and (non-productive) driving time, etc. At a societal level, the financial costs include land purchase and use, building and maintenance of roads & related infrastructure (e.g. tunnels, bridges, runoff drains), traffic congestion, severance, air/water/land pollution and the consequent impacts on ecosystem/public health, healthcare (e.g. due to accidents), and treatment/disposal of a vehicle at its end-of-life, etc. The WHO (2022) reported that ~1.3 million people die each year as a result of road traffic crashes, costing most countries 3 % of their GDP, and with >50 % of all road traffic deaths involving vulnerable road users (VRUs). People who require extra care when roads are in use are regarded as VRUs, mainly pedestrians, motorcyclists, horse riders, and cyclists. Age, health and experience also affect how vulnerable people are, including drivers of vehicles.

The personal benefits of car use include ready availability of convenient on-demand transportation, mobility and independence. The societal benefits include economic benefits, such as job and wealth creation; the industry's annual turnover is equivalent to the world's sixth largest economy with global direct employment at 14–15 million workers (ILO, 2020). Other societal benefits include the widespread provision of transportation, general well-being and enhanced quality of life from leisure/travel opportunities, contribution to Gross National Product (GDP), and revenue generation from taxes. People's ability to move flexibly - locally and around countries and regions - has far-reaching repercussions for the characteristics of societies. Car usage continues to increase rapidly, especially in cash-rich India and China, and other recently industrialized countries.

The transport sector is widely recognised as a significant and increasing source of air pollution worldwide. One of the earliest acknowledgements came after problems of sooty smog from coal combustion had been largely solved in Western European and North American cities (Colvile et al., 2001). A comprehensive array of scientific literature that examines environmental issues of the industry is based on quantitative post-1950 data (e.g. Dore et al., 2004; Paterson, 2000; Lowson, 1998; Harrington, 1997). Little examination of the sector has been undertaken pre-1950, probably due to the sparse and inaccurate nature of statistical records for this period. Fragmented data from different sources can be found in historical books (Saul, 1962). There is little historical perspective about the environmental impacts of the automotive industry prior to World War 2. Paterson (2000) suggests lobbying by powerful stakeholders, such as Daimler Chrysler, General Motors, Ford, and Exxon, in the now deactivated Global Climate Coalition, hindered environmental studies.

The transport sector is a major contributor to global CO_2 emissions, accounting for 16.2 % of the emissions produced in 2016 (Ritchie and Roser, 2020). Within the transport sector, road transport is responsible

Table 1
Milestones/events of the automotive industry.

Date	Milestone/event
1886	Karl Benz receives patent for automotive powered by internal combustion engine
1896	First motoring fatality (Bridget Driscoll)
1903	Motor Car Act: Speed limit of 20 mph
1904	First guidelines of traffic signs
1910	The Road Board is founded which administered grants for road improvements
1912	Roadside telephone boxes introduced by the AA
1914–1918	World War I
1916	London 'Safety First' Council formed
1919	First petrol stations are introduced
1923	Roundabouts are first constructed
1926	First traffic lights
	Safety glass fitted in windscreens for the first time
1930	Road Traffic Act 1930: Abolished speed limit for cars and set and standards and penalties for dangerous driving. Highway Code guidance issued
1932	Pedestrian operated crossing lights
1933	Road and Rail Traffic Act 1933: Driving licenses had to be obtained to drive
1934	Road Traffic Act 1934: Speed limit set to 30mph in built up areas, penalties for dangerous driving increased, pedestrian crossings with Belisha beacons, cyclists required to have rear reflectors, driving tests now compulsory
1935	Restriction of Ribbon Act 1935: Issued to prevent urban sprawl across the countryside
1939–1945	World War II: Over half of passenger vehicles destroyed for scrap metal, introduction of mass production techniques to the UK, blackouts, driving tests suspended, petrol rationing
1940	Blackout speed limit of 20mph
1946	Driving tests are reintroduced
1947	Transport Act 1947: British Transport Commission is set up to promote the use of public transport
1951	Zebra crossings introduced
1958	First motorway in the UK
	Introduction of parking meters
1960	MOT tests
1967	Drink driving laws
1968	Breathalysers introduced
1969	Pelican crossing introduced
1970	Green Cross Code campaign begins
1973	Crash helmets become compulsory for motorcyclists
1977	MOT test includes petrol emissions
1983	Seatbelts compulsory for driver and front seat passenger
1991	Seatbelts also become compulsory for rear seat passengers
1992	Catalytic converters fitted onto cars
1994	MOT test includes diesel emissions
2001	Ultra-low sulfur fuel goes on sale
2003	London congestion charges begin
2006	Volvo introduce one of the world's first autonomous braking systems
2009	THINK! launches the first nationwide anti-drug driving campaign
2014	Slow Down for Bobby campaign launched including the launch of 'Bobby Zones'
2015	Police begin roadside drug testing

for producing the most CO_2 emissions, accounting for 74.5 % of the emissions produced within the sector in 2018 (Ritchie, 2020). This is partially because continual improvements in car efficiency are more than offset by the increasing demand for personal travel. Road transport is a key area where achieving reductions in emissions would significantly contribute to lowering the total emissions produced worldwide. In the UK, transport emissions have stabilised with present day CO_2 emissions from the transport sector being comparable to 1990 as carbon reductions caused by improved vehicle technology are being matched by increases in volumes of travel (Department for Transport, 2021a, b). This is at a time where nationally total CO_2 emissions have been steadily decreasing, and so in this regard the transport sector has fallen behind other industries.

Of course, the environmental and social impacts of the automotive industry are not limited to the 'use' phase. Impacts originate from all phases of a car's life cycle, which can be split into three main phases: manufacture, operation or 'use' and end-of-life. Whilst considerable emissions originate during the operation phase of a vehicle, significant amounts also derive from the manufacture and end-of-life phases (Del Pero et al., 2018). The five main life-cycle environmental impacts associated with the automotive industry are: i) Use of non-renewable resources during operation; ii) Water and energy usage during manufacture stage and the emissions associated with the power generation; iii) Manufacturing processes especially painting of vehicles causes land, air and water pollution; iv) Global logistics used to transport vehicles after manufacture; and v) End-of-life waste stream. The environmental impacts of material manufacturing were not included since it would require a material composition of all types of cars going back 120 years and clearly this is a huge undertaking, probably impossible to do with any degree of accuracy.

Whilst there have been numerous studies on the impact cars have on society and the environment based on post 1950s quantitative data, there is little literature on the numbers of, and impacts from, cars prior to the 1950s. This is due to missing and/or sparse data available from this time period, leaving a considerable research gap. Consequently, there is limited quantitative data/analysis on the effects that significant events such as the Second and First World Wars had on the motor industry and how this could have affected its social/environmental impacts, and what this might mean for future directions for the motor industry.

This study aims to fill this gap by: i) reconstructing datasets for UK automotive industry from the early 20th century to the present day; ii) critically analysing the associated environmental and social impacts from launch to present; and iii) using insights gained and lessons learned to make suggestions for how the motor industry should monitor and attend to its collective impacts in future. Six different variables were selected for examination, each being a significant indicator of environmental and social impacts; fuel consumption; carbon monoxide (CO) emissions; nitrogen oxides (NOx) emissions; road fatalities; road lengths; and number of cars on the road. Subsequently, the environmental and societal impacts that the automotive industry has had on the UK are closely examined. We address a number of issues including; environmental effects of the emissions originating from these vehicles as well as the negative health effects deriving from associated air pollution; increases in congestion because of an increasing number of cars and its effect on levels of air pollutants; the societal impact of road fatalities; and employment generation due to the growth of the sector. The future of the vehicle fleet in terms of electrification, light weighting, and potential wide-spread automation and what this means for the environmental and social impact of the industry is also discussed.

