cenex

Lowering your emissions through innovation in transport and energy infrastructure

MAR 2022

Transport

Energy Infrastructure

Knowledge & Enterprise

Project RUBICON:

Final Dissemination Report

UKRI Innovate UK

EMPEL SYSTEMS

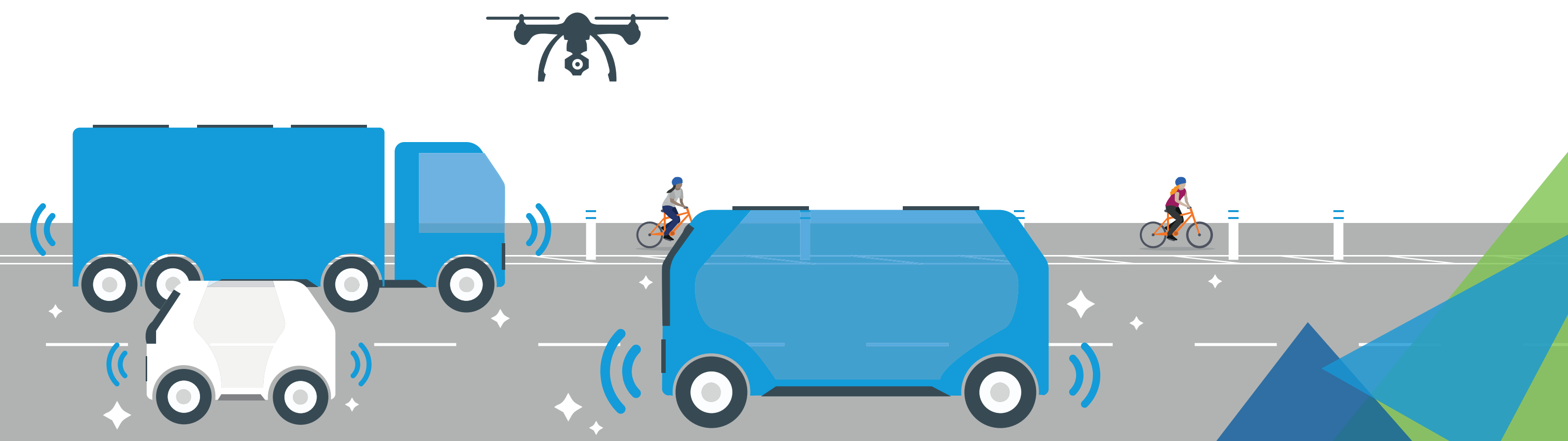
HEXAGON MANUFACTURING INTELLIGENCE

Contents

Documents in this Series

This document is the second of two documents in this series entitled "Future Mobility Insights: Ultra-durable Powertrains for Autonomous Vehicles" and "Project RUBICON: Final Dissemination Report" authored by Cenex for Project RUBICON.

You can view the first report here.



Executive Summary

The Hypothesis

Commerce relies on business models to define the products that are supplied to the marketplace. Success relies on identifying the right product for each market. For over 100 years, the automotive industry has been based on the same general business model i.e., passenger cars sold to owner-drivers who operate the vehicles for limited periods each day. Over time, cars have become more than just a mode of transport – they have become a statement about that person, their status, wealth, values. 'Fashionability' of a vehicle becomes important – no one wants to be seen in a car that is too old, unless it is a 'classic'.

This business model has defined how cars are engineered – a pressure to optimise the design of a vehicle whose cost is minimised and experienced quality is maximised at the showroom door, and which is designed to operate successfully for an expected, typical duration (time and/or distance) for the private owner. Considerations of maintainability and durability are considered only if they contribute to the expected life of the vehicle – going beyond this may not help.

It has been suggested that the forthcoming arrival of connected and autonomous vehicles (CAVs) will change this. With increasing urbanisation and traffic density, it may be possible that urban personal transport will be provided by autonomous taxis that are no longer owned by private individuals, but operated as part of a commercial fleet. These vehicles would operate with much higher levels of utilisation, accumulating far higher mileage within a few years.

The targets and requirements for the engineering of such vehicles would thus be very different, and yet to date, product design specifications for cars are based on 'business as usual'. Should such CAVs become a reality, the alternative business model could become viable, leading to radically different engineering requirements for vehicle design.

Project RUBICON

The Innovate UK-funded project RUBICON (ultRa dUraBle electrIC pOwertraiNs) aims to design an ultra-durable powertrain for CAVs and assess its commercial and environmental case in future deployment scenarios. This report summarises the results of a study investigating CAV duty cycles, their potential deployment numbers in London, and the commercial and environmental case for CAV taxis (referred to in this document as robotaxis). This report is primarily written for stakeholders in the innovation community, and policy makers in local and national government to help create a better understanding of the potential volumes and business case for robotaxi services and the role that CAVs can play.

The project aims to answer several research questions.

- **Is it possible to design a powertrain that can last over one million miles?**
- **Under which conditions can a fleet of robotaxis achieve annual distances of 100,000 km/vehicle?**
- **Is the ultra-durable CAV concept commercially viable?**
- **Does it make sense from an environmental point of view?**

The last two questions are key to evaluate the success of the project and have been frame worked within a graph indicating cost to the user (in $/km) in the horizontal axis, and life cycle emissions (in gCO2e/km) in the vertical axis. Our aim is to place the RUBICON vehicle as close to the origin as possible and compare it to other passenger cars in the same graph, while ensuring the vehicle is engineerable, designable, and can achieve realistic high mileage duty cycles.

Executive Summary

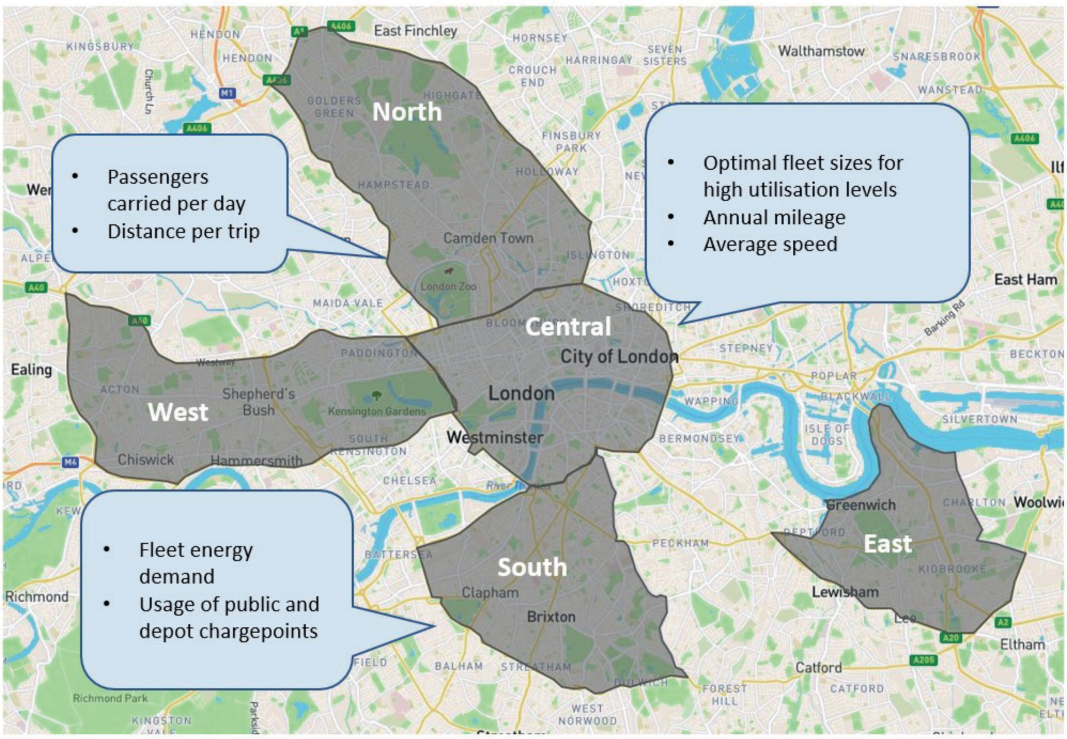
Engineering challenges of designing for ultra-durability

The current business model for the automotive industry shapes the way that vehicles are engineered. The overwhelming effort is focussed on maximising that quality (performance versus cost) of the interaction with the customer in the showroom. The durability performance needs to be sufficient to maintain the reputation of the brand to safeguard that showroom interaction, but little else. This limits how much effort a manufacturer invests in a vehicle's durability, simply because there are diminishing returns.

The arrival of autonomous vehicles, alongside societal changes, may see this alter. An increasingly urban dwelling population with a concern for the life cycle environmental impact of products it consumes, and thirsty for data to legitimise its purchasing decisions, could welcome a transformative business model that saves time, effort, money, and environmental damage. This would challenge the engineering practices of 100 years of the passenger car business. The requirement for extended useful life would mean that new approaches would be taken regarding how vehicles are designed and assembled, with a demand for extended durability. Other considerations would emerge such as design-for-maintenance, and the life cycle monitoring and optimisation of operation of the vehicle would go hand-in-hand with digital services such as Digital Twins and condition-based maintenance.

Duty cycle modelling

The environmental and business case evaluation exercise required an understanding of the duty cycles of robotaxis in a real-world environment. To this end, using the Immense software platform, we simulated a fleet of robotaxis in five London zones with similar sizes to level 4 CAV trials taking place currently (20-30 km2). Customer trip demand and traffic data were sourced from validated historic mobile phone signal data and vehicle telemetry, respectively, adding confidence and credibility to the simulation. To account for uncertainties in the future and analyse the sensitivity of different variables, several scenarios were modelled by varying location of chargepoints (unlimited public infrastructure, limited public infrastructure, and depot charging), types of vehicles (2 and 5-seater vehicles), and percentage of customers willing to share trips with strangers.



Executive Summary

The simulation proved that fleets could afford to be larger in zones where trip demand is higher, while still maintaining vehicle utilisation levels of more than 80%. Utilisation is defined as the proportion of time when the vehicle is not parked. For instance, in the Central London zone (which has the highest trip demand), the fleet can be as large as 500 vehicles for an 80% utilisation. When plotted on a graph, optimal fleet sizes in a vertical axis have an exponential relationship with vehicle utilisation levels in a horizontal axis (meaning a larger fleet size results in lower utilisation).

Under high utilisations and across different zones and scenarios, vehicles achieve between 105,000 and 170,000 km/year, justifying the need for ultra-durable CAVs. Annual distances decrease as the share of 5-seaters and the willingness to ride-share by passengers grow, because distances in service (with passengers) are more optimised with higher trip sharing, which is further favoured by increased number of seats. Likewise, average distance per trip increases as the proportion of shared trips grows. The modelling also showed that average trip speed is only affected by the local road network and congestion.

An average across all zones of 70 passengers are transported per day using a 2-seater vehicle; more than 26,000 passengers per year. For the 5-seater vehicles, this number increases to 100 passengers per day and over 36,000 per year per vehicle. The ratio of travelled distance in service (i.e. with passengers on-board) with regards to total distance ranges between 66% and 77%.

In terms of energy and charging, the West zone presents the highest energy requirements due to its combination of high average speed and high utilisation. The energy demand increases with higher shares of 5-seaters. One of the charging scenarios locates infrastructure only at localised depots, one in each of the five London zones. If 150 kW chargepoints are used, the ratio of required sockets to number of vehicles ranges from 4 to 11% to ensure that no vehicles need to queue for charging. The maximum number of vehicles simultaneously charging at depot is subject to peaks at certain times of the day, particularly in the early afternoon.

Environmental Analysis: Life Cycle Assessment (LCA)

To prove that the ultra-durable powertrain designed in project RUBICON, referred to as the RUBICON vehicle, can provide environmental benefits, we conducted a life cycle assessment (LCA): a technique to analyse the environmental impact of the entire life cycle of a product, from raw material extraction and acquisition, through energy and material production and manufacturing, to use and end of life treatment and final disposal. We used a variety of data sources for this analysis: results from the duty cycle modelling, bills of materials provided by Hexagon and Empel, literature, specialised LCA software, and vehicle modelling to estimate driving energy consumption.

The RUBICON vehicle (a 2-seater CAV with an ultra-durable powertrain) provides an 8% reduction in global warming potential (GWP) during the production phase, compared to the baseline (the same vehicle with a normal powertrain), and a 4% reduction in the total LCA GWP. Even though an ultra-durable powertrain is heavier and larger than a normal one, the reduction in the number of component replacements across the vehicle lifetime still enabled a GWP reduction. Since the ultra-durable philosophy was beneficial, we investigated high-level scenarios to make other components ultra-durable too. For instance, using a 50% smaller battery and making it ultra-durable would enable total LCA GWP savings of 24% compared to the baseline. On top of that, making the CAV subsystem (cameras, sonar, etc.) and the glider (chassis, interior, etc.) ultra-durable too would enable total LCA GWP

Executive Summary

savings of 42%. Considering the range of scenarios, the RUBICON vehicle LCA GWP ranges between 30 and 45 gCO2e/km, which is lower than small sized BEVs.

