

Decarbonising shared mobility: The potential of shared electric vehicles

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ABSTRACT

Car-sharing services offer potential to reduce dependency on private cars, and their electrification may decarbonise the transportation sector even further. This study estimates the potential emission reduction if shared cars operated by GoCar- a car-sharing service in Ireland- are electrified and assesses which trips could be completed using shared electric vehicles (EVs). Based on historical and targeted growth scenarios, appropriate forecasting methods were explored to predict GoCar's fleet size and travel distance for 2030. The corresponding emissions were estimated using COPERT. Results showed that electrifying half of the GoCar fleet by 2030 can reduce total emissions by up to 45% compared with baseline, whereas emissions were elevated by 50% compared to 2021 fleet operations. Results also suggest that the majority (70% to 90%) of GoCar day bookings can be completed using the available EVs in the Irish market, indicating the feasibility of EVs in car-sharing services.

1. Introduction

The transportation sector contributes 17.7 % of Ireland's total greenhouse gas emissions. It is the second highest cause of greenhouse gas emissions that has increased from 5,143.5 kt CO₂eq (in 1990) to 10,915.6 kt CO₂eq (in 2021), with the most significant contribution from road transport accounting for 94 % of greenhouse gas emissions (EPA, 2022). To tackle this issue, following the COP26 and Europe's response to climate change challenges, Ireland has introduced the Climate Action Plan 2021 (CAP, 2021), which legally requires Ireland to reduce emissions by 51 % by the year 2030 and to reach a net zero emission by the year 2050. As per CAP21, the transportation sector is expected to halve its emissions by 2030, which is quite challenging and ambitious. In order to frame the emission reduction policies, it is critical to understand the travel trends in Ireland in the first place. The National Transport Survey carried out by CSO (2019) showed that 73.7 % of all journeys in Ireland were made by car, pointing to car dominance as a mobility mode. CSO (2019) also reported that 58.7 % of all trips were completed in less than 15 min, while 95.9 % took less than one hour. To achieve the emission reduction targets, intense policy initiatives (both financial and non-financial) are required to shift people to sustainable modes of mobility (Caulfield et al., 2022).

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Car-sharing is one of the models that has been proven beneficial in reducing car dependency and greenhouse gas emissions. For example, Steining et al. (1996) found that car-sharing members who previously owned vehicles decreased their car travel distance by 61 %. This reduction in travel distance was substituted by using other sustainable modes like cycling. Similarly, car-sharing was found to reduce car ownership, which, as a result, had a significant impact on reducing the total travelled distance by individuals who previously owned cars (Gross et al., 2009). Every car-sharing vehicle replaces four to eight private cars (Loose, 2010). Interestingly, it was reported that compared to private vehicles, car-sharing vehicles, on average, produce 15–20 % lower CO₂ emissions and, in some cases, even up to 36 % lower (Loose, 2010). Car-sharing operators replace their old fleet with new ones once every few years, helping to reduce the emission of pollutants due to improved engine technology and fuel efficiency. Secondly, compact cars are predominantly used for car sharing as most trips are short and have minimal luggage; therefore, fuel requirements are lower and there are fewer vehicle emissions (Loose, 2010). One of the studies showed that car-sharing models are likely to result in the reduction of CO₂ emissions, saving costs, and increasing the likelihood of using other sustainable travel modes (Rabbitt and Ghosh, 2016). It is worth mentioning that while car sharing may not be a better solution than shifting demand to public transport, it can be seen as a complementary option, giving access to destinations poorly served by public transport.

Since electricity production from renewable resources in Ireland has increased to 42 % (SEAI, 2021), electric vehicles (EVs) seem to be another promising alternative owing to zero-tailpipe emissions and a growing potential to generate electricity from renewable resources. One of the many such initiatives in achieving emission reduction targets is minimising, eventually eliminating, the number of vehicles running on petrol and diesel by 2030 and 2050, respectively. Authorities in Ireland have introduced many policies and incentives to accelerate the uptake of EVs for both the private and commercial sectors. Harris et al. (2021) noted the potential to reduce greenhouse gas emissions further if shared vehicles were electric. Although not specifically, car-sharing is also targeted in a few policies; for example, the Accelerated Capital Allowance Scheme provides incentives for purchasing EVs and related infrastructure. Electric Vehicle Policy Pathway (DoT, 2021) recommended supporting EV sales in the commercial fleet, including car-sharing services. Similarly, the electric Small Public Service Vehicle (eSPSV) Grant Scheme promotes EVs in the taxi (and related) sector to reduce emissions. Moreover, the goal of eSPSV is also to increase the potential consumers' exposure to EVs and positively influence attitudes towards EVs. What is more, a recent report, Sustainable Urban Housing: Design Standards for New Apartments (DoH, 2022), provided guidelines to scale back or do away with parking spaces in new residences and to inevitably include provisions for other forms of transportation, such as spaces for car-sharing services.

Among various barriers towards the uptake of EVs, the two most critical factors, as discussed in the literature, are upfront cost and range anxiety. While the car-sharing services tackle the former as the user does not have to bear the upfront cost of the EV, the range (as well as charging) anxiety within the car-sharing users remains a critical research question that needs to be explored. In this study, the focus is on a car-sharing service in Ireland called GoCar. With over 950 + vehicles spread across over 600 stations nationwide, GoCar is Ireland's most significant car- and van-sharing service (GoCar, 2023). GoCar recently announced their €10 million investment to expand their fleet size (Leonard, 2023; ThinkBusiness, 2023) compared to €1 million a year before (Curran, 2022). In addition to catering for passenger transport needs, its vehicle fleet also facilitates cargo businesses. GoCar works on a roundtrip car-sharing model in which the user needs to return the shared vehicle to the point from where it was picked. The fuel costs are included in the (pre-defined) rates, and refuelling of the vehicles is taken care of by the tie-up with service stations called 'Circle K'. In order to make it more attractive to the public, GoCar also offers free (pay and display) parking within Dublin City. Given the pressing emission reduction targets (CAP, 2022), the interest in eco-friendly travel options and service providers' goals is rising. GoCar has already taken some initiatives by adding a few EVs to its fleet. This research study aims to investigate the different GoCar vehicle targets, calculate the impact of its fleet usage on emissions, and understand the feasibility of electrifying its fleet.

The remaining article is structured as follows: first, a literature review highlighting the car-sharing service types, their potential benefits on transport sustainability and the challenges of electrifying the car-sharing fleets are presented. Next, the research methodology, which includes a description of the data and methods adopted in the study, is presented, followed by a discussion of the results. Finally, this study's key findings, conclusions, and recommendations are reported.

2. Literature review

2.1. Car-sharing service types

Car-sharing is broadly categorised into three types: 1) Cooperatives 2) P2P or Peer-to-Peer, and 3) B2C or Business-to-Customer (Münzel et al., 2018; Shaheen et al., 2015). Cooperative car-sharing refers to a non-profit service that is more or less observed among users with a common interest. In P2P car-sharing services, individuals own and share the cars through a platform offered by a mediating firm. In B2C car-sharing services, the car fleet is owned by the service provider, offering cars to individuals on an hourly or daily basis against a fee. Typically, the fuel, parking and maintenance costs are also covered by the service provider (Cohen and Shaheen, 2016). B2C is further divided into two types: 1) free floating or one-way car-sharing services that require users to pick a vehicle at a point and drop it at a different location (either at a specified station or any suitable location within the service area), and 2) roundtrip car-sharing where the users return the vehicle to the station from where the vehicle was picked. Namazu and Dowlatabadi (2018) provide a comparative analysis of one-way and roundtrip car-sharing services in Vancouver. Their study found that both types of car-sharing services had a similar (positive) impact on transport sustainability, specifically concerning the reduction in car ownership. A few more highlights of the benefits of car-sharing services reported in the literature are highlighted in the next subsection.

2.2. Reported benefits of car-sharing services

Research studies have reported many benefits of car-sharing services. Each car-sharing vehicle is found to replace as many as 15 (Frost and Sullivan, 2010) to 23 (Lane, 2005) private cars. Some research suggests that car-sharing has contributed to a decline in the sales of new private cars since car-sharing members defer/forego buying a new vehicle (Intini and Percoco, 2021; Martin et al., 2010; Schmidt, 2020). While Cervero et al. (2007) found that 29 % of the car-sharing users got rid of one or more personal cars, Martin & Shaheen (2011b) observed a 49 % dip in private vehicles owned after the users were exposed to car-sharing services. Moreover, it is also reported that car-sharing is particularly attractive to the younger generation (Prieto et al., 2017) and that it has substituted the second or third car in households (Nijland and van Meerkerk, 2017). Demand for public parking space within the Central Business Districts has also been found to have decreased due to car-sharing services (Schreier et al., 2018; Sullivan and Magid, 2007). Meijkamp (1998) and DoT (2004) reported a decrease of 26 % and 38 % in parking space requirements. Similarly, Engel-Yan & Passmore (2013) found that the parking space requirements halved after car-sharing services were offered.

The impacts of car-sharing on public transportation and green modes (walking and cycling) are also reported in the literature. Some pieces of evidence have observed an increase in the use of public transport modes (Cazzola and Crist, 2020; ITF, 2020; Koch, 2001; Schreier et al., 2018). Along similar lines, Meijkamp (1998), for example, found a 36 % increase, while Cooper et al. (2000) observed a relatively moderate shift, an increase of 8 % in public transport use after the car-sharing options were offered to the public. Contrary to these findings, some studies reported no significant change in public transport use (Amatuni et al., 2020; Frost and Sullivan, 2010), while other studies even reported a decrease in public transport usage post-introducing the car-sharing services (Chicco and Diana, 2021; Julsrud and Farstad, 2020). Understanding which trips are substituted by a car-sharing system is crucial. GoCar, based on European studies, reported the annual removal of more than 8,000 cars on Irish roads (Leonard, 2023; ThinkBusiness, 2023), with only about a thousand operational fleets in the country. A total of 62 % of their car users abstain from car ownership. Secondly, 57 % of their users frequently use public transportation, indicating their preference for a combination of shared cars and public transport modes for their mobility needs (Leonard, 2023; ThinkBusiness, 2023). It highlights the importance of tailored policy interventions that are required to make car-sharing services complement the public transit modes rather than be competitive and take away the public transit ridership. Sustainable modes of travel (walking and cycling) have risen due to car-sharing services. On the one hand, Frost and Sullivan, (2010) and Lane (2005) reported an increase in walking (2 % and 19 %) and cycling (7 % and 9 %) modes, respectively. On the other hand, a much higher increase in walking (25 %) and cycling (14 %) was observed by Cooper et al. (2000) and Meijkamp (1998), respectively.