2. Methods

2.1. Data recovery

Prior to World War 1, statistics from the automotive industry were almost non-existent, with the only source of relatively reliable data coming from the Society of Motor Manufacturers and Traders (SMMT). The SMMT is the UK's national trade association for the motor industry, supporting and promoting its interests, at home and abroad. The SMMT is a member of the International Organization of Motor Vehicle Manufacturers (OICA), founded in Paris, France, in 1919. The OICA's purpose is to defend the interests of vehicle manufacturers, assemblers, and importers around the world.

The SMMT produced estimates of the UK's "total output", which refers to number of vehicles emerging from production lines. It was only after World War 2 that road statistics became available in increased quantity and quality as the post-war automotive industry began contributing a bigger share to the national economy (Zeitlin, 2000). The Ministry of Supply, which was abolished in 1959, was the first to collate production figures in 1945 and these were published in the Monthly Digest of Statistics and by the SMMT. The quality of statistics became vastly more accurate as registration of motor vehicles became necessary under the Vehicles Excise Act 1949 for all vehicles used on public roads. It was around this period that census became more accurate after it briefly stopped during wartime as it was mandatory for all vehicles to be issued with a license (Ford, 1951).

For a single paper there are too many factors and variables which can lead to environmental damage and negative social impacts to collate and so this was narrowed down to only six variables to be representative of the environmental and social impact originating from the industry. The variables chosen were road fatalities, carbon monoxide and nitrogen oxide emissions, passenger vehicles, road lengths and fuel consumption. NOx and CO emissions were chosen as they can represent the general air quality levels and associated environmental impact of increased anthropogenic pollutants originating from cars. Fuel consumption shows the growth of the industry and the increased use of fuel which can be associated with negative environmental impact. Fuel consumption is able to provide some indication of the effects of potential technological advancements i.e., increased fuel efficiency over time, although this factor is diminished by changes (increases) in total distances travelled over time. Road fatalities were selected as a representative of the development of road safety, both infrastructural and educational.

Data used has been obtained from several different sources as there was no one party which documented automotive statistics since the launch of the industry. Between some of the data sources there were disagreements and inconsistencies in the data and so in these cases the most reliable source of data was chosen i.e., data that agreed and was most consistent with other data sources and was from an official publication. Scatter plots of fuel consumption against number of cars were used to investigate discrepancies identified in archived fuel consumption data. Figures from 1928 to 1938, taken from The Motor Industry of Great Britain (published by the SMMT), were dissimilar to those calculated using Motor Fuel Tax figures found in the book of Basic Road Statistics 1948. Information on how the SMMT acquired their data was missing. Spearman's Rank correlation coefficient, for non-parametric data, produced a near perfect correlation of 0.974, significant at the 0.01 level. For these reasons, the more complete, calculated, figures were chosen for further study and the former discarded as unreliable.

To fully analyse development of the industry, all data sets, other than the number of motor cars, required partial reconstruction. This was due to missing figures from various dates. Due to so many external factors, a simple linear or logarithmic model, for example, would not explain fluctuations in variables. It is often desirable to fit a point set by a curve close to the points, and which has a pleasing shape (Meek et al., 2002; Seymour and Unsworth, 1999; Walton and Meek, 1998). Interpolation has therefore been used to fill in gaps in the data that were especially present prior to World War 2. This assumes that trends did not emerge in the data on timescales smaller than 1 year otherwise more detailed monthly data would have had to be available in to document these trends; unfortunately much of the historical data was only recorded on an annual basis. Trends that could have occurred in data gaps over longer timescales are not accounted for as extra information and data would be needed to map out these trends.

Relaxed cubic splines were used to interpolate all the data, producing smooth curves through each point. Relaxed cubic spline construction was done using Bezier curves. This method is similar to that used and explained by Lee, 1987; Meek et al., 2002; and Yang, 2004. Bezier curves are certain polynomials, and the cubic curves are used in computer graphics and imaging systems for drawing smooth curves (Knuth, 1986). This method enabled missing data to be reconstructed, following given trends. The relaxed cubic spline method of interpolation is the most appropriate for historical data; using a logarithmic or linear model would not appropriate as it would not explain fluctuations in the variables. Additionally, this method was used rather than polynomial interpolation as it avoids Runge's phenomenon (Fornberg and Zuev, 2007). The construction of the relaxed cubic spline is done by using Bezier curves as the piecewise interpolant, four control points for each Bezier curve are needed which are calculated using the two original values that need to be interpolated (Gupta et al., 2013). Use of the relaxed cubic spline model allowed for the data to follow a smooth curve that lacks the rigidity of other models. Issues regarding data fitting using Bezier spline curves are discussed extensively in (Yang, 2004).

A problem with the data sets was that the points were evenly sampled along the curve, not the x-axis. For example, with the fuel consumption data, there were 12 interpolated points between 1910 and 1911, yet between 1909 and 1910 there were almost 50. Data was therefore re-sampled evenly along the x-axis, so that 12 samples per year were taken, inferring estimated monthly values. *Re*-sampling procedures have been thoroughly discussed and validated in the literature (e.g. Krurtz, 1948; Lunneborg, 2000; Mooney and Duval, 1993).

In some cases, to show changes in trends a correlation coefficient was used. For example, when comparing the number of cars to fuel consumption numbers a correlation coefficient was taken for the period 1904–1990 and another for the period 1990–2019 to show how trends have changed in recent decades.

Tables 2-6 show the data sources for each variable for each year of study and the data manipulation techniques used in this study.

Table 2 displays data sources for number of motor cars. This data has been compiled using several different sources. In the years prior to 1950, it is assumed that all motor vehicles were licensed and that all licensed vehicles were in use at the time. Annual census of number of motor vehicles in the UK began again after the wartime period in 1950 the accuracy of data post 1950 is reliant on the quality of the census methods used and assuming all motor cars have been registered with the Driver and Vehicle Licencing Authority (DVLA).

Table 3 displays data sources and manipulation methods for fuel consumption. When calculating consumption from tax receipts it was assumed that all cars in use were taxed; there is a lack of data on fuel tax exemptions which makes the safety of this assumption hard to assess. From 1910 to 1948 it was not possible to separate data for fuel used for motor cars and that used to power other vehicles and so it had to be assumed that proportion of fuel used on motor cars compared to other vehicles remained constant throughout this period.

Table 4 displays data sources and manipulation processes used for CO and NOx data. The assumption was made that the emission factors that were sourced were the average for cars throughout the period 1910–1948. Reconstruction of data through interpolation for the period 1949–1969 is unable to account for any trends that emerged in this period. Differences in emissions from petrol and diesel cars could not be considered as specific detailed datasets are unavailable. Estimated data from 1910 to 1948 makes assumptions on emission factors, using only fuel consumption in the equation. Data interpolation for the period 1949–1969 was unable to account for any possible emerging trends over this period. GDP during this period increased at a steadier rate than any other time (Hicks and Allen, 1999), which could support the previous assumption of no emerging trends. However, a peak and fall in petrol prices from 1950 to 1958 (Hicks and Allen, 1999), following removal of petrol rationing, could have had an effect.