Business Case Analysis

The business case assessment aims to answer the question: how much would a fleet of robotaxis need to charge customers (in $/km fare) to achieve a reasonable payback period of 3 to 5 years from the initial investment? To answer this, we have not only considered vehicle costs, such as capital costs, maintenance, electricity, chargepoints and insurance, but also overheads, such as staff, trip booking systems, land and office rent, and marketing.

We performed a sensitivity analysis to find the variables that have the largest impact on profitability. The top three variables were trip fare, staff salary, and fleet size. We also analysed the difference between vehicle types (2 and 5-seaters) and between the four simulated London zones. Using results from the duty cycle modelling we observed that, even though the Central zone has the largest trip demand, the West and North zones provide larger profits on a per vehicle basis. This is because the annual distance for fleets with high utilisations (more than 80%) is higher in these zones, resulting in higher distances carrying passengers.

We define fleet profit as revenue minus costs, where revenue comes from robotaxis fares and costs include vehicles, electricity, chargepoints and overheads (staff, trip booking system, marketing, land and office rent). For a robotaxi fleet operator in the London Central zone running at 80% vehicle utilisation and covering 100,000 km/year, the annual total business profit is £6m for a fleet purely made of 2-seater CAVs. For a fleet only made of 5-seater CAVs, this figure drops to £1.4m. The profit per vehicle is 72% lower for a fleet purely made of 5-seaters compared to 2-seaters due to higher capital and energy costs: in the Central zone, annual profits per vehicle are £2,500 vs £12,500 respectively. This is accentuated by the fact that 88% of current UK private car trips have one or two passengers on board, hence carrying empty seats (and weight) for large proportions of time. This large difference in per-vehicle profit causes a better overall fleet profitability for fleets purely made of 2-seaters, compared to fleets with small proportions of 5-seaters.

For the range of scenarios considered and a range of fleet payback periods of 3 to 5 years, the RUBICON 2-seater vehicle cost for passengers varies between $0.42/km and $0.71/km. This is in line with BEV private car ownership costs. However, our vehicle has a lower carbon footprint and increased convenience due to the elimination of certain ‘barriers to entry’ that private car ownership presents: learning and being able to drive, capital expense of buying a car and a chargepoint, finding and paying for a parking place, etc. These barriers are currently considered acceptable due to the large cost advantages of private car ownership ($0.3/km to $0.7/km) over current taxis ($5.5/km). But if these cost advantages disappeared, the demand for robotaxis services would significantly increase.

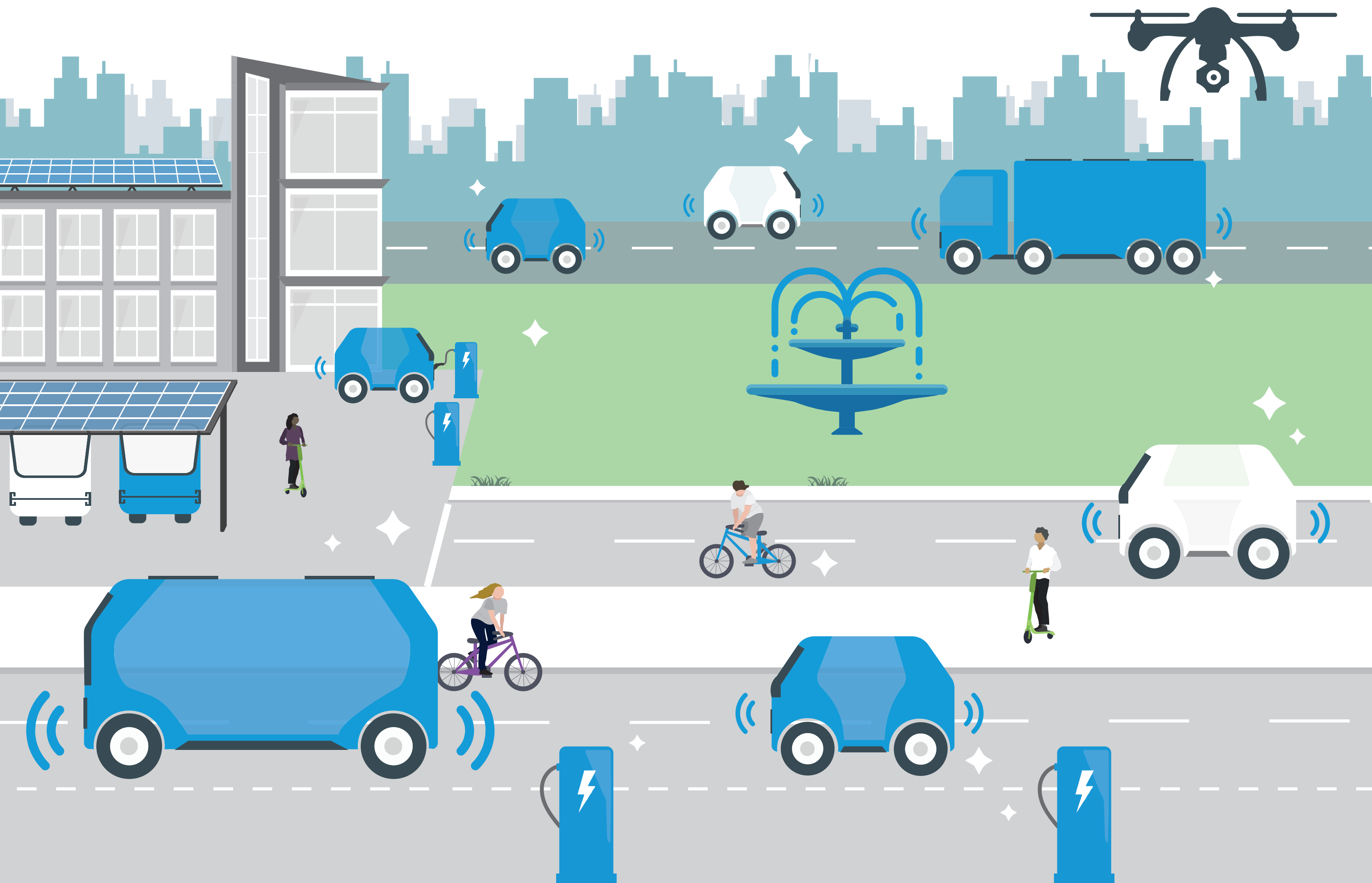
About Project RUBICON

Project **RUBICON** (ult**R**a d**U**ra**B**le electr**IC** p**O**wertrai**N**s) was a collaboration funded by Innovate UK's Smart Grants competition to design a novel powertrain by considering its entire economic and environmental "cradle-to-grave" life cycle. This powertrain was targeted for its use in an autonomous passenger carrying vehicle that has very high utilisation and runs for more than 1.5m km.

Current vehicle powertrains are typically designed for a lifetime of 250 to 500 thousand km, albeit the connected and autonomous vehicles (CAVs) of the future will likely be heavily utilised in cities achieving that mileage in two or three years. Electric powertrains will need to be more robust and durable to withstand the intensive duty cycles that CAVs will cover in their lifetimes. Therefore, there is a need to design ultra-durable powertrains to cater for this heavy-duty drive cycle.

The project team was formed of Cenex, EMPEL Systems and Hexagon. Cenex provided CAV duty cycles and explored the unique differences between future CAV archetypes and existing passenger vehicles. This involved investigating their commercial usage, high-utilisation drive cycles within autonomous mobility services, and the emissions and costs of manufacture to evaluate both the environmental and business cases.

EMPEL's expertise in the design of electric motors and power electronics combined with Hexagon's 30 years of experience in powertrain performance simulation, testing and design allowed the consortium to re-engineer the current state-of-the-art powertrains, which are designed for a life of private-ownership driving, by considering this alternative vehicle application.



Introduction: Research Questions

The hypothesis behind the project idea is that, to meet the growing transport demand in urban and suburban areas, CAVs will integrate into the wider transport network to complement public transport and active travel. The degree of how effective this integration will be is out of scope for this project but has been subject of research in the past [1,2].

The working assumption is that, in five to ten years' time, personal transport within a given city will be partly provided as a service by autonomous electric vehicles that have high utilisation and acquire high lifetime mileages of over one million miles.

The hypothesis is that the combination of no driver, high vehicle mileage and high utilisation could make the total cost of ownership and operation attractive, both economically and environmentally. This means that this transport model could be a viable business model which could compete with and displace some of the conventional urban modes of transport, such as private car ownership and non-shared taxi trips[3].

The aim of the project is to test these hypotheses and answer the following research questions:

- **Is it possible to design a powertrain that can last over one million miles?**
  - What will be the most common failure modes?
  - Which components will fail first and are therefore the critical ones?
  - How can durability be improved?

- **What is the duty cycle of the vehicle?**
  - How will our autonomous ultra-durable vehicles be used? How will they drive and charge?
  - Can they achieve very high mileages operating as robotaxis in a city?
  - What is the best type of vehicle?

- **Is the concept commercially viable?**
  - Where will the main costs and revenues come from?
  - What are the factors that impact the business case the most?
  - Under which conditions will the business case stack up?

- **Is the concept sustainable?**
  - What is the environmental benefit of ultra-durable powertrains from a life cycle assessment (LCA) perspective?
  - Will the increased production emissions from ultra-durable powertrains be compensated during their lifetime?
  - How much do powertrain efficiency improvements affect LCA impact?

[1] Autonomous vehicle ride-sharing services: Will they make cities greener, more efficient and more accessible?, MERGE Greenwich project report, 2018

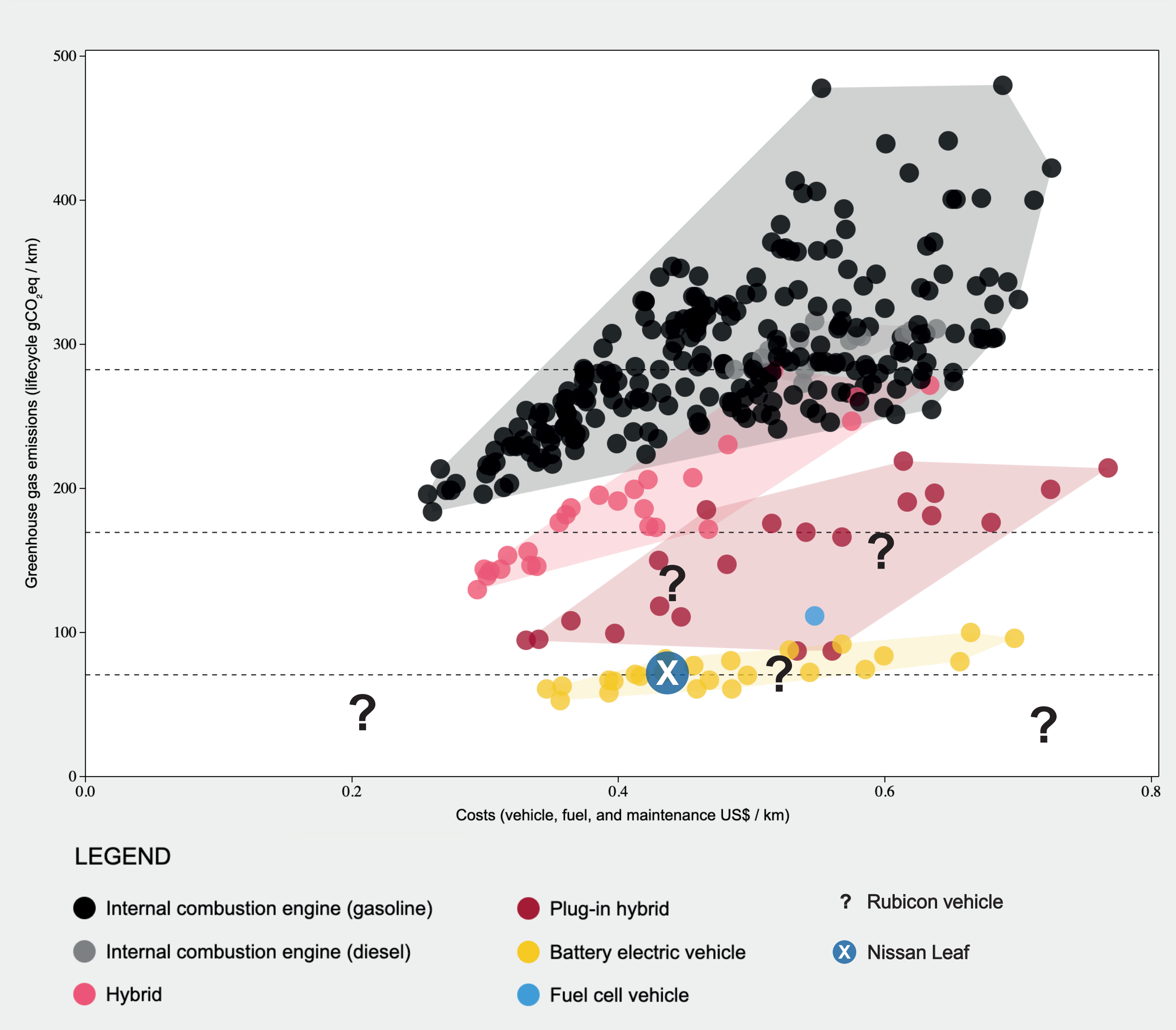
[2] Autonomous taxis and public health: High cost of high opportunity cost?, Nunes et al., 2020

[3] 'Non-shared' trips: carried out by individuals or groups of individuals that know each other

Introduction: Research Questions

Once we prove that it is feasible to design a vehicle for ultra-durability, we need to find out what the envelope of duty cycles for our vehicle will be. The duty cycle information then feeds into the calculations to determine if the RUBICON vehicle is commercially and environmentally viable. To allow a comparison of its environmental performance with current vehicles, we have used the Carbon Counter tool[4] developed by the MIT, which presents mainstream vehicles in an emission versus cost graph and classifies them by powertrain as shown below.