Many research studies have observed a decline in vehicle kilometres travelled (VKT) after the introduction of car-sharing services (Amatuni et al., 2020; Cervero and Tsai, 2004; Schreier et al., 2018; Shaheen and Cohen, 2007). The reported reductions in VKT were as high as 67 % in the San Francisco Bay area (Cervero et al., 2007), while Frost and Sullivan, (2010) and Martin & Shaheen (2011a) reported relatively lower VKT reductions of 31 % and 27 %, respectively. Moreover, car-sharing users have also been found to save on overall travel costs as they tend to be more thoughtful and selective in making travel choices, whether to drive, use public transportation, walk, cycle, or even skip a trip (Cervero et al., 2007; Chicco and Diana, 2021). Fuel efficiency has also been reported to have improved due to car-sharing (Martin and Shaheen, 2011c; Meijkamp, 1998; Rydén and Morin, 2005). One of the most important reported benefits of car-sharing in the literature that can help combat the climate change crisis is that of reduced emissions, both during the production and operation of vehicles (Schreier et al., 2018). Martin and Shaheen (2011a) estimated that car-sharing services reduced greenhouse gas emissions annually between 158,000 and 224,000 tonnes. Chicco and Diana (2021) computed the externalities related to emissions in terms of social costs and observed that car-sharing can reduce up to 1 % of the total emission load produced by the transport sector in Italy; a reduction that can be further increased to 3.6 % if the car-sharing fleets are replaced with EVs. Similarly, a study in the Netherlands found that car-sharing users emit 240 to 390 fewer kilograms of CO₂ per person per year (Nijland and van Meerkerk, 2017). In a recent study, Akimoto et al. (2022) found significant reductions in emissions due to car-sharing when the decrease in the production of iron, steel, plastics, and cement is taken into account. Some studies have also focussed on life-cycle impacts of car-sharing services. For example, Amatuni et al. (2020) noted that life-cycle mobility-related greenhouse gas emissions have a cumulative decline rate that ranges between 3 and 18 %, depending on the area of impact of the car-sharing service. Similarly, car-sharing members in the United States were found to cut their average life-cycle individual transportation energy use and greenhouse gas emissions by around 51 %, which amounts to savings of about 5 % in all household transportation-related energy usage and greenhouse gas emissions (Chen and Kockelman, 2016).

2.3. Electrifying car-sharing fleets

Despite concerns regarding the emissions generated at the source, EVs are considered to be promising in terms of reducing climate change impacts, mainly due to (a) there is significant potential to generate electricity from renewable resources and (b) even after considering the emissions produced at source, the overall (negative) impact is lower when compared with petrol and diesel vehicles (see for example, Kinsella et al., 2023). The literature is flooded with research on barriers and challenges to EV uptake, but largely, the focus has been on private vehicles. The challenges towards electrifying car-sharing services differ from those of private vehicles and need more (in-depth) exploration.

In the past several years, European car-sharing services have implemented all-electric car-sharing programmes or added EVs to their fleets (Burghard and Dütschke, 2019). Studies have found that electrifying car-sharing fleets have a vast potential to reduce greenhouse gas emissions; however, uncertainty remains about the extent of the potential emissions reduction, and this topic is as yet underexplored (Harris et al., 2021). From the car-sharing service operators' point of view, on the one hand, since EVs have lower

energy costs than petrol and diesel cars, deploying them in shared car fleets could potentially result in cheaper operational expenses (Liao and Correia, 2022). On the other hand, considering factors such as the installation of charging infrastructure and low vehicle utilisation due to long charging times, electric car-sharing has more operational complexity, which might increase the overall costs (Perboli et al., 2018). From the users' perspective, the most significant advantage of electric car-sharing is that users need not worry about the high upfront costs of EVs, maintenance, taxes and other risks and uncertainties associated with buying personal vehicles (Liao et al., 2017). However, the perceptions and user experiences concerning charging and range anxiety remain a challenge that needs further exploration (Ortega et al., 2023).

Car-sharing becomes a significant pillar of low-emission transportation when it is accepted, adopted, retained, and institutionalised (George and Uteng, 2021). Research on car-sharing has primarily been based in North America; however, those cities differ from European cities in terms of their spatial spread, availability of public transit systems, and level of car dependence (Ortega et al., 2023). Moreover, compared to strategic long-term decision-making, operational aspects of car-sharing have received more emphasis (Ataç et al., 2021). Therefore, this study attempts to contribute to the car-sharing literature through evaluations directed towards the possible emission reductions and the feasibility of electrifying the roundtrip car-sharing service fleet for the future to inform policymakers for framing long-term strategies considering both climate change targets and sustainability.

3. Research Design and methods

The flowchart of the overall study is provided in Fig. 1. For the first objective, this study calculated the emissions due to the current GoCar fleet based on available data from 2016 to 2021 (taken as baseline), conducted exploratory analysis to forecast fleet size and distance travelled for 2030 under multiple scenarios, and predicted potential emission reduction if the ICEVs are replaced with EVs. A previous assessment indicated that a minimum of 26 % to 40 % of the fleet needs to be electrified in order to achieve improvements in air quality (Soret et al., 2014). Ireland and many other EU countries have targeted to reduce 50–55 % of emissions by 2030 and carbon neutral by 2050. Accordingly, this study scenario was designed to understand whether 50 % electrification in the transport sector, especially whether the shared cars by GoCar could help achieve these climate targets.

The required data was obtained from GoCar, a shared car operator in Ireland (see Fig. 2 which presents the current GoCar fleet operating in Ireland). The data was pre-processed to remove any ambiguities for further analysis. Based on the scenarios for emissions estimation, the fleet size and distance driven were projected for the year 2030 using appropriate forecasting methods which are presented in later sections. The forecasted fleet size and travelled distance were categorised based on Computer Programme to calculate Emissions from Road Transport (COPERT) software requirements to estimate emissions. Finally, the potential reduction in emissions was estimated when 50 % of predicted Internal Combustion Engine Vehicles (ICEVs) were replaced with EVs for multiple scenarios. Section 3.1 presents the details of these scenarios. This study predicted the fleet size and distance travel data required to estimate emissions. It assumes that the number of bookings is proportionately increasing as the fleet size and travel distance predictions.

For the second objective, the data was plotted for different booking durations to study whether the distance travelled during those booking periods can be completed using currently available EVs in Ireland. The travel patterns of these bookings are assessed for multiple scenarios explained in Section 3.4. The primary focus of this study was investigating emission reductions and booking feasibility associated with the adoption of electric vehicles (EVs) by GoCar. Considering GoCar's future, the cost analysis could not be carried out due to data limitations. Detailed information on the total costs incurred by GoCar, particularly in relation to EV adoption and supporting infrastructure, was not available.

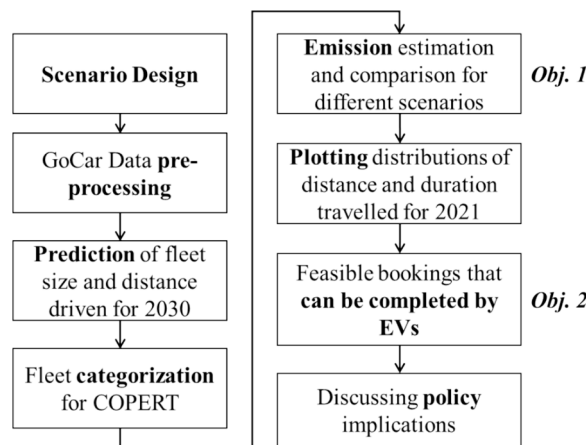


Fig. 1. Study Flowchart.