Table 5 displays data sources for road fatalities. The assumption has been made that all road deaths have been caused by motor cars and that all road deaths were recorded and reported just once. Table 6 displays data sources for road lengths.

The complete dataset is available electronically in Appendix A.

3. Results and discussion

The following sections display and discuss the reconstructed datasets. Trends are discussed variable by variable and interrelations between

Table 2
Data sources used to estimate number of motor vehicles (UK).

Date	Reference sources
1904–1920	Obtained from the SMMT publication “The Motor Industry of Great Britain 1935.”
1921–1925	These figures are the approximate number of licenses in Great Britain in August of each year taken from the quarterly return of Motor Taxation published by the Finance Department of the Ministry of Transport.
1926–1938	Annual Census of Ministry of Transport, this refers to vehicles with a license during each September quarter of the year.
1939–1945	Road Vehicles, Great Britain
1946	Return number 135 issued by Ministry of Transport
1947	Ministry of Transport
1948–1949	Maxcy and Silberston (1956)
1950–2021	Department for Transport, figures from this source are estimations based upon census methods and registrations with the DVLA

Table 3
Data sources and manipulation techniques used for estimates of fuel consumption.

Date	Reference	Calculation used
1910–1922 1929–1948	Calculated using Motor Fuel Tax figures from Basic Road Statistics 1948, these were sourced from Annual Reports and H.M. Customs and Excise. Data for 1922–1928 is missing	Total Fuel consumptions (gallons) = (Total Motor Fuel Tax Receipts (d.) × 1000 × 240 / Rate of Tax (d. per gallon) The receipts were expressed in thousands of pounds so multiplication of 1000 and then 240 converted figures into old pence (d.). The result was divided by the rate of tax per gallon for each year.
1922–1928 1949–1969	Missing data	Interpolation used for reconstruction of dataset
1970–2004	Sourced from NETCEN, available through DTI Energy Statistics Publications, Figure 2.6 Road transport energy use by vehicle type 1970–2004	None
2004–2021	Sourced from The Department for Transport website: ENV0102: Energy consumption by transport mode and energy source: United Kingdom	None

Table 4
Data sources and manipulation techniques used for estimates of NOx and CO emissions.

Date	Reference	Calculation used
1910–1922 1929–1948	Calculated using worked fuel consumption data (refer to Table 3) and fuel efficiency relationship. The most popular vehicle in this period was the Ford Model T which ran an average of 25 miles/gal (mpg) (t-ford.co.uk) Emission factors for carbon monoxide were (90 g per mile) and nitrous oxides were (6.2 g per mile) these figures were taken from Air Pollution from Motor Vehicles (Faiz et al., 1996)	1. Total distance travelled (miles) = average fuel efficiency (mpg) x Total fuel consumption (gallons) 2. Estimated yearly emissions = Total distance travelled (miles) × Emission factor (grams per mile) 3. Yearly emissions were converted into thousands of tonnes ($1\ g = 1 \times 10^{-6}\ t$)
1922–1928 1949–1969	Missing data	Interpolation used for reconstruction of dataset
1970–2004	Obtained online from Defra which sourced data from e-Digest of Environmental Statistics	None
2004–2021	Data sourced from National Atmospheric Emissions Inventory (NAEI)	None

Table 5
Data sources and manipulation techniques used for estimates of road fatalities (UK).

Date	Reference & brief	Calculation used
1904–1914 1919–1923	Deaths from mechanically propelled motor vehicles were from the Journal of the Royal Statistical Society (Edge, 1926).	None
1915–1918, 1924–1925, 1931–1935	Missing	Interpolation for reconstruction
1926–1930, 1936–1938	Ministry of Transport Report on Road Accidents Involving Personal Injury (1938)	None
1939–1947	Taken from "Road Accident Bulletin Number 22", published by the Royal Society for the Prevention of Accidents.	None
1948–2021	Department for Transport website	None
1904–2021	Using the sources above and data of number of cars, the ratio of annual road fatalities per thousand cars was calculated.	Annual fatalities per thousand cars in use = Number of deaths / Number of cars (thousands)

Table 6
Data sources and manipulation techniques used for estimates of road lengths (UK).

Date	Reference	Calculation used
1909–1939	Sourced from 'Annual Reports of the Road fund' with lengths measured in March of each year	None
1940–1947	Ministry of transport	None
1948–1950	Missing data	Interpolation used for reconstruction of dataset
1951–2021	Department for Transport website	0.621 used as conversion factor for kilometres to miles

variables are examined. Significant social and environmental changes of the periods are explored and the relevance of these changes to the reconstructed dataset is addressed.

3.1. Cars and fuel consumption

The estimated annual number of UK vehicles is plotted together with fuel consumption in Fig. 1 (1904–2019 for number of vehicles and 1910–2019 for fuel consumption). Fig. 1 shows a steady increase in both number of cars and fuel consumption, with both dipping during World War 2. While the number of cars has steadily increased to the present day, fuel consumption stabilises around 1990 and begins decreasing after 2008.

During World War 1, car production came to a halt, but many people received driving training. The first small car boom in 1919 occurred simultaneously with introduction of the first petrol stations. It is difficult to speculate whether the production of new cars led to demand for petrol stations or vice versa, although if we accept the principle of induced travel (Yao and Morikawa, 2005), it could be argued that the emerging (convenient) infrastructure caused a higher demand for cars. From 1939 to 1943 the number of cars decreased by 65 %, leaving the UK with the same number of cars as in 1926. However, from 1943 it only took two years to match the number of cars in 1939. During World War 2 cars were taken away for scrap metal in aid of the war effort. The reduction of cars in this period also coincided with a peak in road fatalities, explaining loss of some automobiles. A production boom followed the war, along with creation of motorways, documented to be instigated by Hitler and Ford (Williams, 1991). Maxcy and Silberston (1956) state that after this initial period, the growth in demand for cars became less of a function of the exploitation of a new product in an existing market, but more dependent on factors such as income rise and variations of supply in credit. Saul (1962) discusses the impacts of war on demand growth, particularly flagging changes to production outputs, sources of capital, manufacturing techniques and the sector's strengths and weaknesses.

Until 1998, the UK accommodated traffic growth through a 'predict and provide' approach, whereby road construction would meet forecasted traffic growth (Noland and Lem, 2002). Forecasting was based on an unconstrained growth assumption and was therefore environmentally and financially unsustainable (Lyons et al., 1999), as the SACTRA report of 1994 showed road construction to generate new traffic. Therefore, the theory which includes 'induced travel' as an important component of travel demand with respect to travel cost, travel time, and etc. has been explored by policy makers and transport planners (Yao and Morikawa, 2005). Based upon a simple economic model of supply and demand, increase in infrastructural capacity reduces the generalised cost of travel, especially on congested roads, by reducing the time cost of travel. At the same time, the quantity of those goods demanded increased.