The objective is to be as close to the origin as possible while ensuring the vehicle is feasible to design and can fulfil realistic duty cycles. In our analysis, we have used the same assumptions as the Carbon Counter tool to enable a valid comparison with the vehicles in it. But before determining the location of the RUBICON vehicle in this graph, we will first explore the engineering challenges of designing for ultra-durability, as well as the duty cycles that our vehicle will likely undertake.



[4] https://www.carboncounter.com/#!/explore, methodology detailed in Miotti et al., Personal Vehicles Evaluated against Climate Change Mitigation Targets, Environmental Science & Technology 2016. Tool costs and vehicles updated in 2021.

Engineering Challenges of Designing for Ultra-Durability

The qualitative justification for an ultra-durable CAV is that the cost per mile and the environmental impact per mile would be reduced over the vehicle lifecycle by substantially increasing the lifetime distance covered by the vehicle.

This opportunity does not occur with owner-driven private passenger cars. Typical annual mileages of 10-20,000 miles means it takes 10-20 years for 200,000 miles to be covered, which, when combined with a 'safety margin' for variations in manufacturing, usage and other unquantified influences, is the typical mileage durability of conventional powertrains. By then the vehicle is looking tired simply in terms of styling, and the entire vehicle is scrapped by the private owner once a 'major repair bill' comes along.

The change to a high utilisation model and fleet ownership removes this constraint, providing a reason to engineer powertrains to a higher level of durability. However, this qualitative justification needs to be backed up by a quantitative assessment, to determine the magnitude of this economic and environmental advantage, and for this some detailed engineering design and simulation is required.

Design of an Ultra-Durable Powertrain based on Current Technologies

Powertrain design does not stand still – technological innovations arise on a continual basis, and this, in itself, provides the opportunity for powertrains to increase their durability. Many such technologies were available for consideration at the start of the project. However, their benefits often take time to prove out in practice. Since the RUBICON project already relies on a major technological advance – the legislative approval for operating autonomous vehicles in an urban environment – to avoid stacking uncertainty upon uncertainty, the ultra-durable powertrain design was based on a reasonably conservative approach and the use of well-established methods.

The best way of quantifying the durability/reliability of a vehicle, or a component within a vehicle, is to simulate it. This way, an improved design could be proposed with improved reliability quantified. Invariably improved reliability comes with increased cost, so the study should identify what the cost/benefit trade-off is.

Gearbox

The ultra-durable powertrain consists of the gearbox, motor and inverter. Electric vehicles gearboxes invariably have fewer ratios than the multi-speed ones in petrol or diesel vehicles and are often single speed. The conventional business model for all privately-owned passenger cars drives increasing power density, creating a smaller gearbox, light and cheap to manufacture. Having a larger gearbox runs counter to this: it is heavier, more expensive (more material) and takes up more space. However, it is possible that such a larger gearbox makes sense within the context of a Transport as a Service (TaaS) vehicle that runs for substantially increased distances, especially when the total life cycle cost (economically and environmentally) is considered. During the project, Hexagon modelled and simulated various gearboxes using its Romax software package for gearbox design and simulation. The cost/benefit of different designs in terms of packaging, weight, durability and cost has been simulated, feeding data towards the vehicle-level assessments of economic and environmental life cycle performance.

Engineering Challenges of Designing for Ultra-Durability

Motor

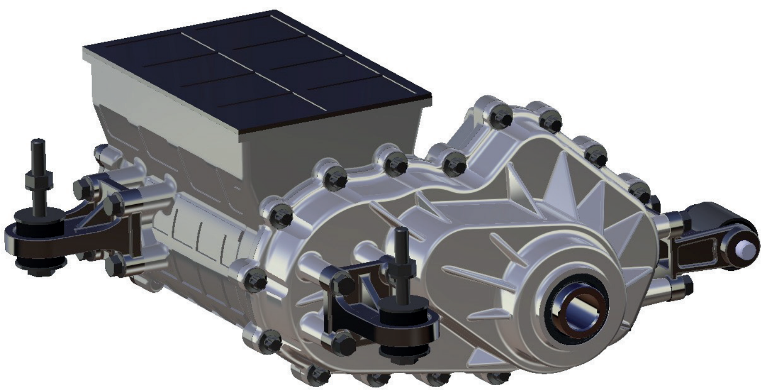
It has long been hoped that replacing the internal combustion engine with an electric machine would increase vehicle reliability. RUBICON has sought to simulate the failure modes of electric machines and quantify the benefits arising from design changes with a view to ensuring that this potential for improved reliability secures the goals of the TaaS operating model. A study into the oversizing of an electric machine for improved durability was carried out. As with the gearbox, this runs counter to the design approaches normally encountered in vehicle development projects, but there are good reasons to consider this for a TaaS vehicle. Increasing the size of an electric machine reduces electric current requirement, thereby reducing the thermal losses and the heating. This in turn reduces the peak winding temperature, which reduces the rate of winding degradation and hence improves reliability. Whilst certain aspects of this 'chain' of physical influences are difficult to simulate with certainty, current best practice methods do indicate that there is merit in this approach.

Inverter

The inverter is a power electronics component that converts the direct current (DC) provided by the battery into alternating current (AC) for the motor, and vice versa. The simulation toolchains used by Hexagon for the shock loads and thermal performance of the gearbox and the motor can also be used to study the inverter. Shock loads from the road get passed through the powertrain mounts and into the structure of the inverter, generating stress cycles in the inverter junctions. Similar cycles arise from thermal cycling. At this stage validated models do not exist and this is an area of on-going research. Instead, empirical-based models have been used to identify the likely cost of improvements to manufacturing quality and robustness, with associated reliability improvements. Such work has a solid basis – the experience of Hexagon's Applied Solutions team extends to other industries where fault-tolerant designs, with no single point of failure, is commonplace and delivers higher levels of reliability. All of this comes at a cost that is, on current commercial models, unacceptable for the automotive industry.

Potential for further steps to enhance powertrain durability

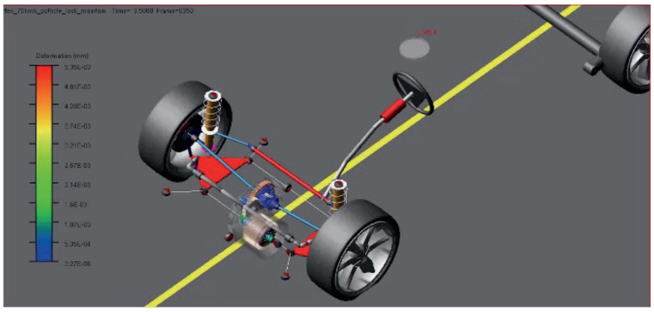
The design of the project's ultra-durable powertrain was thus completed on a 'like-for-like' basis, using well-established approaches but using a radical change to the design philosophy. Thus, the approach gave a quantified increase in weight, material and cost for inclusion in the life cycle economic and environmental assessments. The CAD model of the Hexagon-designed ultra-durable powertrain is **shown below.**

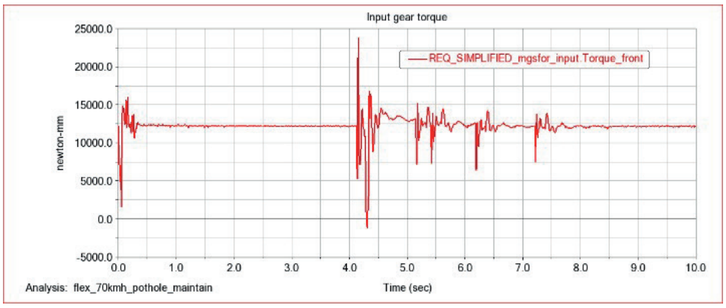


Whilst the design data for the ultra-durable powertrain was based on a 'like-for-like' comparison with conventional designs, the project also highlighted potential areas of development that could yield additional benefits and thus further extend the powertrain
durability.

It has long been recognised that 'shock loads' have a major influence on gearbox durability. These loads arise from driving over potholes, kerb climbing, etc. Experience has indicated that these can be in the region of twice the maximum motor/engine torque, and so clearly, they have an impact on the gearbox durability. Hexagon's simulation model of a vehicle driving over a pothole with the associated gear shock load is **shown at the top of the next page**.

Engineering Challenges of Designing for Ultra-Durability





The problem is that when an automotive manufacturer develops a vehicle for private use, the company has little idea as to exactly how the vehicle will be driven – aggressively, passively, on smooth road, over rough ground? Should a vehicle be designed based on a bad shock load, a **crazy** shock load, or a **totally insane** shock load? If we accommodate the 0.001% most extreme users, then 99.999% of users carry with them excess material for the life of the vehicle.

Similarly, once a vehicle is released, if a vehicle suffers a fatigue failure the manufacturer can only judge the vehicle usage by the odometer reading. A great deal of uncertainty remains.

The move to a CAV changes a lot of this. The vehicle is in control of how aggressive the acceleration is, so 'idiot starts' become a thing of the past. Additionally, as the vehicle drives over a pothole and experiences a shock load, there is potential to use this data. The location of the pothole could be recorded, so that next time the vehicle drives more sedately in that specific location, or at least along highways that have low instances of shock loads. Such information could also be shared with other vehicles in the fleet so that the entire fleet 'learns' from experiences of each vehicle and builds up a complete picture of the road conditions in the (limited) areas of operation of the TaaS fleet.

The project was also able to show how such data could be used in the development of a Digital Twin of the gearbox. The term 'Digital Twin' has been used and misused in recent years, but Hexagon believes that it correctly refers to a simulation model that resides alongside a physical asset, providing information on its health and performance based on real-life loading and other environmental factors.

A dynamic model of the vehicle powertrain was created and simulations carried out. This included not just the gearbox, motor and inverter, but the corresponding systems that define the shock loads on the powertrain – the road surface, tyres, suspension and driveshafts. All of this was used to develop an understanding of how the driving style of the vehicle (either from the human driver or the autonomous driving system), the road surface, and the vehicle design parameters (powertrain mount location and stiffness, vehicle suspension properties) affect the shock loads and hence reliability of the powertrain and the rest of the vehicle.

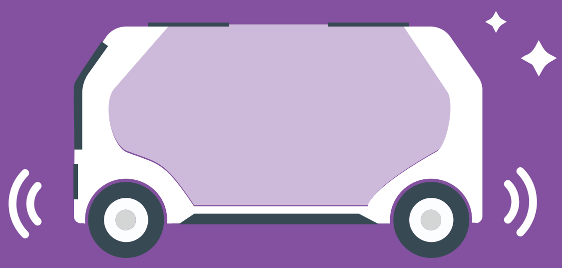
The transition to an autonomous fleet provides further opportunities that arise from two additional changes. In privately-owned vehicles, decisions on reliability are based on a sample of one (a single vehicle), and data regarding the vehicle usage belongs to the individual, limiting the potential for data analysis. The statistical uncertainty in any reliability prediction means that valid predictions regarding system reliability are difficult to justify when considering the single vehicle. However, when operating the fleet, all vehicle data is owned by the fleet operator, pertains to the same vehicle design, and the statistical spread of predicted outcomes mean that cost/benefit calculations that pertain to a fleet of many vehicles are still valid.