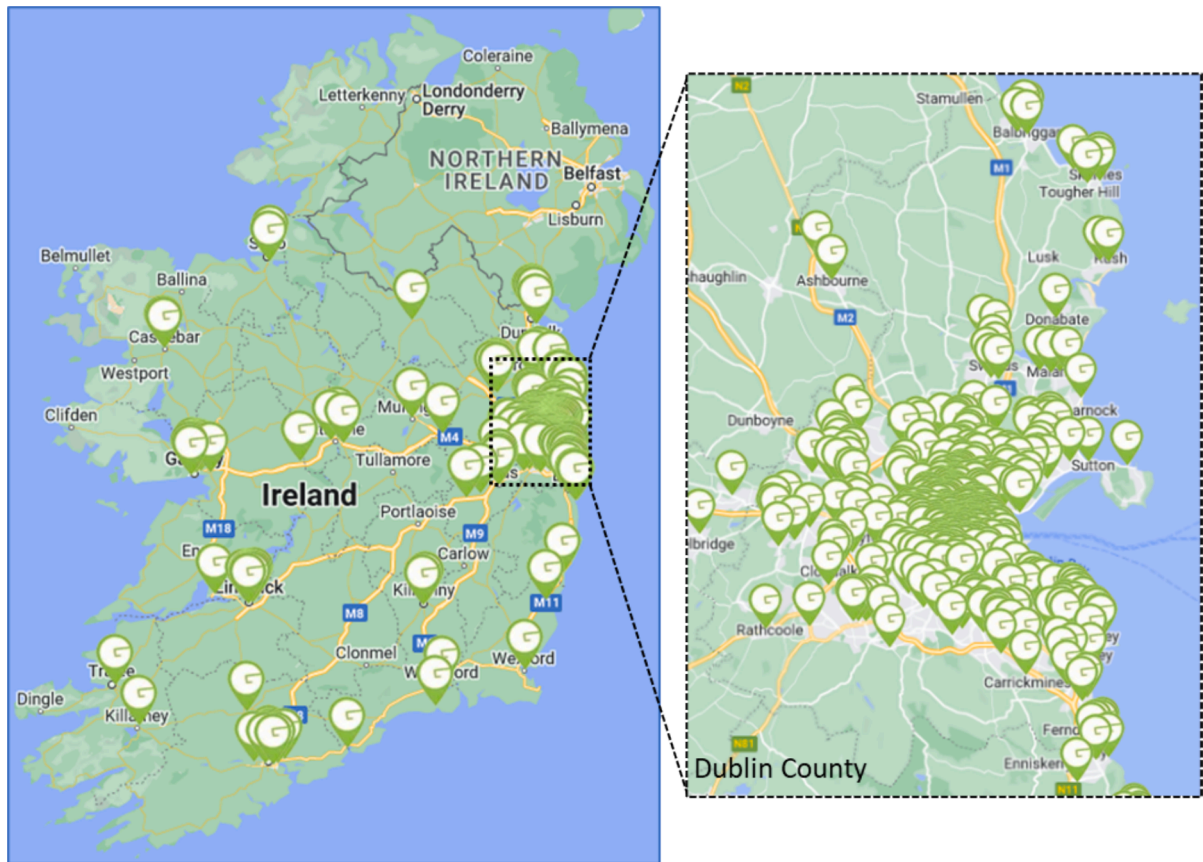


Fig. 2. GoCar fleet location in Ireland (○).
Source: GoCar website, 2023

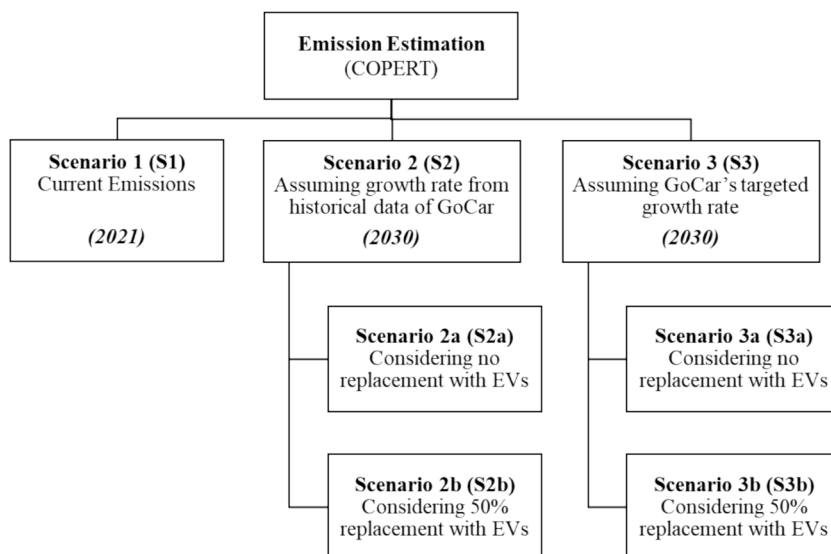


Fig. 3. Scenarios for Emission Estimation

3.1. Emission estimation scenarios

Fig. 3 presents three different scenarios considered in this study. Scenario S1 considers the observed emissions for the GoCar fleet for the base year, i.e. 2021. Scenario S2 estimates emissions using the predicted GoCar fleet size and distance travelled for 2030. For this purpose, scenario S2 uses a few forecasting methods to predict such data for 2030. The forecasting methods previously used in the literature are arithmetic increase, incremental increase, geometric increase, logistic curve and decrease in growth rate methods, which forecasts a region's population (Jain et al., 2013; Lal, 2020; Maji et al., 2020) are explained in section 3.2. Using these methods, the available fleet size and distance travelled from 2016 to 2020 were used to forecast the same for the year 2021. The percentage error (see Equation 1) between the forecasted and available data for 2021 was compared for all methods, and accordingly, a suitable method was selected for fleet size and travelled distance. Finally, selected methods were used to forecast the fleet size and distance travelled for 2030. Such forecasted data were considered in scenario S2a to calculate emissions, assuming that the proportion of GoCar fleet type is the same as that of 2021. Accordingly, scenario S2a is considered as business-as-usual scenario. Scenario S2b considers the calculation of emission factors if 50 % of ICEVs and corresponding travel distances in the scenario S2a data are replaced with EVs; however, that is in addition to the existing EVs (and corresponding travel range) in scenario S2a.

Scenario S3 followed the same process as scenario S2 with additional consideration of the GoCar operator's target to increase fleet size to 5000 vehicles by 2025 (O'Connor, 2019; Roddy, 2021). Here, the available forecasting methods were tested to predict the fleet data for 2025 using the data between 2016 and 2021. The method resulting in the lowest percentage error with the target of 5000 vehicles was selected for predicting emissions for 2030. Since there is no target for distance travelled (i.e., the usage of vehicles), it was predicted by taking the ratio of fleet size to the distance travelled corresponding to scenario S2. The distance travelled for S3 was calculated using this ratio. It was compared with all the predicted values between the forecasting method for 2030 in scenario S2 and the method providing the least error between calculated and forecasted travel distance was used. Finally, the forecasted data was considered in scenario S3a to calculate emissions assuming that the proportion of GoCar fleet type is the same as that of 2021. Similar to S2b, scenario S3b considers the calculation of emission factors if 50 % of ICEVs and corresponding travel distance are replaced with EVs taking into consideration the S3a data.

3.2. Forecasting methods

Forecasting the fleet size and distance travelled need detailed data such as GoCar's financial data, demand status, futuristic EV adoption rate, charging station plans, business uncertainty, and its competitor's status in the market. Due to unavailability of such information, this study explores well-established forecasting methods that require minimal historical data. Accordingly, this study used exploratory analysis to identify the best forecasting method among the methods considered in Table 1. Such forecasting methods provide different perspectives on growth, helping researchers understand and predict future trends based on historical data and theoretical assumptions. The majority of these methods are generally used for population forecasting in previous studies (Jain et al., 2013; Lal, 2020; Maji et al., 2020) based on historical data and specific assumptions about future trends, without any quantitative data. Remarks have been added to Table 1 to indicate in which case each method is used. In this study, due to the absence of any information on future trends, all the methods were tested with historically available data the method providing the least percentage error (see equation (6)) was used for further analysis. Since these methods use historical data, a significant change in numerical values, e.g., due to emergencies such as COVID-19, affects the future trajectory of the trend.

Note: n is the number of time period, P_n is the quantity at current step, P_{n+1} is the quantity at next step t is time (here it is the year), P_0 is the initial quantity, $P(t)$ is the quantity at time t , k is the average increase per unit time (slope), r is the growth rate, e is the base of natural logarithms, K is carrying capacity, R is the intrinsic growth rate, r_n is the growth rate for n step, S is the average decrease in growth rates.

Table 1
Methods considered in different forecasting techniques.

Equation	Method	Equation	Remarks
1	Arithmetic increase	$P_n = P_0 + nk$	- Used when relatively stable and incremental growth is assumed for quantity such as fleet size or distance travelled - Trend similar to linear regression
2	Incremental increase	$P_n = P_0 + na + \frac{n(n+1)}{2}b$	Used to account for changes in the rate of increase of quantities
3	Geometric increase	$P_n = P_0 \left(1 + \frac{r}{100}\right)^n$	- Used where there is a significantly high probability of growth - Trend similar to an exponential growth function
4	Logistic curve	$P(t) = \frac{K}{1 + \frac{K - P_0}{P_0}e^{-Rt}}$	- Used when there is limited land space and economic opportunity hindering growth after particular time - Trend similar to a cumulative logistic function
5	Decrease in growth rate	$P_{n+1} = P_n +$ $\left(\frac{r_n - S}{100}\right)P_n$	Used when growth decreases due to extraordinary changes like an epidemic, war, or any natural disaster

$$PE_i = \frac{|A_i - F_i|}{A_i} \times 100 \quad (6)$$

where, PE_i is the percentage error for a forecasting method i , A_i is the actual value and F_i is the forecasted value using method i . The values are fleet size, or distance travelled based on the available data.

3.3. Data for emission estimation

The emission models include static and dynamic models, where a static model is categorised into average speed emission and aggregated emission factors methods (Elkafoury et al., 2014; Kinsella et al., 2023). COPERT is an industry-standard software used by many European countries for reporting official emissions data (Dey et al., 2019; Ntziachristos and Samaras, 2020). It is also used as a research tool to calculate annual emissions at national, regional, or local scales based on the availability and granularity of the dataset. The average speed emission model in COPERT typically considers the relationship between vehicle emissions and average speed. Such a relationship is usually derived from empirical data collected using real-world driving conditions. The European Environment Agency (in collaboration with various stakeholders and experts in vehicle emissions, air quality, and environmental policy) utilises such data to calibrate the model, which further helps estimate vehicle emissions under different vehicle and driving conditions. Such a model also accounts for the vehicle's stock and activity data, circulation data, environmental information, and trip characteristics of the vehicles (Ntziachristos and Samaras, 2020). The COPERT model is updated at regular intervals with more data availability related to changing emission standards, vehicle technologies, and driving conditions to increase model accuracy. This study utilised average speed emission models using COPERT (software version 5.6.5) for a Tier 3# level detail.

COPERT considers important vehicular pollutants such as greenhouse gases (GHG), air pollutants, and other species (Ntziachristos and Samaras, 2020). This study extracted the tailpipe emissions, including GHG and non-GHG emissions, using the COPERT model. The emissions estimation in this study considered carbon monoxide (CO), carbon dioxide (CO₂), nitrogen oxides (NO_x), particulate matter 2.5 µm (PM_{2.5}), and volatile organic compounds (VOCs). These emissions are calculated using vehicle fuel type, distance driven, surrounding environment (urban, rural, or highway), and ambient weather conditions.

GoCar supplied fleet details and users' trip information for all bookings between 2016 and 2021 for the research. The fleet information includes vehicle registration number, category (Passenger Car [PC] or Light Commercial Vehicle [LCV]), fuel type (petrol, diesel, hybrid, or electric), weight (in kg), cylinder capacity (in cc), and other details such as colour, number of seats and doors, and maintenance information. The trip information included the date and time of booking, booking period, distance travelled (in km), and other details such as completed vs. cancelled bookings, as well as the availability of valid trip insurance. The data was appropriately fed to the COPERT model to estimate the emissions produced by all GoCar trips.

3.4. EV travel range scenarios

Table A1 presents five different types of EVs considered for travel range estimation which include three PCs and two LCVs. It also presents their travel ranges as per the Worldwide Harmonised Light Vehicle Test Procedure (WLTP). WLTP measures the travel range when an EV travels at an average speed of 46.5 km/h in summer temperatures from 100 % (full capacity) to a 0 % state of charge. The certified WLTP range only helps to compare different car makes and models. It is generally not always achievable in regular driving conditions. This study considered three scenarios to estimate the EV travel range as presented in Fig. 4. Further, Table A2 explains the calculation of these percentages of travel range for each of the following scenario.