With improved socio-economic conditions, such as population growth and income increases, the travel demand curve shifted. Respectively, population increased by 51 % from 1901 to 1999 and GDP per capita rose by 37 % from 1900 to 1947 and 191 % from 1948 to 1998 (Hicks and Allen, 1999). Goodwin (1996) highlights a report conducted for the

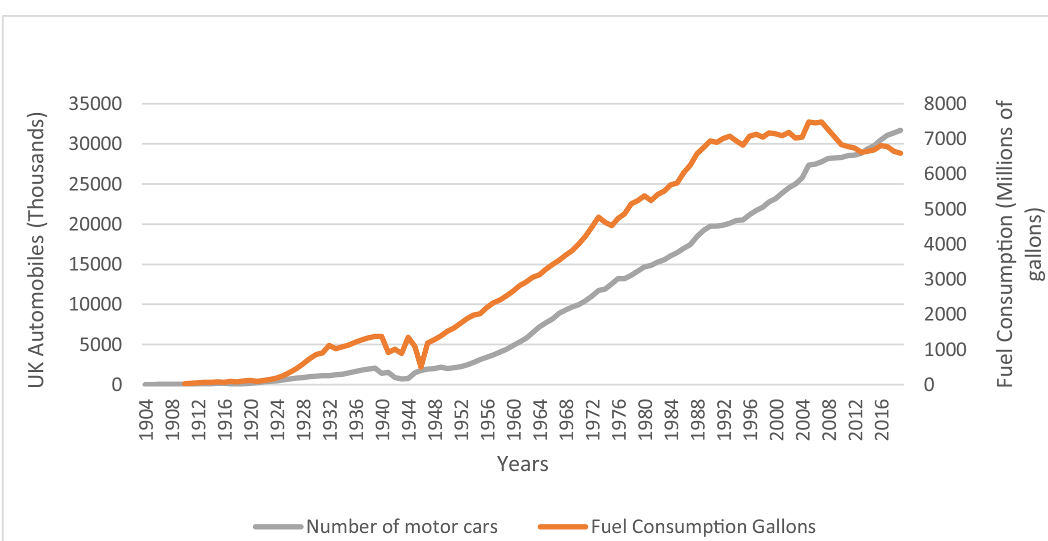

Fig. 1. Estimated annual number of motor vehicles (1904–2019) and fuel consumption (1910–2019) (UK).

Ministry of Transport in 1938 that evaluated a significant increase in traffic on a new road. Induced travel suggests society will use private transport to the same extent that the infrastructure will support them; in Great Britain in 2013 there were 304 billion vehicle miles travelled compared to 29 billion in 1949, although growth in road traffic has slowed more recently (Department for Transport, 2015). As a further illustration, in 1980 only 5 % of retail sales were made in out-of-town locations, but by 1992 this had risen to 37 % (Maddison et al., 1996). The results from this study show this period has the fastest road construction rates in history.

Walking and cycling for short journeys declined with expansion of the automotive industry; Beckmann (2001) explains that the central role of the motor vehicle in society sets up a precondition promoting the car as the only suitable form of mobility. From 1992 to 2001, the proportion of children walking to school declined from 63 % to 54 %. This was primarily due to increased concern over personal safety and schools being further away from home (Nessa and Gallagher, 2004). Beyond the health concerns of exposure to poor air quality due to traffic, children being driven to school means they are engaging in less daily exercise contributing to the rapidly declining fitness levels among children (Sandercock and Cohen, 2019). Other factors, such as high Internet use and high television watching, have been strongly associated with childhood obesity (Aghasi et al., 2020; Zhang et al., 2016). It is probably not a coincidence that all these major social changes overlapped with the tripling of child obesity to 2001 (House of Commons Health Committee, 2004), a trend that has continued to 2020.

The reconstructed fuel consumption, CO and NOx emission data are illustrated in Figs. 1-3. Fig. 1 shows a steady increase in fuel consumption from 1910 until about 1920 before dropping off slightly and then increasing at a much higher rate than previously until 1940. There is an atypical peak in 1932 and after 1940 the fluctuations in fuel consumption are dramatic, with pronounced peaks in: September 1939, May 1944, and September 1947. In January 1946, a considerable depression in fuel consumption is over 270 % lower than both 18 months previous and subsequent to this date. This could be explained by fuel rationing and the economic exhaustion of the UK following World War 2. From 1949 until 1990, the figures show a steady increase in fuel consumption, with a pronounced drop in the mid-1970s caused by the Stock market crash in January 1973 that was compounded by the 1973 Oil Crisis in October the same year. The Oil Crisis during this period raised the prices of petroleum and therefore decreased fuel consumption as consumers bought less (Painter, 2014). From 1990 to 2004, fuel consumption levels out, with only small fluctuations. This period is the steadiest of the century, and perhaps reflects that fossil fuel consumption in the UK reached a zenith, impacted upon by issues like: road congestion and pricing; taxation; personal mobility and vehicle ownership getting closer to capacity; improvements in vehicle technology; concern about climate change; etc. After 2008 fuel consumption begins to decrease up until present day. This can be explained by increasingly stringent regulations imposed upon vehicle manufacturers to increase fuel efficiency, and as automotive technology improves fuel consumption decreases.

Until 1995 there is a very strong positive linear correlation between number of cars and fuel consumption (0.95). Similar fluctuations are evident between the two datasets until post-1995, when fuel consumption stabilised whilst car ownership increased. The 1970s depression was due to the oil crises (Hicks and Allen, 1999). However, in 1999, accounting for inflation, petrol was more expensive during the Suez war, tax rises of 1906–21 and the oil crises than it was then (Hicks and Allen, 1999). Addition of amenities such as air conditioning, power steering and automatic windows reduced fuel economy in cars, leading to higher consumption of fossil fuels (Zachariadis, 2006). From 1970 to 1991, there was an increase from 11 to 19.2 million tonnes of carbon emissions from cars alone, which was higher than for any other sector (NETCEN, 2006).

Increased levels of environmental awareness and the electrification of some of the vehicle fleet could play a role in reduction in fuel consumption. However, whilst official laboratory-measured monitoring data suggests a progressive decline in average fuel consumption of the passenger vehicle fleet, there is increasing evidence to suggest that this laboratory monitored levels of fuel consumption may not reflect fuel consumption levels in real world scenarios. There are neglected factors in laboratory observations such as side winds, rain and road grade which can all have an impact on levels of fuel consumption in real world driving (Fontaras et al., 2017).