When combined, this provides a tantalising opportunity to deliver tangible engineering, economic and environmental benefits from the use of Big Data, feeding into a viable and useful Digital Twin of the powertrain and, in time, the whole vehicle. A clear roadmap identifying further development actions has been formulated, which also anticipates delivering supplementary benefits to the industry for human-driven vehicles, well before autonomous vehicles get their legislative approval.

Duty Cycle Modelling: Methodology

Justification for duty cycle modelling

When fleet operators want to deploy a fleet of robotaxis in a city, they will need to estimate the number of vehicles they deploy, size of their depot, ideal charging locations, number of chargers at depot, peak energy requirements to identify if a grid upgrade is needed, amongst others. The outputs of our duty cycle modelling below would be used to design and optimise a CAV robotaxi service by fleet operators and businesses alike.



Selection of model type and platform

An analysis of the Total Cost of Ownership (TCO) and Life Cycle Assessment (LCA) of a fleet of Level 4 CAV electric robotaxis in 2030[5] requires an understanding of their duty cycles in a real-world environment: we used London as our case study city. Due to the variable nature of traffic conditions in an urban area throughout the day, duty cycle statistics take values within wide ranges. The consortium agreed that the best way these values could be estimated would be using traffic modelling software.

Microscopic simulation (microsimulation) modelling represents the road network with a great level of detail and each vehicle is represented individually. Whilst microsimulation would have provided the level of detail required, the development of a validated base model of a large area of London was unachievable, as the labour and data input required would have been in excess of the resources available to the project. Therefore, an alternative solution subject to the criteria below was sought:

- The platform to be used should incorporate a ready-to-use validated base model of London.
- It should be able to provide all desired outputs to a sufficient level of detail (individual vehicles and chargepoints, to short time intervals).
- Configuration and simulation of a wide range of scenarios should be relatively fast.

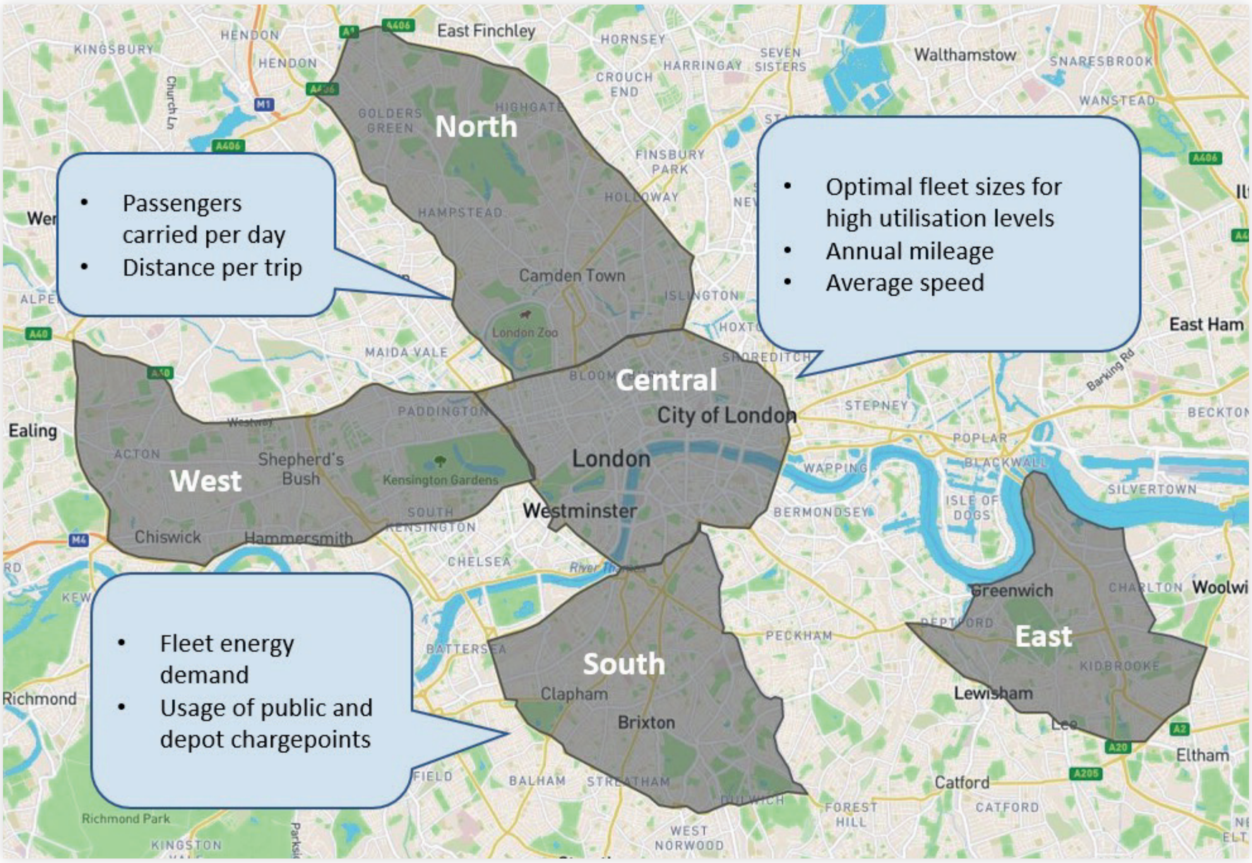
Upon engagement with industry players, a modelling solution providing all the above was identified: Immense Fleet. Immense is an online modelling platform which provides up-to-date validated base models of multiple metropolitan areas worldwide.

Spatial and temporal extents of the model

The definition of Level 4 CAV means that these vehicles are fully autonomous within the boundaries of a limited area, where they have the information they need to operate safely. Whilst the typical extension of a Level 4 CAV area may increase over time, it is not clear whether by 2030 this could cover all London. Hence, smaller areas which could be serviced by current Level 4 CAVs were defined. Desktop research was carried out to understand the typical area of a Level 4 region in recent trials, and an area of 20-30 km^2 would be in line with the current state of the industry. **The map on the next page** shows the four areas in London that we selected, all within this size range.

[5] Whereas L4 CAVs are already being trialled and are expected to be deployed at scale between 2025 and 2030, there is a consensus across the industry that L5 CAVs are not to be expected until 2035, which represents too long a horizon for our project. Our use case is therefore L4 CAVs.

Duty Cycle Modelling: Methodology



All scenarios were run over 24-hour periods. This ensured that variable traffic conditions during the day and their impact on duty cycles, energy consumption, vehicle demand and vehicle utilisation, were captured. We deemed that a central day of the week, Wednesday, would be representative of typical traffic conditions in the modelled areas.

The data behind the base model

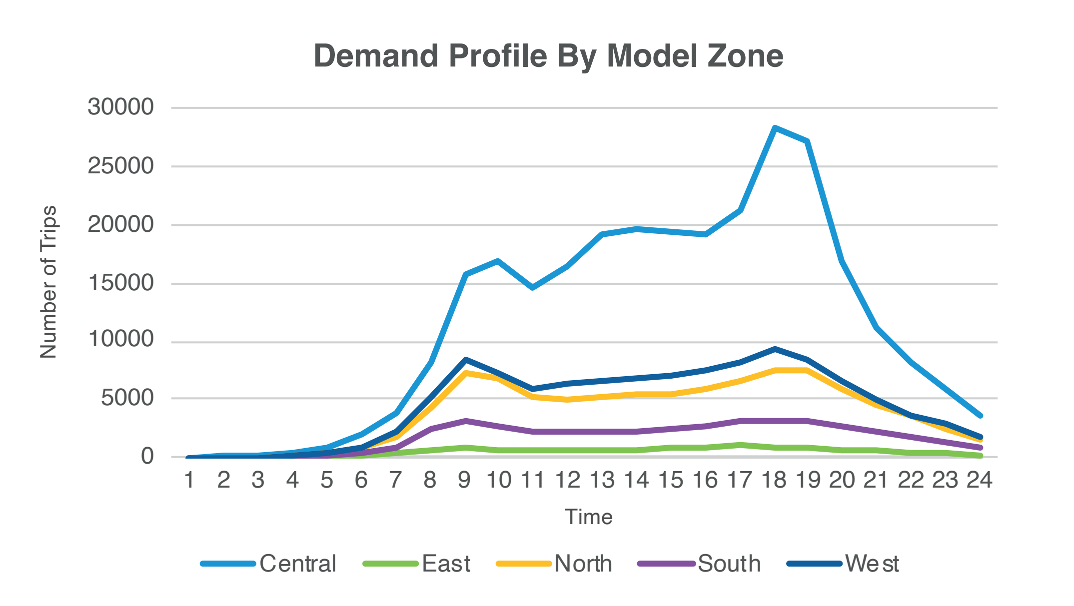
The traffic data driving the model is vehicle telematics data from a 3-year rolling average, covering 2018, 2019 and 2020. This is weighted so that less importance is given to times with reduced traffic volume, reflecting seasonality and the impact of COVID restrictions. The data describes the time taken to traverse the road network at different times of day. Whilst predictions on traffic levels are available from public sources, it was agreed that duty cycles of Level 4 CAV robotaxis would not be significantly different whether current or 2030 traffic conditions were used. Likewise, the road network and its capacity are expected to change over time. However, due to the spatial and temporal extension of the models, this is not deemed to compromise the validity of the conclusions extracted from them. Consequently, it was agreed that all scenarios would be assessed in the existing validated base model of London.

Trip demand data in the model results from processing a data sample provided, under license, by a large mobile phone operator. The sample relates to users of the operator's network, which has been expanded to cover the entire population. This data reflects the movement of people over time and, for each trip, it provides its origin and destination coordinates, as well as the time that the trip starts and ends. The modelled robotaxi service operates 'on-demand', the passengers need to pre-book trips by phone or app.

Duty Cycle Modelling: Methodology

To estimate maximum potential demand for our robotaxi service, a review of existing literature on the matter was carried out. A report[6] by the Greenwich Merge consortium[7], based on bespoke surveys carried out for their study, estimates that around 46% of all users would be willing to use ride-sharing transport services. Demand for a future robotaxi service is likely to derive from current private car and taxi users, as these are the most similar modes in terms of costs and utility.

Hence it was assumed that 46% of current car and motorcycle users, as well as 100% of taxi users, would be the target demand of the service. The combination of these users represents a 17.6% of all current trips in London. This target percentage was applied to the total transport demand in each of the five Level 4 CAV zones previously defined, resulting in the 24-hour **profile below**.



Demand data in the model does not contain information on number of passengers per trip. This is an important input, as it determines the compatibility of two or more trips to share a single vehicle. Data on trip occupancy was obtained from DfT[8], which is presented in the **table below**. These occupancies were randomly assigned to the trips in the demand file provided by Immense.

OCCUPANTS	PERCENTAGE OF TRIPS
1	62%
2	26%
3	7%
4 or more	5%

Approach: Simulation of Scenarios

Given the uncertainty over some of the inputs in the model, and the interest to understand how several constraints may affect the technical viability and business case of the future robotaxi service, it was decided that a sensitivity-testing approach was to be employed.

We identified several key variables expected to have a significant impact on the results and, for each one, a range of values was used in the model. **These are shown in the table on the next page.**

[6] Autonomous vehicle ride-sharing services: Will they make cities greener, more efficient and more accessible?

[7] Addison Lee, Catapult, Ford, Immense and TRL

[8] NTS0905: Car occupancy, England: since 2002. Vehicle mileage and occupancy, statistical data set, DfT.

Duty Cycle Modelling: Methodology

VARIABLE	DESCRIPTION	VALUES
Chargepoints	Vehicles to recharge at public chargepoints or at depot.	Public chargepoints, Public chargepoints with reduced availability, or Depot.
Vehicle types	Seating capacity and battery size.	Split between 2-seaters and 5-seaters. From 100% 2-seaters to 100% 5-seaters in 25% increments.
Ride-sharing	Percentage of trips in which customers accept sharing the vehicle with other customers.	From 0% to 30% in 10% increments.

The modelling consists of 60 scenarios for each of the five zones, which result from all permutations across the three key variables, so 300 scenarios in total. The rationale for analysing these three variables and the values adopted for them is set out below.

All scenarios were simulated for a fleet of 1,000 vehicles, and results for smaller fleets were extrapolated from the larger 1,000-vehicle fleet results. However, we also ran several simulations with smaller fleet sizes to validate this extrapolation, and checked that the extrapolated results remained valid. The extrapolations enable to understand results for both small and large fleets while keeping a high level of confidence.