Scenario A (SA): It is an ideal scenario that considers the EV to be new and fully charged. However, the WLTP travel range is a standardised travel test, and the actual EV range is 80–90 % lower due to individual driving styles and the regional topography of the

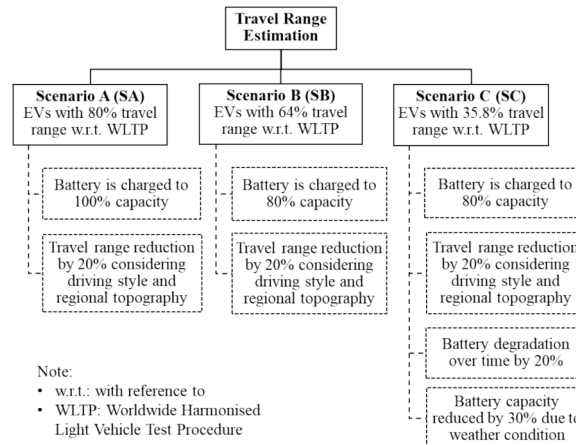


Fig. 4. Scenarios for Travel Range Estimation

driving area (Gridserve, 2023). Hence, it was assumed that a fully charged EV may provide only 80 % of its WLTP (full) travel range. In Ireland, over 87 % of EVs are fully charged at home (Ronald, 2023; SEAI, 2023) and hence can charge fully with a slow charging facility. SA will also be an ideal scenario whenever the GoCar operator starts providing a charging facility at its dedicated parking spot.

Scenario B (SB): Besides the ideal scenario, scenario B considers that the EVs are fast-charged to only 80 % capacity. It considers that people without dedicated facilities at home depend on the public charging infrastructure. Secondly, GoCar EVs are also depending on public charging facilities. A vehicle can be charged up to 80 % with fast chargers (up to 50 kW DC) in 30 min (ESB, 2024); however, it takes longer to charge it to 100 %. Hence, charging up to 80 % in public fast chargers is preferable. Therefore, SB was considered a practical scenario with a 64 % travel range compared to the WLTP range.

Scenario C (SC): This scenario adds two more factors to scenario B, further reducing the EV travel range; hence, it was considered a worst-case scenario. Travel range was observed to have dropped by 30 % at an ambient temperature of 15 °C or less when compared to 25 °C due to the use of heaters inside the car (Steinstraeter et al., 2022). Further, lithium-ion batteries used in EVs tend to have a life expectancy of 5 to 10 years, which is assumed to have reached its expected life once it loses 20 % of its capacity (Cluzel and Douglas, 2012). These criteria conceptualise the idea of reselling EVs in the second-hand market, where users understand their available travel range. Overall, this scenario considers 35.6 % of the WLTP travel range.

4. Analysis and results

Initially, the observed data from GoCar was pre-processed, as provided in Figure A.1 (refer to Appendix A). The dataset consisted of 1.24 million GoCar bookings from 2016 to 2021. Since some of the bookings were cancelled (9.66 %), unused (14.34 %), and had incomplete booking information (4.42 %), they were excluded from further analysis. The remaining 0.88 million (71.56 %) bookings were included in the analysis. Fig. 5 shows the annually registered new GoCar fleet by different fuel types. Observing fewer new registrations during 2020 and 2021 was probably due to the COVID-19 pandemic. Further, Fig. 6a presents the total available fleet with GoCar operators in the years considered. It is noteworthy that Fig. 5 only presents new vehicles purchased by GoCar each year and that Fig. 6a is their total active fleet size for each year. Fig. 6b showcases the total distance travelled for different fuel types. The data showcased in Fig. 6 was further used to predict the operational fleet size and distance travelled for 2030. Further, it should be noted that 2022 was excluded from further analysis since the booking data was incomplete (available from January to May 2022 only).

4.1. Prediction of fleet size and distance travelled for 2030

Table 2 provides the observed percentage errors in all the methods for scenarios S2 and S3. Of the five methods attempted in this study, only incremental increase and arithmetic increase methods, in scenario S2, have shown the lowest error in GoCar fleet size and distance travelled, respectively. The incremental increase method generated the lowest error (9.5 %) of all the methods when comparing the prediction to the actual fleet size in 2021. This method predicted a fleet size of 1930 for the year 2030 (see Fig. 7a). The arithmetic increase method produced the lowest error (11.1 %) for the distance travelled for S2 (see Fig. 7b). It predicted a total distance travelled of 38 million km for the year 2030.

As mentioned earlier, GoCar has a target of operating a fleet size of 5,000 vehicles by the end of 2025. Hence, in the case of scenario S3, a similar process was followed for prediction; however, the forecasted and actual fleet size (GoCar target) for 2025 were compared. After comparing all the forecasting methods, the geometric progression method produced only a 1 % absolute error; however, the forecasted fleet size was computed to be 33,373 vehicles by the end of 2030. It was 3004 % increase in fleet size, which does not seem practically feasible. Moreover, GoCar has around 950 + vehicles operating in Ireland as of December'23 (GoCar, 2023), which is expected to be 2300 vehicles (by the end of 2023) using the geometric progression method. Therefore, the arithmetic increase method was used with an absolute error of 62.2 %. This error seems significantly high; however, it should be noted that, from observing the

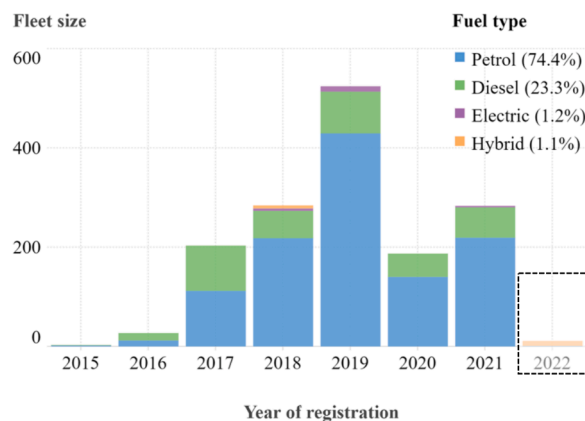


Fig. 5. Newly Registered GoCar fleet (Notes: [i] the 2022 data shown within the dashed rectangle was available only from January to May 2022 and therefore was excluded from the analysis, [ii] the percentage values in the legend show the cumulative share of the fleet with respect to fuel type).

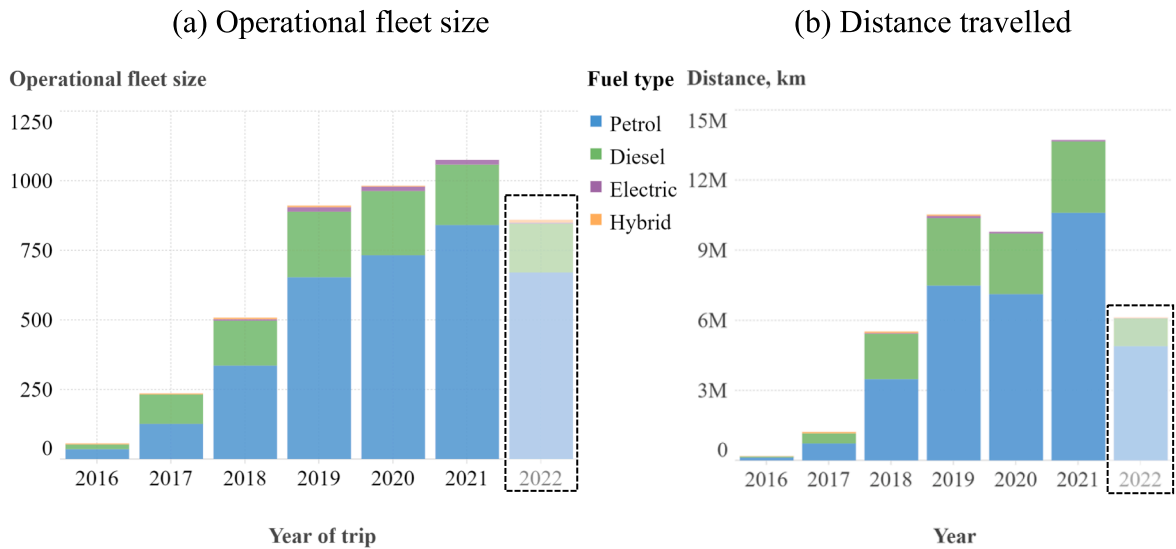


Fig. 6. (a) Operational fleet size and (b) total distance travelled for different vehicle fuel types (Note: the 2022 data shown within the dashed rectangle was available only from January to May 2022 and therefore was excluded from the analysis).

Table 2

Percentage error observed in forecasting methods.

Method	Scenario S2		Scenario S3		Remark(s)
	Error in operational fleet size (%)	Error in travelled distance (%)	Error in operational fleet size (%)	Error in travelled distance (%)	
Arithmetic Increase	12.80	−11.10	−62.20	33.49	Observed suitable for distance travelled in scenario S2 (in km).
Geometric Progression	54.50	—	−1.00	—	Observed suitable for fleet size in S3, but predicted significantly high.
Incremental Increase	9.50	−15.40	−66.50	−22.50	Observed suitable for (a) fleet size forecasting in scenario S2, and (b) distance travelled in scenario S3.
Decrease in Growth Rate	−97.30	171.1	107.9	—	Observed not suitable considering the error.
Logistic Curve	—	—	—	—	Unable to calculate, since the calculated saturation population was lower than the observed data.

growth of fleet size over the years, it is an ambitious and challenging target to achieve 5,000 vehicles by 2025. Finally, an operational fleet size of 2909 vehicles was predicted for 2030 (see Fig. 7a). Fig. 7a and Fig. 7b also present the performance of four different forecasting methods. The decrease in the growth rate method did not perform well for the given data. Moreover, the geometric progression method failed in the case of distance travelled for scenario S3.

Since the GoCar's targeted distance travelled was not available, the ratio of predicted fleet size to distance travelled was used from scenario S2 for 2030. The ratio for scenario S2 was 1930 fleet to 38 million km travelled. With this ratio, the distance travelled was estimated as 57 million km for the fleet size of 2909. This value was taken as a reference point to find the minimum error among forecasting methods used for finding distance travelled for 2030. Accordingly, it was compared with the forecasts of the distance travelled (see Table 2). The least error was observed in the incremental increase method that provided the predicted distance travelled as 70 million km for scenario S3 (see Fig. 7b). Finally, Fig. 8a and Fig. 8b present the overall fleet size and travel distance, respectively, considered within each scenario based on the forecasting methods selected above. Further, Table A3 provides the various type of available stocks (i.e., fleet size) for the year 2021 which was considered in the COPERT software for emissions estimation.