Pearson's correlation coefficients were calculated to quantify any association between the annual number of cars and fuel consumption 1910–1990 and again 1990–2019. The r value for the coefficient 1910–1990 is 0.986

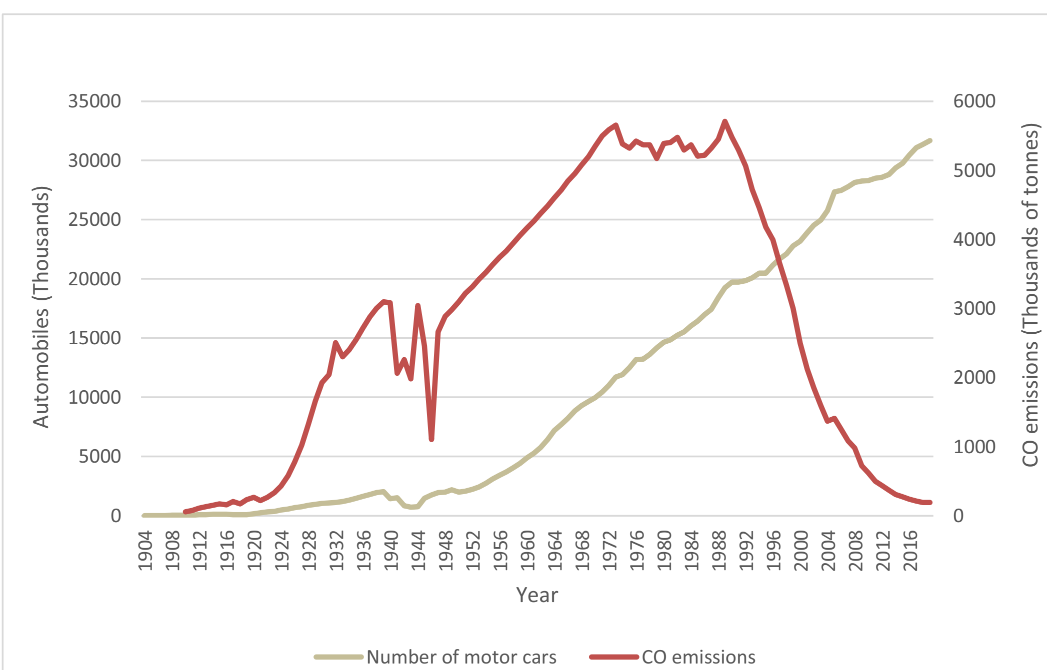

Fig. 2. Estimated annual number of passenger cars and carbon monoxide emissions (UK), 1900–2020.

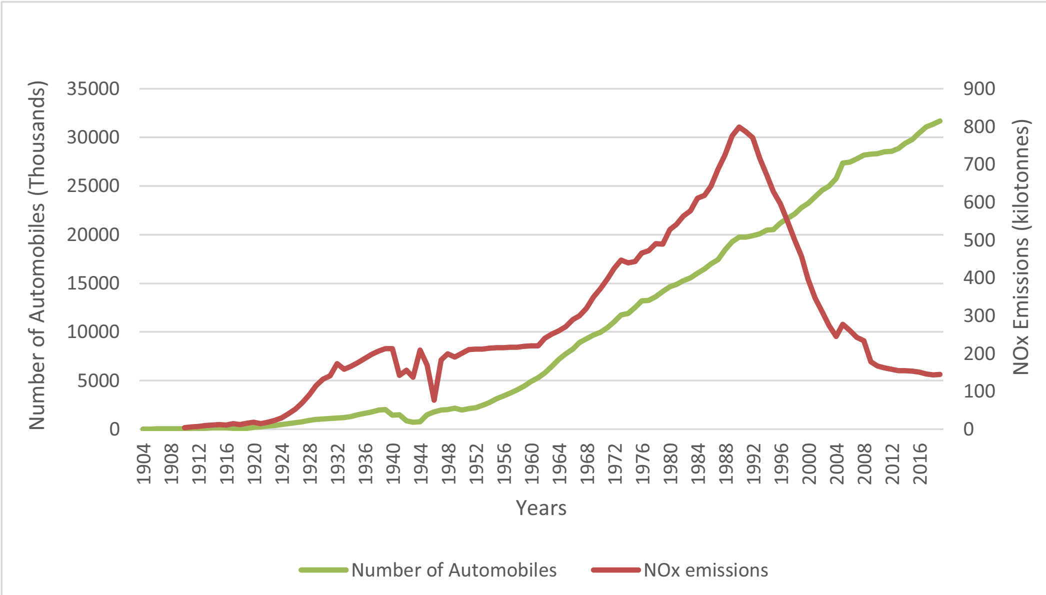

Fig. 3. Estimated annual number of passenger cars and NOx emissions (UK), 1900–2020.

suggesting a very strong linear correlation whilst for 1990–2019 it is −0.351 suggesting a moderately negative correlation for this period. This shows a stark difference in the relationship between number of cars and fuel consumption between these two periods.

3.2. Emissions

Fig. 2 shows annual estimates of carbon monoxide emissions and number of motor vehicles over time and Fig. 3 does the same for nitrogen oxides emissions. Both figures show a similar pattern of a general uptrend of emissions before a drastic decrease around 1990; in 1993, it became law for all petrol cars manufactured in the UK to have a catalytic converter fitted to the exhaust to meet European emissions standards.

Both CO and NOx emissions were calculated as a function of fuel consumption 1910–1948. Figs. 1 and 2 hence follow the same patterns as Fig. 3 up until 1948, with a general uptrend until the World War 2 where emissions experience a dip followed by a further dip in the post-war years. The ratio of CO emissions to NOx emissions are ~100:6.9. For the period 1949–1969, interpolation was used to reconstruct the dataset (see Methods). Interpolation is unable to account for any new emerging trends in this period, however, it was a time of relative economic stability with no events that were likely to have a significant impact on emissions.

After this period CO emissions stabilise until 1989 where CO emissions drop drastically. Unlike CO emissions, NOx emissions continue an upwards trend for the period 1969–1989 before dropping drastically. A detailed overview of emissions from motor vehicles (1950–2015) and the associated impacts of increasing vehicle numbers, congestion, fuel types, combustion conditions, emissions reduction technologies, and other approaches taken to reduce emissions, can be found in Tiwary et al. (2018). This drop can be partially explained by the introduction of oxidation- and three-way catalytic converters onto petrol cars which drastically reduced emissions of regulated pollutants, even though the number of vehicle miles travelled has steadily increased. The reduction in emissions was further assisted by the rapid market penetration of diesel vehicles due to their fuel economy until the Volkswagen emissions cheating scandal in 2015, known popularly as "Dieselgate" (Mujkic and Klingner, 2019). The drop continued and by 2019, emissions of CO are comparable to the emissions of 1917 when there were only 0.35 % of cars on the road that there were in 2019. There has been a 96.6 % reduction of CO emissions in 2019 from peak emissions in 1989. NOx emissions in 2019 are comparable to 1932 levels when there were only 3.55 % of cars on the road that there were in 2019. There has been an 81.8 % reduction in emissions in 2019 from peak emissions in 1990.

The introduction of catalytic convertors is significant since both NOx and CO are particularly harmful pollutants. Studies have found that ambient NOx pollution can be associated with an increased risk of respiratory tract infections and both acute and chronic exposure to CO can increase the risk of negative pulmonary events (Chen et al., 2007). NOx emissions were linked to ~110,000 premature deaths globally (Anenberg et al., 2017). NOx, CO and volatile organic compounds (VOCs) emitted from vehicles and how they interact with sunlight are responsible for much low-level ozone pollution in urban settings (Shao et al., 2009). The development of this low lying ozone layer can contribute to the formation of photochemical smog that becomes trapped close to the ground because of temperature inversions (Sher, 1998). Photochemical smog can be damaging to both human health, ecosystems and built infrastructure (Wang et al., 2020; Kumar and Imam, 2013; Tiwary et al., 2018).