Chargepoints

For the public charging scenario, the existing provision of publicly available chargepoints was extracted from the National Chargepoint Registry, which Cenex manage. It is assumed that 2030 charge rates will be greater than the existing ones. Hence, the capacity of these chargepoints was uplifted to reflect forecast technological progress. Current fast chargers (7-22 kW) are modelled with a recharge rate of 50 kW, whereas current rapid chargers (50 kW) are modelled with a rate of 150 kW. The total number of sockets available for the robotaxi fleet per zone ranges from 27 (South) to 83 (Central).

To reflect that some of the existing chargepoint network will be subject to demand from other road users, public charging scenario with reduced availability was modelled. From every station, one socket was withdrawn from the model, so for this scenario the number of sockets per zone ranges from 17 (South & East) to 40 (Central).

An additional charging scenario was modelled where vehicles would only charge in one depot per zone located in the outskirts of the area, where land is expected to be cheaper. As one of the desired outputs from the model is to determine the optimum charging infrastructure of the depot, the models have been run with very high charging capacity at depot, provisioning them with 300 sockets, which is the maximum that the platform permits.

Moreover, two recharge policies were specified. A recharge policy in Immense is a set of instructions defining when vehicles in the fleet will start looking for a charger and how long they will charge for. Policies are defined by a lower and an upper boundary, both expressed in remaining range (in metres), and representing:

- **Lower boundary:** what is the remaining driving range in the battery when the vehicle starts looking for available infrastructure to recharge.
- **Upper boundary:** the minimum available range that the vehicle must have achieved before it considers ceasing the charge to go service a trip call (if no call is received, then the vehicle continues charging until completing a full charge).

Duty Cycle Modelling: Methodology

The recharge policies **in the table below** were adopted, expressed in battery state of charge (SoC).

POLICY NAME	TIME	LOWER BOUNDARY (SoC)	UPPER BOUNDARY (SoC)
Overnight	22:00 - 06:00	70%	100%
Daytime	06:00 - 22:00	40%	80%

Vehicle types

For each vehicle type scenario, we used the same battery capacity for all vehicles in the fleet. The reason is that the boundaries of a recharge policy can only be defined as remaining range in distance, and we could not define bespoke recharge policies for individual vehicle types. If we used different battery capacities within the same fleet, a given remaining distance range would represent different percentages of battery left in batteries with different capacity. This limitation was bypassed using weighted average battery capacities as per current mainstream battery electric vehicles (BEVs), which result in the vehicles shown in the table below. The energy consumption values were given by Hexagon's Concept software[9], which simulates all vehicle components to calculate energy consumption for a given drive cycle. We used the drive cycles developed by Cenex at the beginning of the project, which are representative of real-world urban taxi operation in London. We then uplifted these values to account for CAV subsystem energy use[10] and charging efficiency.

Additionally, an initial battery SoC is provided, which resulted from a ***warm-up*** simulation run carried out beforehand. This way, the battery SoC at the beginning of the simulation results from the operation in the previous 24-hour period, which is common practice within traffic modelling.

Ride-sharing

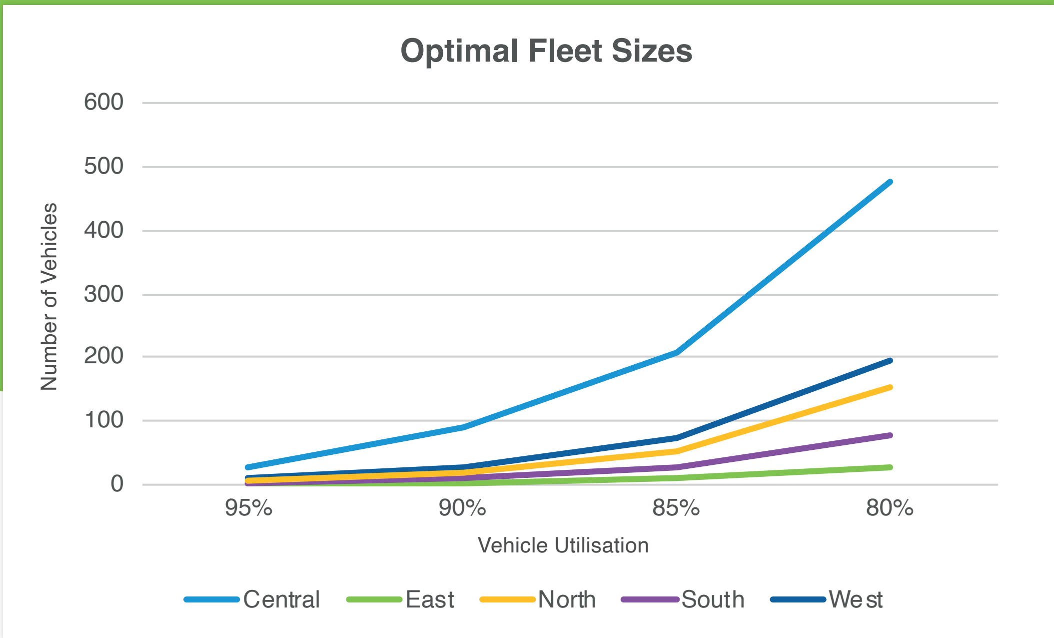
Research by the MERGE Greenwich[6] project found that 68% of all passenger trips could, in theory, be shared based on compatibility of origin-destination pairs and times of travel. However, when customer willingness to share a vehicle was incorporated to the estimation, the percentage of all trips which could realistically be shared dropped to 28%. Therefore, we decided to assess the impact of ride-sharing in the model by increasing it from 0% to 30% of all trips, in 10% increments.

SCENARIO	BATTERY CAPACITY (kWh)	ENERGY CONSUMPTION (kWh/km)	MAXIMUM CHARGING POWER (kW)	VEHICLE TYPE
100% 2-seaters, 0% 5-seaters	30	0.119	150	Battery Electric Vehicle (BEV)
75% 2-seaters, 25% 5-seaters	41	0.147		
50% 2-seaters, 50% 5-seaters	53	0.174		
25% 2-seaters, 75% 5-seaters	64	0.202		
0% 2-seaters, 100% 5-seaters	75	0.228		

[9] https://romaxtech.com/software/concept-design/

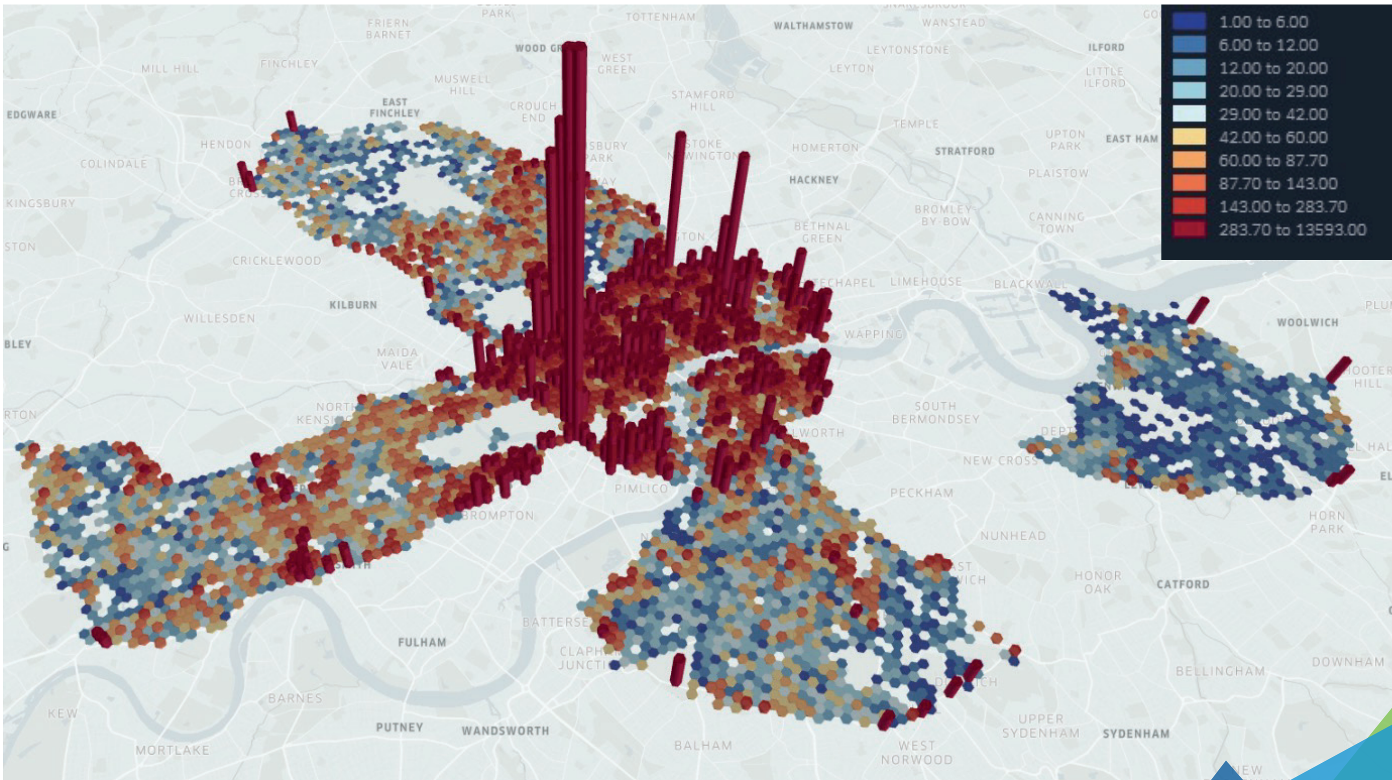
[10] Gawron et al., 2018. LCA of CAVs: sensing and computing subsystem and vehicle level effects. Environmental science & technology, 52(5), pp.3249-3256.

Duty Cycle Modelling: Vehicle Utilisation Results

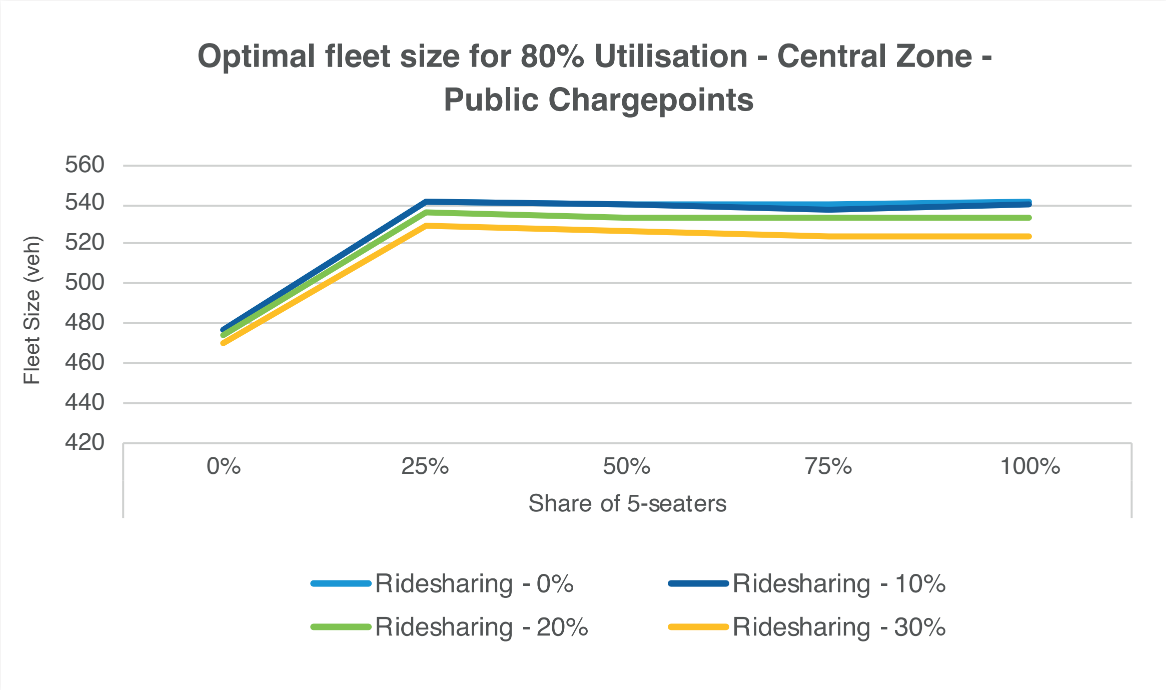


In this report, we define ‘vehicle utilisation’ as the proportion of time when the vehicle is not parked, i.e. doing something useful or meaningful such as transporting passengers, driving to pick them up, charging, etc. Cenex analysed, for each scenario, what would be the optimal fleet size to result in target utilisation levels of 80 to 95%. The **graph above** provides, for each zone and utilisation target, the average optimal fleet sizes across all scenarios.