4.2. Emission analysis using COPERT

Table 3 presents the estimated emissions and emission differentials among scenarios using the COPERT model for CO, CO₂, NO_x, PM_{2.5}, and VOCs. For example, Table 3 shows that 21.8 kg of CO emissions were produced in 2021 for S1. In 2030, scenario S2a

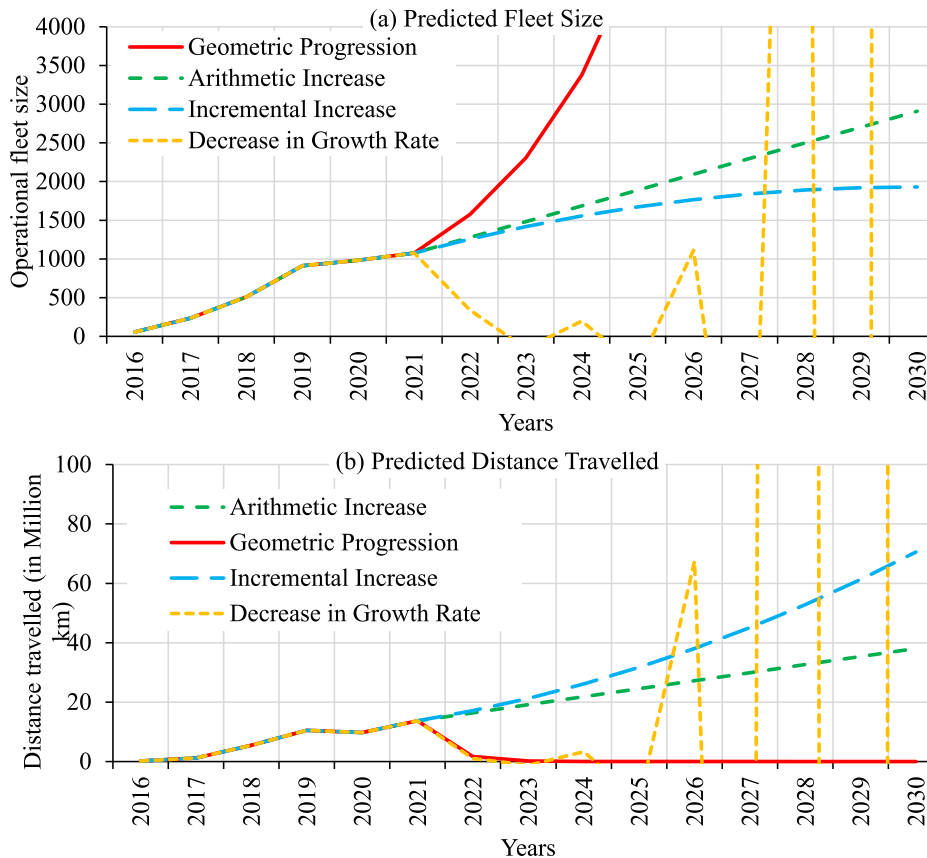


Fig. 7. Growth plot of (a) operational fleet size and (b) distance travelled using four forecasting methods.

presents that the CO emissions are expected to increase by 77 % to 38.7 kg when the growth factor using historical trend data is considered. An increase of 167 %, leading to 58.4 kg for scenario S3a, was generated when considering GoCar's targeted fleet size. If 50 % of the ICEVs and their travelled distance are replaced with EVs, i.e., S2b and S3b, the CO emissions were reduced by 50 %, leading to 19.5 kg and 29.3 kg compared to S2a and S3a, respectively. Moreover, due to the presence of EVs, the CO emissions were less by 11 % for S2b compared with that of 2021 (i.e., scenario S1) despite the fleet size increase. However, it was more by 34 % for S3b. Overall, the results demonstrate that replacing ICEVs with EVs will significantly help in reducing CO emissions.

Similar results were observed for CO₂, NO_x, and VOCs. As the tailpipe emissions from EVs are zero, a 50 % reduction in fleet size and travel distance halves these emission factors. However, this may not be the case when one considers the source of electricity generation. COPERT does not consider exhaust emissions produced during electricity generation. In the case of PM_{2.5}, the ICEVs replaced with EVs by 50 % may only result in a 27 % decrease in PM_{2.5} emissions. PM_{2.5} emissions can be produced from tyre wear, brake wear, road abrasion, and resuspension of vehicles (Hosseini and Stefaniec, 2023; Kinsella et al., 2023) in addition to the combustion of ICEV fuel. Overall, Table 3 shows an average increase in emission levels by 82 % to 175 % (with a deviation of 5.2 % to 7.2 %, respectively) for 2030 if the fuel type proportions are similar to 2021. These emission levels can be reduced by 46 % on average (deviation of 9.4 %), with the introduction of 50 % EVs by 2030.

4.3. Travel range (TR)

While estimating the percentage of GoCar bookings that can be completed using EVs, it was considered to sum up all multiple bookings in a day into single-day bookings, assuming that an EV is charged only once to its capacity as mentioned earlier in scenarios A, B, and C. It provided an understanding of whether all these bookings can be completed with an EV charged only once a day. Accordingly, the GoCar booking data was aggregated and tagged as day bookings. Fig. 9 shows these day bookings for PCs and LCVs according to the total day booking hours. It was observed that nearly 52 % of the bookings were between 0 and 6 h for both PC and LCV. Only 10–15 % of bookings were more than 24 h; the rest were all single-day bookings. It suggests that most GoCar users use the vehicle for their single-day trip. Since each day booking is a round trip, all users should complete their activity and end the trip at the origin.

As mentioned earlier, three PCs and two LCVs along their WLTP travel ranges are considered in the study. Table 4 presents their estimated TR for scenarios A, B, and C. These TRs are obtained by multiplying the total battery efficiency (TE, see Table A2) by the

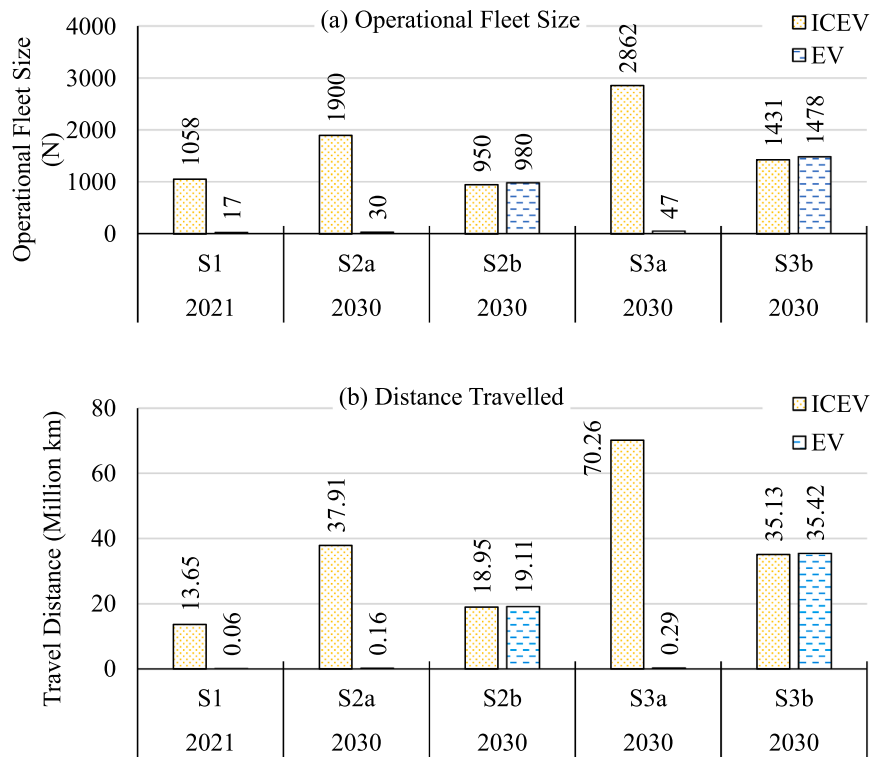


Fig. 8. (a) Operational fleet size and (b) distance travelled considered in each scenario (Note: ICEV: Internal Combustion Engine Vehicle, EV: Electric Vehicle).

Table 3

Estimated emission and percentage change between different scenarios.

Emission factors			Scenarios				
			S1	S2a	S2b	S3a	S3b
CO	Emission (kg)		21.85	38.73	19.46	58.38	29.31
	Percentage change compared to:	S1	—	+77 %	−11 %	+167 %	+34 %
		S2a	—	—	−50 %	+50.72 %	—
		S3a	—	—	—	—	−50 %
CO ₂	Emission (kg)		20181	36204	18211	54594	27433
	Percentage change compared to:	S1	—	+79 %	−10 %	+171 %	+36 %
		S2a	—	—	−50 %	+50.79 %	—
		S3a	—	—	—	—	−50 %
NO _x	Emission (kg)		8.86	16.29	8.21	24.55	12.37
	Percentage change compared to:	S1	—	+84 %	−7 %	+177 %	+40 %
		S2a	—	—	−50 %	+50.74 %	—
		S3a	—	—	—	—	−50 %
PM _{2.5}	Emission (kg)		1.34	2.41	1.76	3.64	2.65
	Percentage change compared to:	S1	—	+79 %	+31 %	+171 %	+97 %
		S2a	—	—	−27 %	+50.89 %	—
		S3a	—	—	—	—	−27 %
VOC	Emission (kg)		905.9	1736.3	826.1	2617.3	1304.5
	Percentage change compared to:	S1	—	+92 %	−9 %	+189 %	+44 %
		S2a	—	—	−52 %	+50.74 %	—
		S3a	—	—	—	—	−50 %
Mean [and Std. dev.] change compared to:			S1	—	+82 % [5.2 %]	−1.2 % [16 %]	+175 % [7.7 %]
			S2a	—	—	−46 % [9.4 %]	+51 % [0.1 %]
			S3a	—	—	—	−45 % [9.1 %]

individual WLTP TR of EVs considered. Accordingly, Table 4 provides the respective TRs as TR_A, TR_B, and TR_C for each EV considered. For example, the WLTP TR for PC.EV.1 is 484 km, while its TR for scenarios A, B, and C are 387 (80 %), 310 (64 %), and 173 (35.8 %) km, respectively. Based on the available distance travelled for all the GoCar day bookings, the number (N) and percentages (P) of these bookings that can be completed using each EV are presented in Table 4. Note that, currently, GoCar operator does not have LCV EVs in