Emissions of CO and NOx were calculated as a function of fuel consumption based upon fuel efficiency and vehicle numbers, and so this does not consider factors influencing emissions such as vehicle age, engine characteristics, levels of maintenance, congestion, manufacturer and country of origin, all factors that Beydoun and Guldmann (2006), Washburn et al. (2001), Bin (2003) and Grote et al. (2016) found critical when determining outputs of emissions. Borken-Kleefeld and Chen (2015) discusses vehicle emission control systems degrading with use, and so as a vehicle ages emission rates increase and mentions the concept of high emitters, defined as "vehicles that have consistently emission rates many times higher than 'normally' functioning cars", which could be a result of previously mentioned factors. Previous studies such as Lau et al. (2012) and Bishop et al. (2012) using on road remote sensing have suggested that these 'high emitters' are responsible for 50 % total car fleet emissions whilst making up only 10 % of the vehicles. Bishop et al. (2012) flag that a main cause for high emitters is malfunctioning aftertreatment controls, such as the oxygen sensor, and so the idea has been put forward that repairing or deregistering these vehicles is the most cost-effective strategy to reduce emissions originating from cars. Huang et al. (2020) has suggested that this strategy may be oversimplified as on-road remote sensing only measures a snapshot of emissions from vehicles and so this method cannot fully represent overall emission levels. However, roadside measurements record emissions from tens of thousands of vehicles and are typically set up on ramps with a small incline. Drivers accelerate at different rates and hence thousands of measurements can cover a wide portion of the vehicle specific power range, even by vehicle model and model year. Combining emission and air quality modelling in order to achieve the spatial coverage required for exposure and health impact assessment and sufficiently capture local-scale pollutant variability is a sound route to securing the best available data (Hood et al., 2018).

3.3. Road fatalities

Fig. 4 shows the total number of road fatalities per year and road fatalities per 1000 cars. Note that the source data provides an estimate of the number of personal injury road traffic accidents that were reported by the relevant authorities in the stated year. Modern statistics refer to personal injury collisions on public roads (including pedestrian footways) that become known to the police within 30 days. Damage-only collisions, with no human casualties, and collisions on private roads or car parks are not included in the statistics. There is no obligation for people to report all personal injury accidents to the authorities and so figures do not represent the full range of all accidents or casualties in the UK. Nevertheless, total fatalities appear to follow an upward trend before stabilising and eventually falling whilst fatalities per 1000 vehicles has a downward trend with peaks during wartime.

From 1904 to 1941 fatalities increased; this is likely due to the increasing number of people who were driving as the car became more commonplace. Road fatalities data bears some resemblance to fuel consumption and emissions data as fatalities follow the same trend of a steady increase up until 1923 ~ before a rapid increase. Between 1930 and 1938 fatalities seem to stabilise with occasional drops. This coincides with the 1930 Road Traffic Act that issued standards and penalties for dangerous driving and outlined the Highway Code. One notable trough in the graph appears after 1934, the year in which the 1934 Road Traffic Act was introduced, which introduced the driving test and the 30 mph speed limit.

Again, there is a significant change during World War 2. Road fatalities peaked in 1941, potentially due to blackouts that occurred throughout this period, making driving unsafe, as well the removal of signposts which made navigation harder and lead to more drivers driving along unfamiliar roads. Another factor that may have played a role in road fatalities peaking in 1941 is road damage caused by bombings and lack of road maintenance due to resources being focussed elsewhere. However, road fatalities show a sharp decrease after 1941, probably because there were fewer cars on the road throughout the war as there was wartime petrol rationing and many cars were scrapped for metal.

After the end of the war, starting from 1948 fatalities began to increase as more cars became present on the road. This is consistent with fuel consumption as this did not start to increase again until a few years after the war due to economic pressures. Increases in fatalities were due to increases in the number of people driving. Improvements in road safety did not fully offset the fatalities caused by an increased number of cars on the road. Whilst overall road fatalities increased 1948–1967, road fatalities per thousand cars consistently dropped year by year during the same period, reflecting new regulations, higher level of driving skills and increased familiarity with the danger from moving vehicles.

Fatalities began decreasing with the introduction of the Ministry of Transport (MoT) test for vehicle roadworthiness for cars >10 years old in 1960, drink driving laws in 1967, and the breathalyser in 1968. Further decreases were stimulated by the oil crises of the 1970s that reduced the numbers of cars on the road, and the introduction of the Green Cross Code, one of the UK's most memorable safety campaigns (Driver and Vehicle Standards Agency, 2019). The code itself is a simple step-by-step procedure taught to pedestrians to cross the road safely. From this period, total fatalities have shown a continuous decline with the introduction of more road safety laws such as compulsory seatbelt wearing and a driving license penalty points system for driving endorsements and motoring violations; improvements in car design and road infrastructure; and in-vehicle safety equipment, including airbags, side impact panels, anti-lock braking systems and electronic stability controls. As a result of all these initiatives, the road safety record of the UK is one of the best in Europe (and the world), although still judged unacceptably high (Koornstra et al., 2002; Department for Transport, 2019).

Modern community-based initiatives are still around such as 'Bobby zones' that have arisen as part of the 'Slow Down for Bobby' campaign. 'Bobby Zones' promote the practice of limiting speed around schools and are a bottom-up community led approach to improving road safety (Department for Transport, 2019). It is difficult to determine the impact of campaigns and introduction on road safety laws as reduction in fatalities can also be explained because of the car becoming more ingrained within our society and behaviours naturally adjusting around them. However, fatalities per thousand cars shows a consistent decline in fatalities from the start of the 20th century to present day with dramatic peaks in fatalities

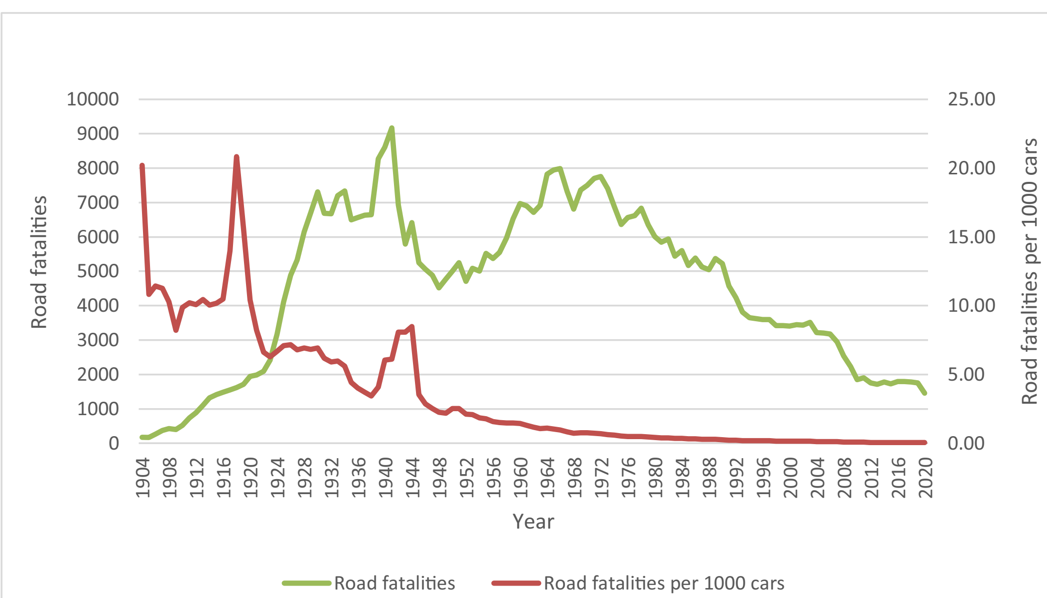

Fig. 4. Estimated annual road fatalities and annual road fatalities per 1000 passenger cars (UK), 1900–2020.

during both World Wars. In 2019, whilst fatalities are higher than in 1904–1918, the number of people killed in proportion to cars on the road is 404 times lower than 1904.