Fleets can afford to be larger when the trip demand in the area is higher, like in the Central zone. Moreover, **the correlation between optimal fleet size and utilisation is not linear but exponential**, with R-square values higher than 0.99 for all zones. The difference between zones can be clearly appreciated **in the heatmap below**, which shows the location of passenger pickup points for a fleet of 1,000 vehicles.



Duty Cycle Modelling: Vehicle Utilisation Results

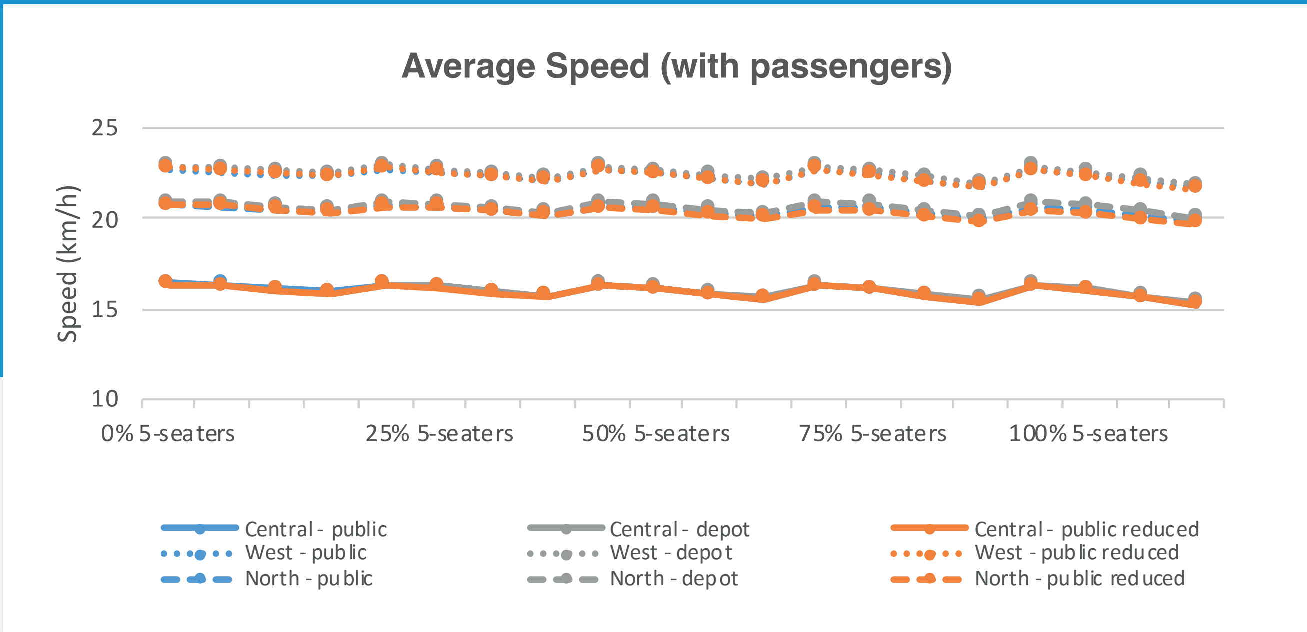


For a greater understanding of the impact of variables, scenarios with public recharge infrastructure are **presented above** for an 80% utilisation target.

As the graphs show, when there are only 2-seaters in the fleet, its size must be lower to achieve a given utilisation level. This is because 12% of trip calls are for services of three or more passengers, which can only be serviced by 5-seaters. Therefore, if the fleet is exclusively made of 2-seaters, the effective customer demand is lower than the total, and consequently the fleet size must be reduced to achieve the desired utilisation. However, once 5-seaters are introduced to the fleet, there is not a great difference in the optimal fleet size regardless of the share of 5-seaters from 25% to 100%. This suggests that **the ideal share of 5-seaters in the fleet is somewhere between 0% and 25% in all zones**. Moreover, the greater the percentage of shared trips in the model, the lower the fleet size, which is a logical consequence of single vehicles servicing more than one trip at a given time.

The optimal fleet sizes shown earlier are based on calculations, because the model was run with a fleet of 1,000 vehicles. Utilisations for a fleet 1,000 vehicles ranges from 13% in the East zone, to 73% in the Central zone.

Duty Cycle Modelling: Vehicle Operating Patterns



Average speed

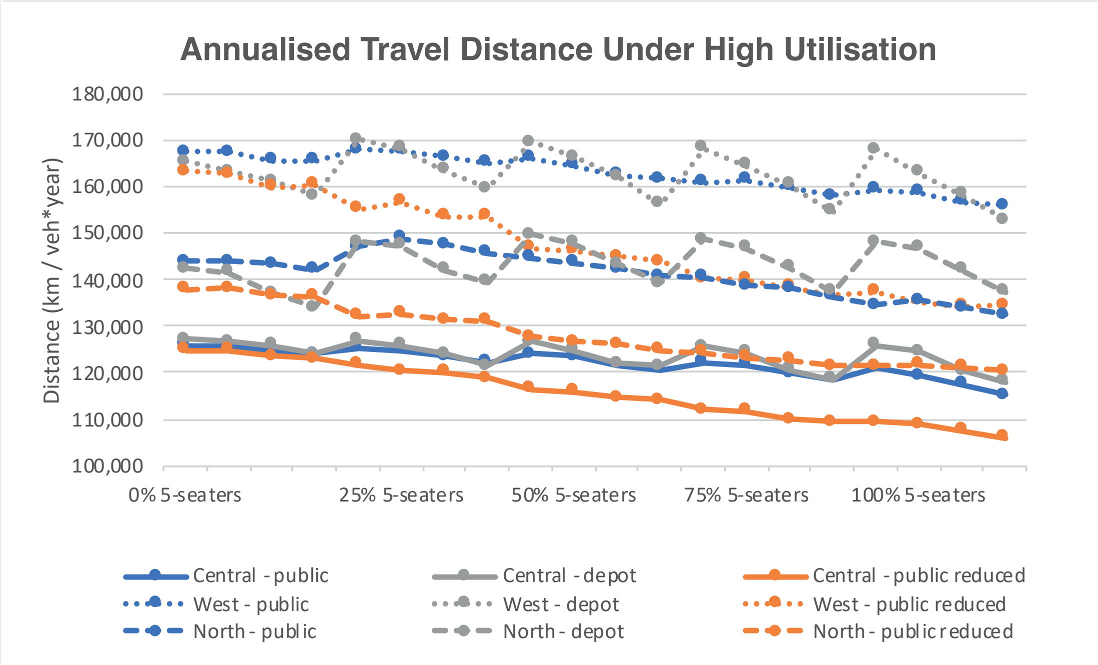
As per **the graph above**, average speeds (when transporting passengers) are nearly identical across all scenarios within each zone, meaning that **only the characteristics of the local road network and congestion of the zone affect vehicle speed**. In this and the following graphs, each dot represents one of the 60 scenarios modelled per zone. Each colour represents one charging scenario, each dash type represents one zone, and the horizontal axis represents the variation in both percentage of ride sharing and proportion of 5-seaters in the fleet. For example, between 0 and 25% of 5-seaters, there are 4 increments of ride-sharing trips (from 0 to 30% in 10% increments). South and East zones are excluded from the graph due to their low trip demand.

Annual travel distance

As the model only represents one ***typical*** day, Cenex produced a ballpark figure for annual distance by multiplying daily distance by 365 days. The large fleet size used in the models, 1,000 vehicles, may have an impact on the distance results. The greater the fleet size, the greater the relative share of idle time when vehicles do not move. Consequently, we produced an estimation for travel distance under high utilisation by extrapolating distance travelled during the hours of the day where trip demand is higher, between 8am and 8pm, to the whole 24-hour period. As shown **in the table below**, daytime (8am-8pm) utilisations in areas of low demand, such as East and South, are still very modest. The full set of annualised travelled distances under high utilisation, for all scenarios in zones Central, West and North, is provided in **the graph on the next page** using the format previously described.

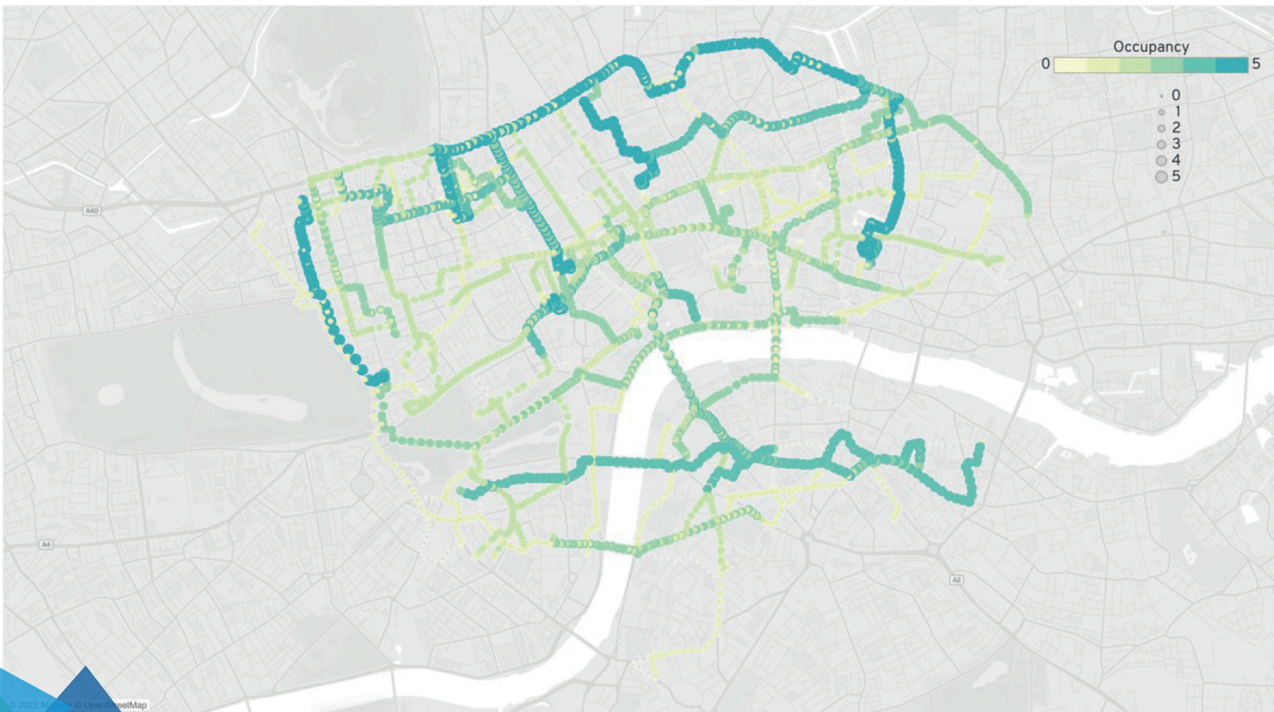
UTILISATION 8AM TO 8PM		
ZONE	**MIN**	**MAX**
Central	98%	100%
East	15%	17%
South	50%	63%
West	88%	98%
North	80%	94%

Duty Cycle Modelling: Vehicle Operating Patterns



Full results from zones East and South are not provided in this graph, since the modelled fleet is oversized against customer demand and projections on travel distance are not deemed to offer value to the conclusions of the project. **West presents the highest travelled distance** due to its combination of high average speed and high utilisation. The graph shows how, generally, **travel distances decrease as the share of 5-seaters and the willingness to ride-share by passengers grow**.

This happens because distances in service (with passengers) are more optimised with higher trip sharing. This is further favoured by increased number of seats. A representation of vehicle occupancy in the Central zone for 5-seaters only can be **observed in the map below**, where main roads usually have a higher occupancy than secondary roads. This happens because main roads are usually the intersection between routes for different passengers willing to share trips.