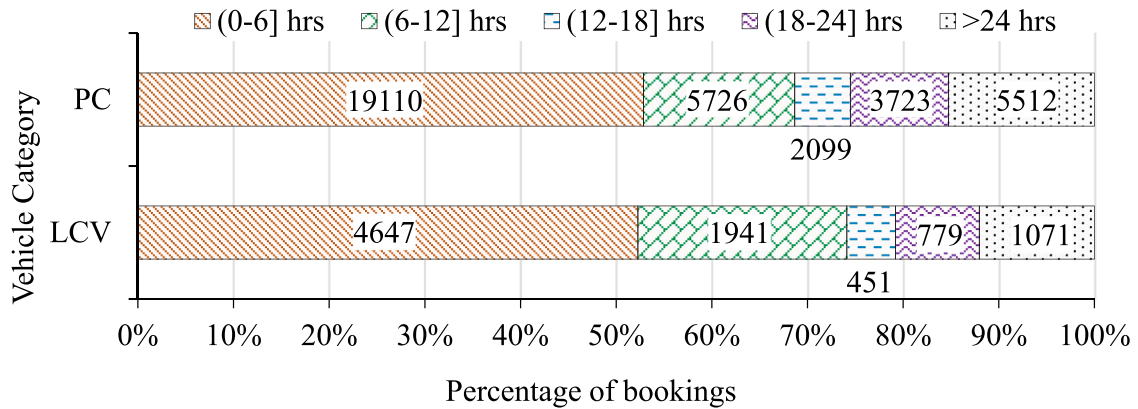


Fig. 9. GoCar's total day bookings for (a) PC and (b) LCV in 2021 within the range of booking time (in hrs).

Table 4

EVs considered and their travel range estimations for different scenarios.

Scenarios			Scenario A			Scenario B			Scenario C		
EV Category	EV ID*	WLTP TR (km)	TR _A (km)	N _A	P _A	TR _B (km)	N _B	P _B	TR _C (km)	N _C	P _C
PC	PC.EV.1	484	387	30020	98 %	310	29693	97 %	173	28048	92 %
	PC.EV.2	317	254	29330	96 %	203	28747	94 %	114	25342	83 %
	PC.EV.3	270	216	28926	94 %	173	28048	92 %	97	23915	78 %
LCV	LCV.EV.1	270	216	7204	92 %	173	6917	89 %	97	5717	73 %
	LCV.EV.2	314	251	7347	94 %	201	7126	91 %	112	6106	78 %

Note:

(1) *EV ID: EV identity only; the names of these EVs are provided in Table A.1.

(2) TR: Travel Range of EV for the given scenario in km, N: Number of day bookings that can be conducted using a given EV, and P: percentage of day bookings that can be conducted using a given EV.

(3) The subscripts A, B, and C show the different scenarios for Note 2.

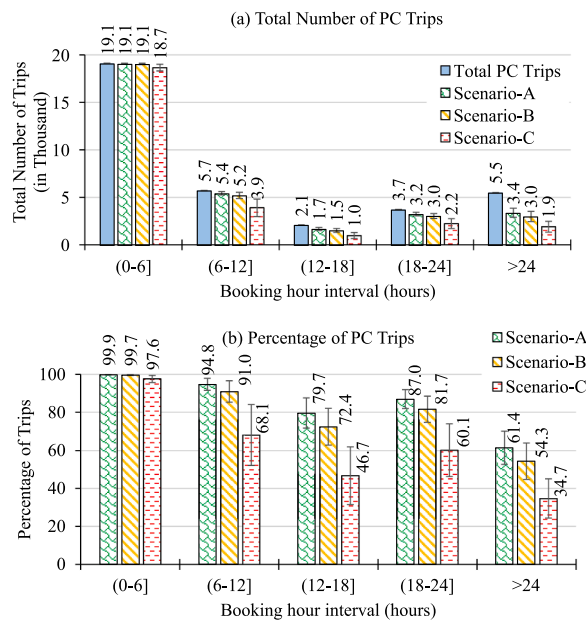


Fig. 10. (a) Total number and (b) Percentage of trips that can be conducted using EVs.

their fleet; however, it is assumed that they will be available in operation by 2030.

Table 4 showcases that for scenario A, 92–98 % of day bookings can be completed with the EVs considered in this study. Scenario A is similar to using a newly purchased EV with a fully charged battery with which more than 90 % of day bookings can be completed. Further, 89–97 % of day bookings can be covered in scenario B. It is a more reasonable scenario where the EV is only 80 % charged due to user time constraints. Despite this fact, more than 89 % of bookings can be made using EVs. In the case of scenario C, a total of 73–92 % of day bookings can be completed using EVs. In this worst-case scenario, the battery capacity is reduced to 35.8 % due to weather conditions, battery degradation, driver behaviour, and terrain conditions. Despite such conditions, interestingly, more than 70 % of day bookings can be completed with EVs. Moreover, this percentage will probably increase with the technological improvement in EVs and their battery efficiency by 2030.

Fig. 10 and Fig. 11 present the total number and percentage of PC and LCV bookings, respectively, that can be completed using EVs for the scenarios considered. Fig. 10a shows the number of day bookings, while Fig. 10b shows the percentages. It can be observed that the maximum number of bookings has a 0–6 h interval duration. Moreover, more than 95 % of these bookings can be suitably completed using EVs for all the scenarios considered. The percentage of bookings significantly reduces as the booking duration increases, especially for scenario C. Evidently, the decrease in travel range would reduce the number of bookings that can be completed using EVs. For bookings within 6–12 h, more than 90 % of bookings can be completed for scenarios A and B; however, only about 70 % of bookings can be handled in the case of scenario C. For bookings of more than 12 h, approximately 61–87 % can be completed using EV in scenario A, 54–81 % in scenario B, and 34–60 % in scenario C.

Fig. 11 shows similar trends observed for EV LCVs with minor differences in the quantitative terms compared to EV PVs. The maximum number of bookings has 0–6 h interval duration. Moreover, more than 90 % of these bookings can be suitably completed using EVs for all the scenarios considered. For bookings within 6–12 h, more than 80 % of bookings can be completed considering scenarios A and B; however, only 58 % of bookings in the case of scenario C. For bookings of more than 12 h, approximately 63–75 % can be completed using EVs in scenario A, 54–68 % in scenario B, and 31–45 % in scenario C. Assuming that the average distance travelled for PC and LCV bookings are the same, these LCVs percentages are marginally lower compared to PCs, probably because of the smaller travel range of LCVs compared to PCs considered in the study. LCVs tend to have more weight-carrying capacity and hence require more power, resulting in reduced travel range compared to PCs. Moreover, LCVs are used for freight transport with considerably more distance travelled than PCs (CSO, 2021).

The error bars in Fig. 10b present a significant variation of completed bookings among scenarios A, B, and C that can be completed using EVs. Such deviation also suggests uncertainty in the feasibility of completing the bookings as the travel range decreases over time and among different scenarios. It is also possible that differences in the travel range among the limited number of EVs (PCs) considered in this study can be an issue with such a significant variation. However, this is not the case for the LCVs showcased in Fig. 11b. The two LCV EVs considered have a maximum WLTP travel range difference of 44 km (see Table 4), while the same for PC EVs have a maximum difference of 214 km, which is significantly high.

5. Discussion

The fleet sizes and their proportion by vehicle type in different scenarios are provided in Fig. 8a using the prediction methods considered in this study. It shows that, compared to scenario S1, scenario S2b already has the required number of ICEVs for the year 2021. In other words, the required ICEVs at the end of 2030 (in S2b) are already available in 2021 and there is a need to acquire only EVs. In the case of scenario S3 (considering GoCar's targeted growth), S3b (2030) already has 76 % of ICEVs compared to S1 (2021). Accordingly, as discussed in this study, the GoCar operator may need to acquire ICEVs and EVs in the proportion of 2:9 to achieve 50 % replacement. Such consideration will help reduce emissions by 45 %, on average. To achieve the 51 % carbon reduction target, GoCar operators must target more EVs by the end of 2030 than the required proportion (2:9), the minimum requirement.

Observing GoCar's target mentioned in this study, if the operator plans to replace at least 50 % of their ICEVs with EVs by 2030 (i.e., scenario S3b), it would allow only a 45 % reduction in total vehicular emissions when compared with scenario S3a (i.e., business-as-usual scenario where there is no replacement of ICEV with EV fleet). It is an average reduction potential compared to Ireland's target of reducing 42 % to 50 % of transport sector emissions by 2030 (CAP, 2021). Additionally, under the same scenario (S3b), the estimated emissions could rise by 50 % in 2030 compared to 2021 (base scenario S1). It may not be desirable considering Ireland's emissions reduction target. The operator needs to deploy a significantly higher than 50 % replacement considered in this study to reduce emissions instead of increasing them.