3.4. Road lengths and congestion

Fig. 5 shows the annual road length and the annual number of cars in the UK. Parker (2005) has provided a history of road construction in the UK since 1930, highlighting many social and environmental consequences, including that: many technological developments stemmed from building aircraft runways in World War 2; improvements to techniques for surface dressing in the 1950s gave roads longer life; major road building took place in the 1960s; there was strong emphasis on management of road projects in the 1970s; and since then we have seen particular challenges around road congestion and maintenance, and the use of private finance initiatives for road building. Whilst over time road length has clearly increased, it is not proportionate to the increase in the number of cars, with cars experiencing a much higher percentage rise. This is because some infrastructure was already in place as roads were initially built for bicycles as well as cars (Reid, 2015). Road networks bring a myriad a of social benefits, including increased mobility, giving people more choice on where they want to live, and brings prosperity to zones previously peripheral to economic (urban) hubs (Ericsson, 2000). However, the construction of roads brings about negative social and environmental effects, for example; impacts related to construction; increased surface-run off; ecological damage; air, water, land, visual, light and noise pollution, severance, etc. (Spellerberg, 1998).

The graphical abstract shows the annual number of cars per mile of road over time, and as we can see this has dramatically increased. This graph shows a clear increase in congestion on roads in the UK. Congestion related to passenger cars can have significant impacts on fuel consumption and therefore emissions. De Vlieger et al. (2000) found that intense city traffic could increase fuel consumption between 20 and 45 %. Grote et al. (2016) discuss in detail the influences on, and effects of, congestion in urban areas. Congestion is a global issue; Shaheen et al. (2019) report that municipal authorities are implementing or considering a variety of actions to curb congestion and its negative effects on the economy, the environment, and public health, and also discuss in detail the social equity implications and available congestion management strategies.

3.5. Electrification, light weighting and automation

The UK, along with 192 other nations, has committed to keeping global surface temperatures below a 2 °C increase compared to pre-industrial levels. Reducing CO_2 emissions has been identified as a solution to slow down global warming. Whilst emissions of both CO and NOx have reduced, CO_2 emissions from the transport sector in the UK have stagnated and are at a similar level to 1990 (Department for Transport, 2021a, b). One proposed idea to meet the net-zero commitments set out by the UK is electrification and light weighting of the passenger vehicle fleet. The UK government has proposed to phase out the sale of new petrol and diesel cars through a two-step approach; step 1 is the phase-out of the sale of new petrol and diesel cars (2030) and step 2 will see all new cars be fully zero emission from the tailpipe by 2035 (Department for Transport, 2021a, b).

A report by the Climate Change Committee states that the full transition to electric vehicles will be "one of the most important actions" the UK will take in reaching its net zero carbon emission target (Wills, 2020). However, the report further indicates concern the UK is "not on track" for new electric vehicles to meet the demand of new petrol and diesel vehicles once their ban comes into effect in 2030 (Wills, 2020). Many barriers exist with respect to battery electric vehicle adoption such as high electric vehicle cost, lack of charging infrastructure, vehicle battery durability and range (Berkeley et al., 2018; Wills, 2020; Krishna, 2021).

Furthermore, whilst battery powered electric vehicles (BEVs) tackles the issue of emission reduction during the operation phase of a vehicle, greenhouse gas emissions are still prominent within the other phases of these vehicles' lifecycles. Kapustin and Grushevenko (2020) have calculated that the adoption of BEVs around the world will correspond to a global increase in electricity consumption in-between 11 and 20 %. Milev et al. (2021) report on the environmental and financial implications of expanding the BEV fleet and highlight that whilst the initial financial and environmental cost may be higher, the use of BEVs is expected to be cheaper in the long run, and overall carbon emissions are expected to decrease.

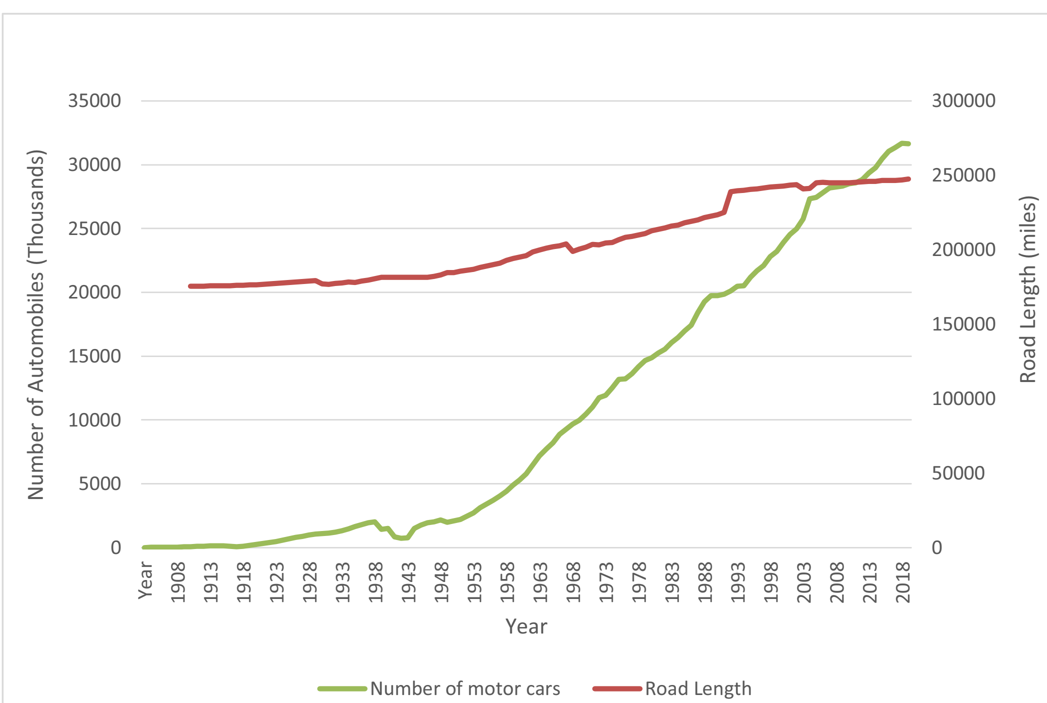

Fig. 5. Estimated annual number of passenger cars and road lengths (UK), 1900–2018.

There have been several studies comparing traditional petrol- and diesel-powered cars to BEVs, primarily using a life-cycle assessment approach (Aichberger and Jungmeier (2020), Bauer et al. (2015), Cox et al. (2020), Ellingsen et al. (2016), Hawkins et al. (2013), Hwang et al. (2013) Del Pero et al. (2018) and Kawamoto et al. (2019)). All these studies found a significant reduction in carbon emissions throughout the life cycle of a BEV when compared to a traditional internal combustion engine vehicle, citing the lack of exhaust emissions as the primary reason for emissions reduction. However, it should be noted that this assessment only held true in scenarios where the electricity used to power the BEV was produced through non-fossil fuel mechanisms.