Duty Cycle Modelling: Vehicle Operating Patterns

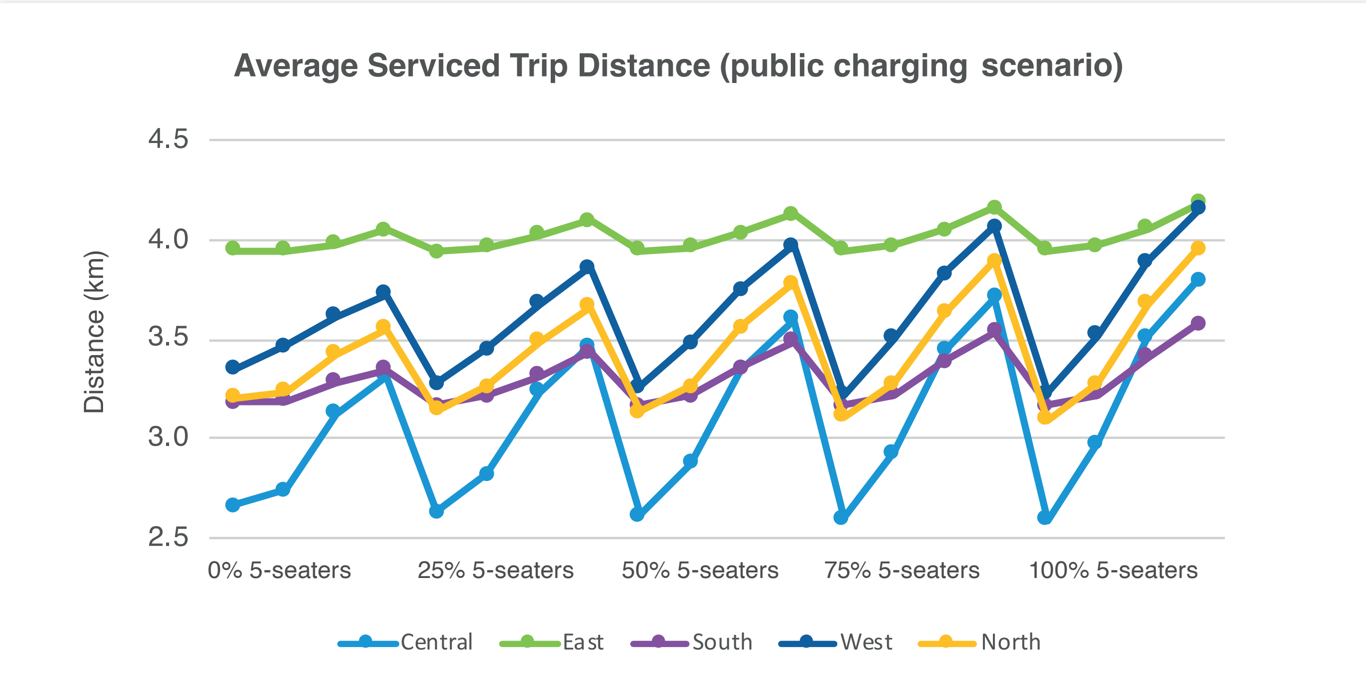
Features of serviced trips

Serviced trips are the trips in which passengers are being transported. Their distance is not affected by utilisation levels, and therefore results from all zones are presented. We observed that trip distance is neither affected by infrastructure location and availability. Therefore, for ease of reading, a comparison of different zones is presented **in the figure below** using the results from scenarios of fully available public infrastructure.

Average distance per serviced trip depends on the geographical extents and trip demand of each area, but also on the proportion of trips being shared. **There is an increase in the average distance per trip as the proportion of shared trips grows.** This is due to the diversions that services incur into in order to reach subsequent pick-up locations. Likewise, the share of 5-seaters in the fleet also impacts trip distance, due to the greater number of shared trips that 5-seater vehicles allow in comparison with 2-seaters.

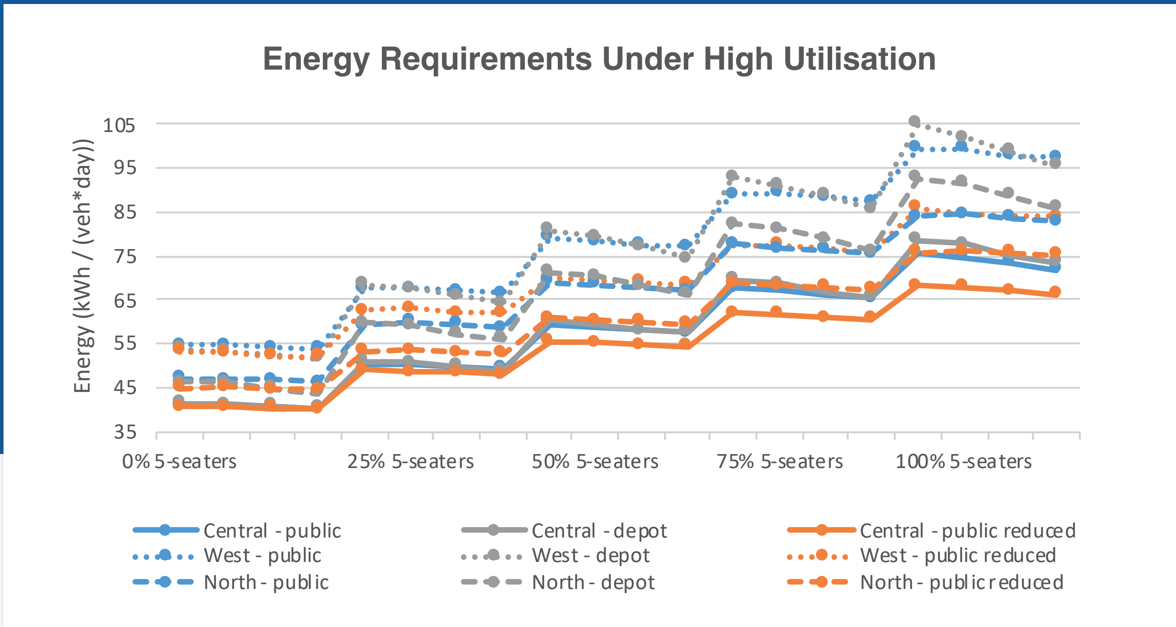
The number of serviced trips per vehicle and day is higher in zones with higher utilisation. Scenarios with high trip-sharing willingness result in the fleet servicing more trips. The number of serviced trips ranges between 45 and 75 for the Central, West and North zones. The average number of passengers per trip is 1.3 for 2-seater vehicles, which results in around **70 passengers transported per day and vehicle (more than 26,000 per year)** as an average across zones. For the 5-seater vehicles, this number increases to **100 passengers per day and over 36,000 per year**.

The ratio of travelled distance in service (i.e. with passengers on-board) with regards to total distance ranges between 66% and 77%, being slightly higher in the scenarios of public charging than in those of charge at depot. This is explained by the shorter distances driven to reach a chargepoint in scenarios of public charging, as infrastructure is spread across the city. These ratio values compare favourably with average Uber's statistics in the USA of around 60%[11], which can be explained by the relatively small size of the analysed 'level 4 CAV' zones and the lack of human drivers.



[11] Disruptive Change in the Taxi Business: The Case of Uber, Cramer et al., 2016

Duty Cycle Modelling: Energy and Charging



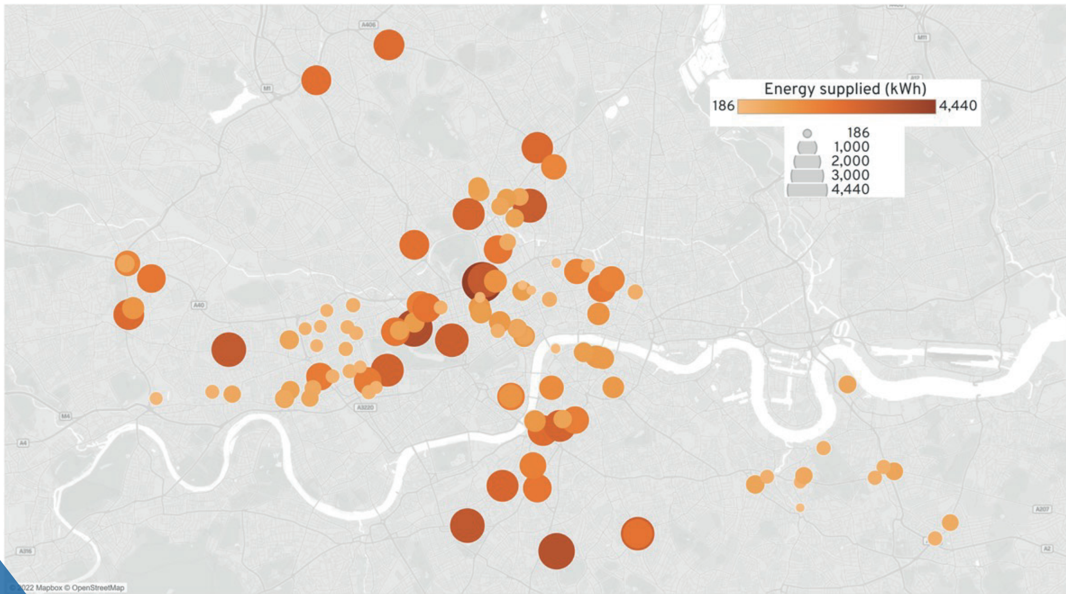
Energy requirements

An estimation of daily energy requirements under high utilisation **is shown above**, extrapolating 12-hour results between 8am and 8pm to 24 hours.

Electricity demand increases with higher shares of 5 seaters in the fleet due to their greater energy consumption. The West zone presents the highest energy requirements due to its combination of high speed and high utilisation. The daily energy requirement figures are in line with typical battery sizes for small and medium-sized BEV cars in the market today. Generally, in all zones, energy taken from the grid is the lowest in scenarios of constrained availability of chargepoints. This is a consequence of the greater time spent looking for recharge infrastructure, which results in less time available for the charge.

The **heatmap below** shows the public chargepoints classified by their daily energy supplied to a fleet of 1,000 robotaxis in all five zones (scenario of full chargepoint availability). Note that each chargepoint usually has 2 sockets, and sometimes even 3 or 4.

The higher trip demand in Central, West and North zones is again evident from this heatmap. Chargepoints that are close to the main roads are also the most used ones.

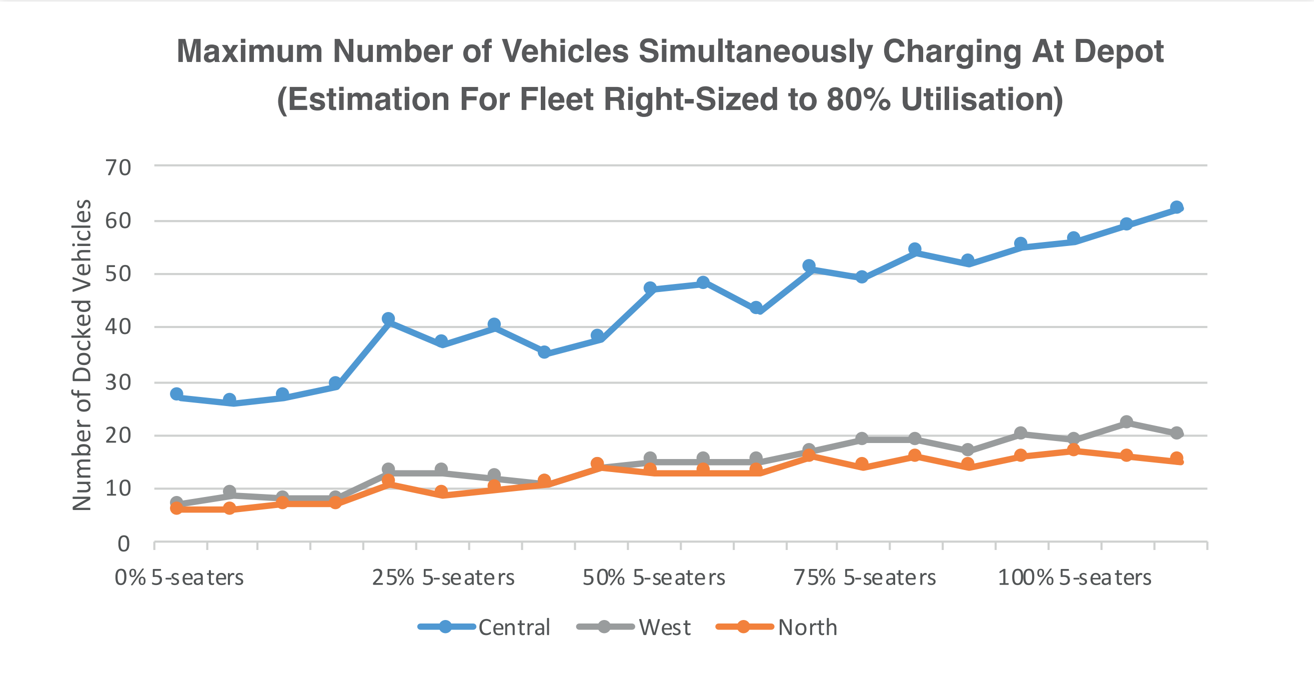


Duty Cycle Modelling: Energy and charging

Maximum number of vehicles simultaneously charging at depot

The previous example shows a scenario where the robotaxis use public charging infrastructure. Here we look at a scenario where charging is undertaken at a depot. This output provides an indication on the size of the depot (or number of vehicles) that would be needed to accommodate peaks in recharge demand. Results presented here have been extracted from the period of daytime recharge policy (6am to 10pm), excluding the rest of the day. This is because, when the overnight policy is in place, vehicles can go recharge when their battery SoC drops to just 70%, as opposed to 40% in the daytime policy. This, in conjunction with the low overnight demand, results in most vehicles going back to depot to charge during the night. However, there is more value in understanding depot requirements during the day, when customer demand is higher and coordinating fleet charging poses a greater challenge.