Previous studies reported that travel range anxiety is one of the major barriers to EV uptake and that limited options for EV charging networks are a primary contributor (Anderhofstadt and Spinler, 2020; Kinsella et al., 2023). The impact of the availability of charging infrastructure on EV adoption has also been explored and discussed in the literature (Anderhofstadt and Spinler, 2020; Dubarry et al., 2017; Freeman et al., 2017; Globisch et al., 2018; Skippon and Chappell, 2019; Tsakalidis et al., 2020). Interestingly, based on the results obtained in this study, the lack of public charging networks should not hinder more than 90 % of day bookings that are less than 6 h. Such trips can be comfortably conducted using EVs with a single charge, even without fast-charging infrastructure at the GoCar station. Due to the short booking period and round trip nature (i.e., the trip start and end locations are the same), the remaining time can be utilised to charge the EV fleet at their dedicated parking space. It is also noteworthy that the current GoCar fleet consists of less than 2 % EVs; electrifying the GoCar fleet will require a much higher share of EVs to be introduced to achieve the long-term target of reaching net zero emissions by 2050. In fact, all the new entrants into the GoCar fleet should preferably be EVs. Therefore, with the projected increase in GoCar EVs over the coming years, there will be a substantial demand for public charging infrastructure. Moreover, GoCar EVs are expected to generally be charged at designated public parking spaces instead of home chargers. It will

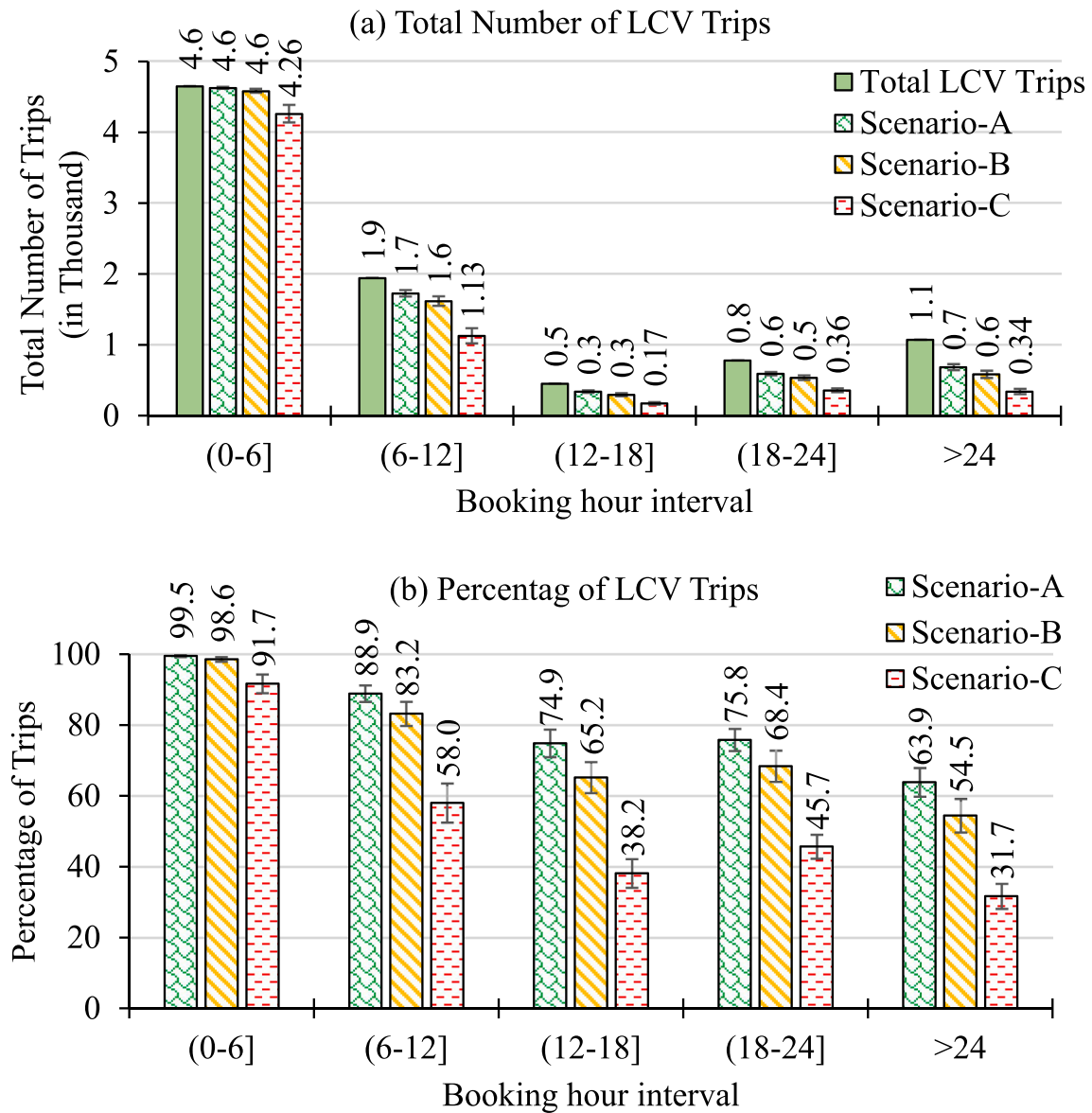


Fig. 11. (a) Total number and (b) Percentage of trips that can be conducted using EVs.

introduce a higher burden on the charging infrastructure, and further government investment in public charging facilities will be required. Also, the requirement for public fast-charging facilities in future would be vital if the dynamics of demand increase significantly.

While it is true that private car-sharing service providers such as GoCar should own and operate charging points, the overarching infrastructure required to support the widespread adoption of electric vehicles often falls within the purview of governmental initiatives. In many cases, the establishment of public charging facilities is essential to ensure equitable access to charging infrastructure for all users, irrespective of the type of end-user which may be a private EV, a commercial EV or a car-sharing EV. In other words, public charging points not only serve the customers of GoCar but also benefit the broader community, including private EV owners and other stakeholders and therefore are vital for an overall EV uptake. However, it is equally important to acknowledge the potential role of private organisations, such as GoCar, in supplementing public charging infrastructure. Collaborative efforts between governments and private operators can lead to feasible solutions that optimise the utilisation of resources and mitigate the burden on public finances.

Installing chargers at GoCar dedicated parking slots seems to be a practical solution to reduce the burden on public charging infrastructure. By integrating charging infrastructure into existing parking facilities, GoCar can not only enhance the convenience for its customers but also contribute to alleviating pressure on public charging infrastructure. Furthermore, formulating policies that encourage charging stations at GoCar parking lots could be an added advantage. While the integration of charging infrastructure into GoCar parking slots may entail initial investment costs for the company, the long-term benefits, including enhanced customer

convenience and satisfaction, expanded market reach, and contribution to sustainable mobility, are likely to outweigh these expenses, rendering it a profitable venture in the long run.

In the case of bookings for more than 6 h, it seems impractical to drive continuously for the whole booking period. The observed results indicate that only 68 % of PC- and 58 % of LCV-ICEV trips can be conducted using single-charged EVs for such booking periods. It means the distance travelled for these trips is less than (a) what could be covered in the booking period and (b) the corresponding EV travel range. The remaining bookings (32 % PC, 42 % LCV) with a travel range above EV capacity would require access to public charging stations; otherwise, users may select an ICEV and not an EV while planning to book such a trip. It points out that a robust charging infrastructure network would be critical for trips with higher travel distance requirements to facilitate successful journeys using EVs.

Notably, in the case of GoCar LCVs with bookings of more than 6 hrs, the percentage of successful travelled distance was significantly lower than for PCs. It could be possibly due to higher travel distance and gross vehicle weights on those vehicles, including freight weights, resulting in lower travel ranges (Christensen et al., 2017). Hence, LCVs would need to charge more frequently compared with PCs. As mentioned earlier, GoCar does not have LCV-EVs in operation as of 2023. The GoCar operator may need to facilitate LCV-EVs in the near future to align with Ireland's emissions reduction target. The introduction of LCV-EVs may still face another issue, considering the end users' demands in weight carriage capacity and distance travelled (Christensen et al., 2017). Therefore, considering current EV capacities, if the end users have options between LCV-ICEV and –EV with the car-sharing operator, there is a higher probability of selecting an ICEV over an EV. As mentioned earlier, a robust charging infrastructure or battery range could overcome such issues. Alternatively, the GoCar operator can analyse (a) the origin–destination matrix of their current LCV booking, replacing any repetitive and short-distance bookings with LCV-EVs and (b) conduct surveys among their current LCV-ICEV users to understand their EV concerns.

This study mainly supports EV adoption by car-sharing services from the emission reduction perspective. However, the operator's investment towards EV ownership and maintenance plays a major role in their survival in the market (Anderhofstad and Spinler, 2019; Sierzchula, 2014; Tsakalidis et al., 2020). For example, one of the shared car operators in the USA, Hertz, has decided to replace one-third of their EVs (roughly 20,000) with ICEVs due to high damage-repair costs and the decline in EV prices affecting its resale value (Gomes and White, 2024; Naughton, 2024; Valdes-Dapena, 2024). Hertz reported that the maintenance costs of EVs are twice as much as ICEVs. Moreover, the potential decline in EV prices over time affects operators' long-term benefits since car-sharing operators replace their older fleets with new vehicles, and the growing innovations in EV technology are making them economical and affordable (Naughton, 2024). Hence, at this point, the government grants need more diversification to subdue such issues, in addition to the one-time grants for EV purchases. In the case of Ireland, it is a relatively small country, unlike the USA, with comparatively less travel distance. Therefore, it should not matter in generalising such example in Irish context unless supported by research evidence.

The current Sustainable Energy Authority of Ireland (SEAI) policies support users by providing a grant amount of about 13–21 % on the upfront cost of EVs (PBOI, 2022). It has potentially benefited both private and commercial EV buyers (Rezvani et al., 2015; Setiawan et al., 2022; Sierzchula, 2014). As discussed earlier, GoCar has already started introducing EVs in its fleet; in the near future, it could help penetrate on-road EV operations compared to ICEV. However, from the end-user perspective, GoCar has introduced EVs (GoElectric) whose booking fares are marginally higher (from €1/hr for a similar PC-ICEV model to €5/hr for the lowest fare model) than counterpart ICEVs (GoCar, 2023). It may affect end-users' car selection choices and potentially limit the use of EVs. It suggests that GoCar should adopt more affordable EVs to the end users. Furthermore, the GoCar booking rates may need revision to nudge users to try EV models over ICEVs. To make it viable, government policies could play an essential role in leveraging such car-sharing operators or end-users in the form of subsidies.

The Irish government has already recognised the importance of the Avoid-Shift-Improve framework for transport sustainability and towards the net-zero goal (CAP, 2022). It suggests the decarbonisation potential of the transport sector through *avoiding* travel needs, *shifting* to environmentally friendly modes (such as public transport/ shared vehicles/ active transport), and *improving* the energy efficiency of vehicle technology. A shared car helps *shift* from private cars to shared vehicles, and electrifying shared cars helps *improve* energy efficiency. Moreover, as explained earlier, car-sharing operators like GoCar are helpful in the following ways: (a) It helps reduce the number of cars on the road, resulting in reduced congestion and parking space requirements; (b) It reduces customer's burden of ownership and maintenance costs; (c) It can provide a well-maintained and potentially newer version of models to the general public. Shared cars also have shown the potential to reduce pressure on the road network as one shared car removes 15 to 23 private cars on the road (Frost and Sullivan, 2010; Lane, 2005). It means that such a fleet is already helping to reduce carbon emissions in the transport sector. The electrification of such a fleet can further decrease the tailpipe (carbon) emissions and help move closer to achieving Ireland's emissions reduction target. Considering the growing trends of GoCar usage, EV adoption may need considerable support from the Irish government in the form of continued support on upfront costs, relaxation in taxes, subsidies to developing and improving charging infrastructure, and support towards affordable fares for end-users.