Bauer et al. (2015) and Del Pero et al. (2018) found BEVs performed worse when considering other environmental indicators during the production phase, such as particulate matter formation, resource depletion, photochemical ozone formation, acidification, and toxicity. This is largely associated with the production of lithium-ion batteries. Several studies carrying out life-cycle assessments of lithium-ion batteries have been carried out. Dai et al. (2019) and Shu et al. (2021) found that use of active cathode material, aluminium, and energy for cell production are the largest contributors to negative environmental impact of lithium-ion battery production. Ellingsen et al. (2017) states there is a high degree of uncertainty in the amount of energy use during the production stage of lithium-ion batteries and found studies reporting massively varying results. Results varied from 38 kg–356 kg CO_2eq/kWh; the main cause of this variation is different assumptions about what constitutes direct energy demand for the cell manufacturing process. Rivera and Reyes-Carrillo (2016) found that up to 90 % of all emissions during the manufacturing phase originated from painting, and this process is unlikely to differ between petrol/diesel car and BEV manufacture.

With the introduction of BEVs comes an increasing demand for critical resources such as rare earth metals (Shittu et al., 2021) and a vast end-of-life waste stream of lithium-ion batteries. Chen et al. (2019) discusses the end-of-life phase of lithium-ion batteries and their potential to be recycled. Chen et al. (2019) describes end-of-life recycling of these batteries as a necessity to leverage fluctuating material costs and reduce uneven distribution and production, however the authors also highlight that none of the current battery recycling technologies are ideal and potential technological improvements will have to be made to minimise environmental impact of this phase.

Light weighting of the vehicle fleet is a potentially effective means to reduce emissions as it increases fuel efficiency. Light weighting is important to BEVs to increase their range over a single charge. Whilst BEVs currently on average have a lower range than petrol/diesel powered cars, significant strides have been made recently to improve range. A concern with light weighting is that many materials used in the light weighting of vehicles are often more carbon intensive to extract and manufacture (Kim and Wallington, 2013). So, while emissions may be reduced during the operation phase a concern is that these emissions, rather than being reduced, are just being moved to the production stage. However, Dai et al. (2019) concluded that whilst light weighting results in an increase of emissions during production phase, these are more than offset by the reductions in emissions during the operation phase.

New autonomous passenger vehicle technology could also play a major role in future reduction of greenhouse gas emissions. This can be achieved through the reduction of idling time and more efficient driving patterns. De Vlieger et al. (2000) found an up to a 40 % increase in emissions with aggressive driving patterns when compared to normal. The introduction of autonomous vehicles would eliminate aggressive driving patterns. Rahman et al. (2013) found idling emissions can be as high as 16,500 g/h of CO_2. Bagloee et al. (2016) conceptualised a model for the navigation of autonomous vehicles that involves using the most efficient traffic circulations to maximise fuel efficiency therefore reducing emissions or energy used. Autonomous driving has potential to reduce road fatalities as it is generally accepted that 90–95 % of road accidents occur partially or fully due to human error. A widely shared view is that more advanced assistance systems leading towards automation will be needed to achieve this goal (Eugensson et al., 2013), and automation of vehicles could grant additional mobility to the physically challenged who would be unable to drive otherwise. However, there are some disadvantages to autonomous vehicles, namely, decreased fuel economy due to the energy demands of the computers controlling the vehicle, and increased cost.

4. Conclusions

Datasets for annual numbers of UK cars, fuel consumption, CO and NOx emissions, road fatalities and lengths from the early 20th century to the present day have been reconstructed to original time series plots, enabling a concise critical analysis of the associated environmental and social impacts from launch to present. We have demonstrated that technological developments and regulatory interventions relating to the motor industry, alongside events that have catalysed societal change, have been crucial in terms of subsequently providing benefits to society whilst also acting to mitigate (but not prevent) the adverse and frequently devastating impacts of motor vehicles on human health and the environment. A periodic, regular, overarching, independent review of the collective positive and negative impacts of the motor vehicle industry and appropriate interventions is essential to maintain and improve social benefits and public and environmental health, as well as supporting delivery of the United Nations' Sustainable Development Goals by 2030 and beyond. This review process would enable the automotive sector to: check its economic and social health/benefits; its prevailing health and environmental impacts; to identify areas for continual improvement and development; and should take place approximately every 5 years in order to match with typical operational industrial asset management plan periods.

All the reconstructed datasets indicate responsive health, social and environmental effects throughout sector growth. In the early part of the century, increased road deaths are strongly associated with vehicle numbers and in the latter part, with safety laws. Conflicting impacts such as loss of life and social gains from the industry are difficult to quantify. However, it is estimated that the social and economic costs of fatalities have increased over time, illustrating the importance of road safety legislation to the national economy, especially the Road Traffic Acts of 1933 and 1934; roadworthiness tests, restrictions on drink-driving; the Green Cross Code from the 1970s; and improvements to car design and in-vehicle technology. Ratios of fatalities to numbers of cars further indicate social ingraining of the car. Automation of the vehicle fleet has potential to reduce road fatalities even further.

The emission estimates underline that the early industry was more important as a source of air pollution than perhaps expected. Time series plots reveal successful emission reductions. Road construction has provided increased mobility, prosperity and choice, but has also had unintended adverse consequences, including (in no particular order) reduced air, water and soil quality; flooding; impacts on water resources; ecological damage; visual intrusion; property development; noise; nuisance; land degradation. Walking and cycling for short journeys has declined with expansion of the automotive industry and the failure of city/road planners in many urban areas to provide roadways/pavements for these forms of active transport. More recently, the freedom of movement and security provided has inadvertently promoted unsustainable shopping habits, contributed to an increasingly obese nation and discouraged the use of other transportation methods, especially active transport.

Although temporal and spatial scales have been generalised, the study suggests that World War 2 was a significant milestone. All variables studied were delicately interrelated, demonstrating development and intervention at key points to be essential. Trends show potentially devastating deterioration of fatalities and emissions, and therefore health, environmental and economic impact, had interventions not occurred.

Significant strides have been made in reducing fuel consumption and emissions, with fuel consumption showing the first signs of a downtrend for the first time in decades and CO and NOx emissions being comparable to the early 20th century. Much of this reduction in emissions is largely due to the introduction of catalytic converters, although CO_2 emissions from vehicles have not experienced the same dramatic reductions. BEVs and light weighting of vehicles could potentially provide an effective route in the reduction of CO_2 emissions. However, this approach is reliant on the increasing proportion of 'clean' renewable energy to generate electricity as opposed to fossil fuel use and improvements to battery technology. Other potentially very significant environmental impacts associated with securing adequate raw materials, and well-documented challenges associated with the production and end-of-life phases of BEVs (Sanguesa et al., 2021) will have to be realistically and cautiously managed, especially as there is still uncertainty around emissions produced by the manufacturing process.

CRediT authorship contribution statement

Michael Blyth: Data curation; Formal analysis; Investigation; Methodology; Validation; Visualization; Roles/Writing - original draft.

Ian Williams: Conceptualization; Formal analysis; Investigation; Methodology; Project administration; Resources; Supervision; Validation; Visualization; Roles/Writing - review & editing.

Data availability

Data file with reconstructed datasets is provided as an Excel spreadsheet

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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