Car-sharing may slightly elevate carbon emissions for non-car owners who use public or active transport (walking and cycling) (Rabbitt and Ghosh, 2013). Hence, it is equally important to understand that car-sharing services should not compete with sustainable modes like public transport and active travel options with much lower carbon footprints. Moreover, the availability of GoCar can result in induced demand, adding trips that would otherwise not have been undertaken. Future studies are required to understand what kinds of trips are replaced with shared cars to understand the holistic emission reductions. The growth of car-sharing services should be optimised to complement the public transport sector, improving its accessibility. The policies should aid in increasing the share of public transport ridership with the help of car-sharing services, especially in the areas poorly served by public transport.

Delving deeper into the demand for shared cars and potential market saturation within the car-sharing service providers presents an avenue for future research, which is the limitation of the current study. To address these points, future studies could focus on gathering

additional data to validate assumptions about market saturation and identify specific end-user demographics that would drive increased utilisation of car-sharing services. Surveys or longitudinal studies could provide valuable insights into consumer preferences, travel behaviours, and the evolving dynamics of the car-sharing market. Additionally, exploring whether new or added bookings exhibit similar trip behaviours to existing ones, or if they represent different types of trips, would be beneficial for understanding the growth potential of car-sharing services. The analysis could encompass factors such as trip lengths, frequency of use, and trip purposes.

6. Conclusion

This study analyses the possible reduction in emissions by electrifying shared vehicles operated by GoCar and the feasibility of successful trip completion with the electrified fleet. It considered GoCar bookings data from 2016 to 2021 and forecasts the fleet size and possible travel distance in 2030. Initially, the COPERT emissions for 2021 were compared with forecasted data for 2030 with the help of three scenarios (S1, S2, and S3). It observed an average of 82–175 % increase in total emissions (CO, CO₂, NO_x, VOC, PM_{2.5}) assuming the proportion of fleet size with respect to fuel types (petrol, diesel, hybrid, and electric) is similar to 2021. It was also observed that such emissions can be reduced by around 45 % if approximately 50 % of ICEVs are replaced with EVs in 2030.

Further, the feasibility of successful day bookings completion using EVs was tested using the three travel range scenarios for 2021 data. It was observed that, for the EVs considered in this study, more than 90 % of GoCar day bookings (both PC and LCV) can be completed for new EVs, and more than 70 % of the same can be completed if the battery capacity is reduced over time to 35.8 % of the total efficiency. Interestingly, more than 70 % of GoCar trips were less than 12 h of booking duration a day, implying the EV batteries can be charged in the remaining time of the day and reused for the next day. Moreover, bookings over 12 h may not travel incessantly for the whole booking period. Users can charge the vehicles intermittently if they can access nearby charging infrastructure.

Despite the encouraging results of this study in relation to the uptake of EVs as shared vehicles, this study has a few limitations. The emissions estimated in the paper using the COPERT model focus only on tailpipe emissions. It assumes zero emissions for all EVs, except in the case of PM_{2.5}. The overall data was analysed for GoCar operator only; hence, the emission estimation results are biased towards one car-sharing company, while the data for other operators such as Yuko (Toyota), Enterprise Car Club, and DriveYou was unavailable. This study does not consider the emissions generated due to the production of electricity required to charge EV batteries. Although EVs can potentially reduce transport emissions significantly, the emissions due to electricity generation should be considered in future work. Moreover, estimating the reduction in emissions considering the potential future increase in the share of renewables in electricity production is also recommended to explore in future. Secondly, the travel range estimations were done using a limited number of EVs. The analysis in this study can be extended to more EVs for better clarity on travel range calculations.

CRedit authorship contribution statement

Tushar Pramod Choudhari: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Ubaid Illahi:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Mazen Al-Hosni:** Data curation, Formal analysis, Software. **Brian Caulfield:** Writing – original draft, Supervision, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Margaret O'Mahony:** Writing – review & editing, Writing – original draft, Supervision, Software, Resources, Methodology, Formal analysis, Data curation, Conceptualization.

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.

Data availability

The data that has been used is confidential.

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Appendix A

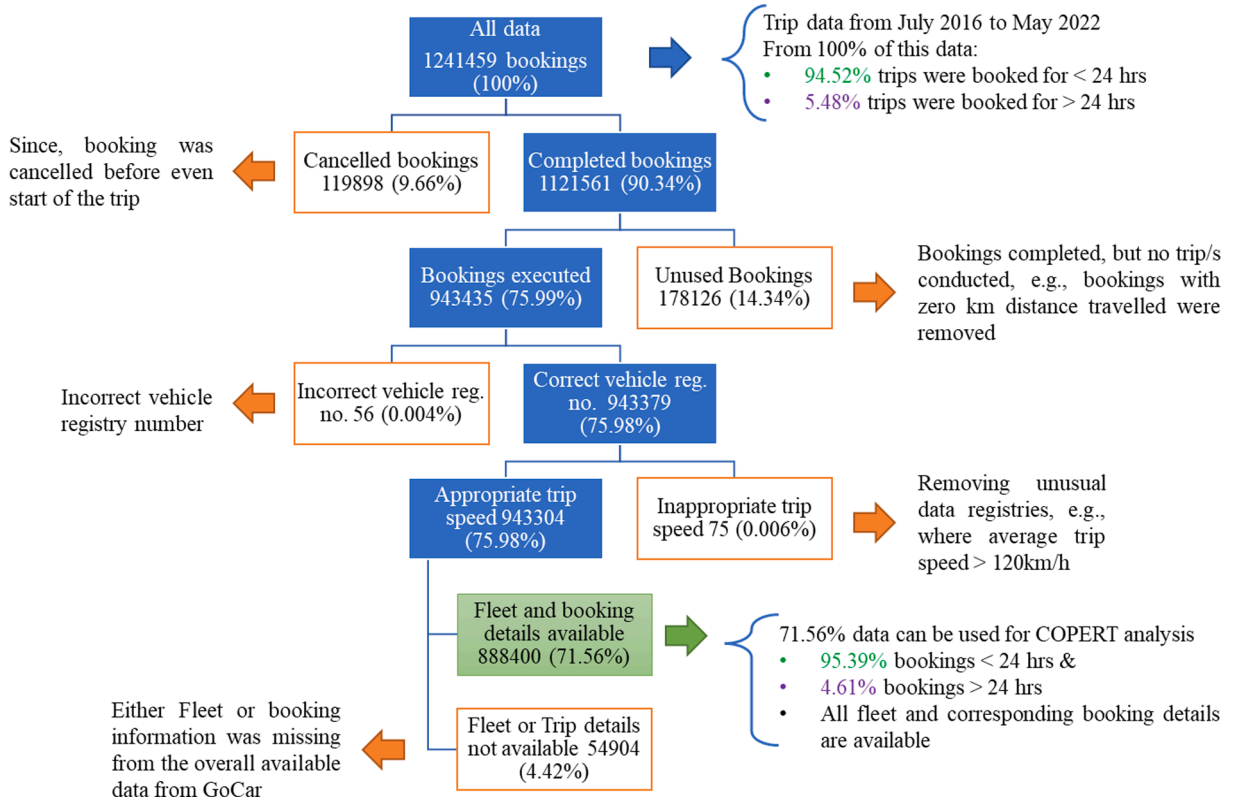


Fig. A1. Pre-processing of GoCar usage information data from Jan 2016 – May 2022

Table A1

Electric vehicles with their charging time and travel range.

Category	EV ID	EV Name	Fast		Normal		WLTP Range [km]
			80 kW	50 kW	11 kW	7.2 kW	
PC	PC.EV.1	KONAElectric	—	64 min	—	9 h 15 min	484
	PC.EV.2	Renault ZOE	—	65 min	—	9 h 33 min	317
	PC.EV.3	NISSAN NEW LEAF XE	—	60 min	—	7 h 30 min	270
LCV	LCV.EV.1	Renault Kangoo Z.E.	—	4 h 5 min	—	6 h	270
	LCV.EV.2	eVito Panel Van	35 min	—	6.5 h	—	314

Table A2

Calculation of available percentage of travel range.

Scenarios (X)	Assumptions (i)	Efficiency ($E_{(X,i)}$, %)	Total Efficiency* (TE_X , %)	Reduction ($100 - TE_X$) %
A	A1 Travel range reduction by 20 % considering driving style and regional topography, i.e., 80 % efficiency	80 %	80 %	20 %
	A2 Battery is charged to 100 % capacity	100 %		
B	B1 Same as A1	80 %	64 %	36 %
	B2 Battery is charged to 80 % capacity	80 %		
C	C1 Same as B1	80 %	35.8 %	64.2 %
	C2 Same as B2	80 %		
	C3 Battery degradation over time by 20 %, i.e., remaining efficiency 80 %	80 %		
	C4 Battery capacity reduced by 30 % due to weather condition (15 °C when compared to 25 °C), i.e., remaining efficiency 70 %	70 %		

*Note: Total efficiency (TE_X) for each scenario X is calculated using equation A(1).

$$TE_X = \prod_{i=1}^n E_{(X,i)} \quad (A1)$$

where, X belongs to scenario A, B, or C; n is the number of assumptions considered in each scenario X and $i \in \{1, \dots, n\}$; and $E_{(X,i)}$ is the efficiency in travel range for each assumption i in scenario X .

Table A3

Type of fleet considered for emission estimation scenarios.

Category	Fuel	Segment	Euro Standard
PC	Petrol	Small	Euro 6 a/b/c
PC	Petrol	Small	Euro 6 d-temp
PC	Petrol	Small	Euro 6 d
PC	Diesel	Small	Euro 6 d-temp
PC	Diesel	Medium	Euro 6 a/b/c
PC	Diesel	Medium	Euro 6 d-temp
PC	Electric	Small	Euro 6 a/b/c
PC	Electric	Medium	Euro 6 d-temp
PC	Electric	Large-SUV-Executive	Euro 6 d-temp
PC	Electric	Large-SUV-Executive	Euro 6 d
LCV	Diesel	N1-II	Euro 6 d-temp
LCV	Diesel	N1-II	Euro 6 d
LCV	Diesel	N1-III	Euro 6 d-temp
LCV	Diesel	N1-III	Euro 6 d

Note: PC: Passenger Car, LCV: Light Commercial Vehicle, LCA: Lifetime Cumulative Activity.

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