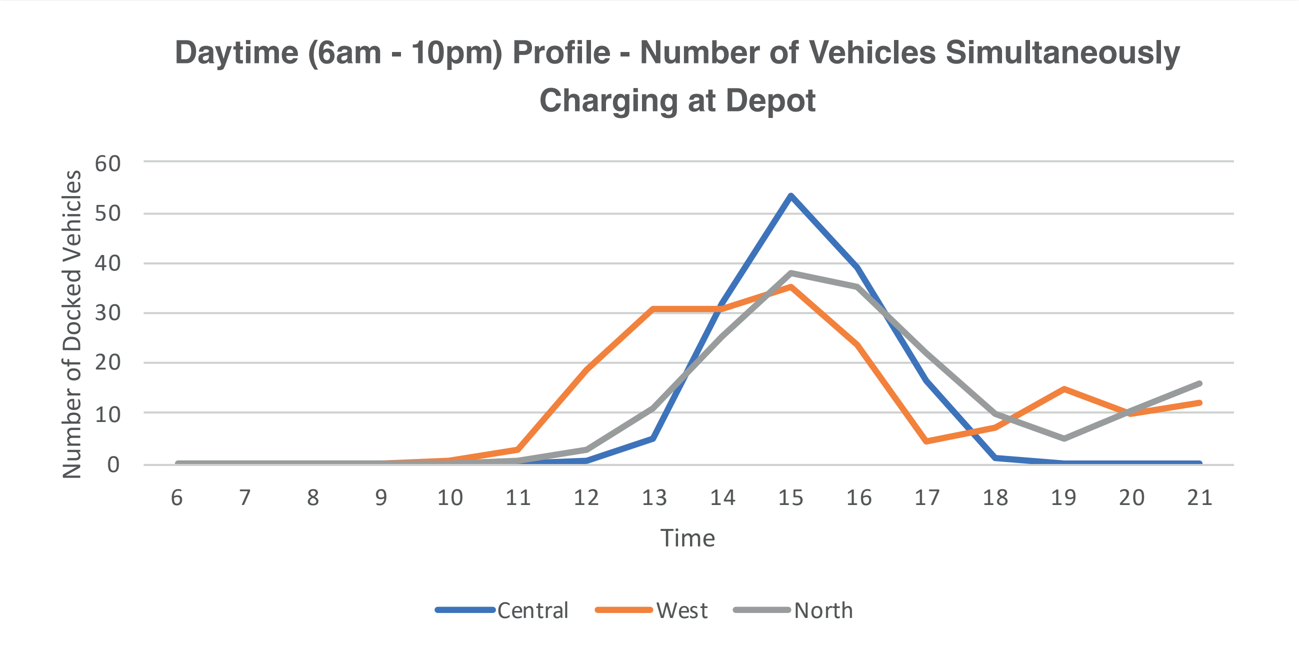
Due to the impact that large fleets of 1,000 vehicles can have in the utilisation of the fleet, Cenex made an estimation for the number of chargepoints needed at the depot if the fleet size had been optimised to target a 80% vehicle utilisation. These fleet sizes were provided previously and ranged from 155 in the North zone to 479 in the Central zone. East and South zones were again excluded from this analysis due to their low fleet sizes to achieve 80% utilisation.



The ratio of sockets to fleet size ranges from 4 to 11% (4 to 11 sockets for every 100 vehicles). Typically fleets use a ratio of sockets to fleet size of 25 to 100% when sizing their infrastructure depot today, with chargepoints ranging from 22 to 40 kW in power. However, our results are lower due to two reasons. Firstly, we assume a 150 kW charging power (reflective of likely depot power in 2030), which means vehicles can charge in reduced time windows. Secondly, the vehicles are highly utilised, which means they spend a large proportion of the time on the road, reducing the likelihood of many vehicles charging simultaneously at depot.

Duty Cycle Modelling: Energy and charging

It is worth noting that the maximum number of vehicles simultaneously charging at depot is subject to peaks at certain times of the day, particularly in the early afternoon. A daytime (6am to 10pm) profile of recharge infrastructure occupation at depot is provided **in the graph below**. For ease of reading, this is provided for a single scenario: depot charging with 50% split between 2-seaters and 5-seaters and a 20% ridesharing.



Recap: Engineering and Vehicle Use

We have already answered several of our research questions:

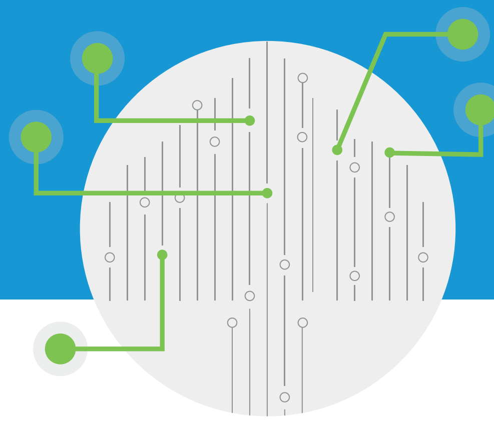
- Will the vehicle run for one million miles? How can we improve durability? We have observed how vehicles and powertrains can be designed for ultra-durability, with very long lifetimes, thanks to the insights from Hexagon and Empel. This can be achieved through detailed engineering design and simulation.
- How will our autonomous ultra-durable vehicles be used? Can they achieve very high mileages operating as robotaxis in a city? Yes, reasonably large fleets of robotaxis (400 to 500) can achieve high utilisations (and hence high mileages) if they are placed in the right areas of a city. It is important to right-size the fleet to trip demand levels to maximise vehicle utilisation.

But will this vehicle and TaaS operating model be environmentally beneficial? And will it make a reasonable business case? We will answer these questions in the following sections.

Environmental Analysis: Life Cycle Assessment (LCA)

Methodology

To prove that our RUBICON vehicle can provide environmental benefits, we conducted a Life Cycle Assessment (LCA).



To prove that our RUBICON vehicle can provide environmental benefits, we conducted a Life Cycle Assessment (LCA). This is a technique to analyse the environmental impact of the entire life cycle of a product, from raw material extraction and acquisition, through energy and material production and manufacturing, to use and end of life treatment and final disposal[12]. We performed this analysis using specialised software[13] to compare a 2-seater level 4 autonomous battery electric small vehicle with normal durability components (the baseline) against the same vehicle with ultra-durable and more efficient components (the RUBICON vehicle). These vehicles would be similar in size to a Citroen Ami, Smart Fortwo or Renault Twizy.

The raw material acquisition and production phases consider the environmental impact of extracting the raw materials, transporting them to factories, manufacturing them into components, and finally assembling them to create the final product. To model these phases, we have used Hexagon's and Empel's bills of materials for all powertrain components: gearbox, electrical machine (motor/generator), power electronics (inverter plus associated parts) and housing. For the rest of vehicle components (battery, glider and CAV subsystem) we have performed literature research[14,4]. The CAV subsystem is formed by cameras, sonar, radar, lidar amongst other electronic components. The glider comprises the rest of vehicle components that are not the powertrain, battery or CAV subsystem (i.e. chassis, interiors, tyres, etc.). The LCA software holds a vast library of data with the environmental impact from obtaining materials and producing components. Where materials or components were not available in the software, we have sourced them from literature.

The use phase is divided into 'CAV subsystem use', energy required by the CAV subsystem to enable the autonomous features, and 'Rest of vehicle use', energy required to move the vehicle forward. We obtained the CAV subsystem energy use from literature[15], while the rest of the vehicle energy use was given by Hexagon's Concept software[16], which simulates all vehicle components to calculate energy consumption for a given drive cycle. We used the drive cycles developed by Cenex at the beginning of the project, which are representative of real-world urban taxi operation in London. Finally, we assumed the average grid carbon intensity in the UK between 2019 and 2021 (both incl.). The end-of-life vehicle phase (recycling and/or disposal) was out of scope and, in any case, it typically represents a very small fraction of the LCA impact. We assumed the same high mileages, vehicle utilisation and same charging patterns as provided by the transport modelling work package described earlier.

[12] ISO 14040:2006 LCA, principles and framework

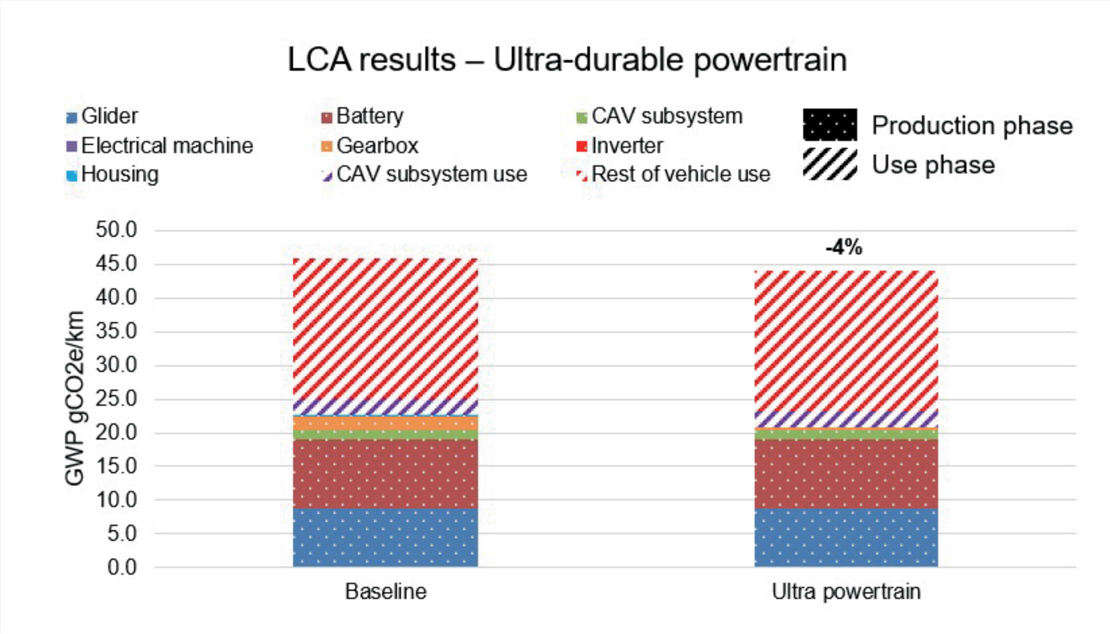
[13] Software: GaBi Professional.

[14] Bauer C et al. The environmental performance of current and future passenger vehicles: Life Cycle Assessment based on a novel scenario analysis framework. Appl Energy (2015)

[15] Gawron et al., 2018. LCA of CAVs: sensing and computing subsystem and vehicle level effects. Environmental science & technology, 52(5), pp.3249-3256.

[17] https://romaxtech.com/software/concept-design/

Environmental Analysis: Life Cycle Assessment (LCA)



Results

The global warming potential over 100 years (GWP100) is the most popular LCA impact category and is defined as the heat absorbed by any greenhouse gas in the atmosphere, as a multiple of the heat that would be absorbed by the same mass of carbon dioxide. **The graph above** shows the modelled GWP100 of the baseline and the RUBICON vehicle.

The production and use phases represent each ~50% of the GWP, which is in line with previous LCA studies on BEV passenger cars[17,18]. **Glider and battery dominate the production phase with 84% of the GWP** in the baseline vehicle. In the use phase, the GWP linked to the CAV subsystem use (powering the cameras, sonar, radar, lidar, etc.) represents 10% of the total use phase GWP. The only difference between the baseline and the RUBICON vehicle is that the latter has a powertrain (electrical machine, gearbox and inverter) with a lifetime of one million miles, as opposed to the 200,000 mile lifetime of the powertrain of the baseline vehicle. This enables an **8% reduction in the production GWP** because we only need to replace the powertrain once in the RUBICON vehicle for every five times we replace it in the baseline vehicle. The total LCA GWP gets reduced by 4% thanks to the ultra-durable powertrain components.

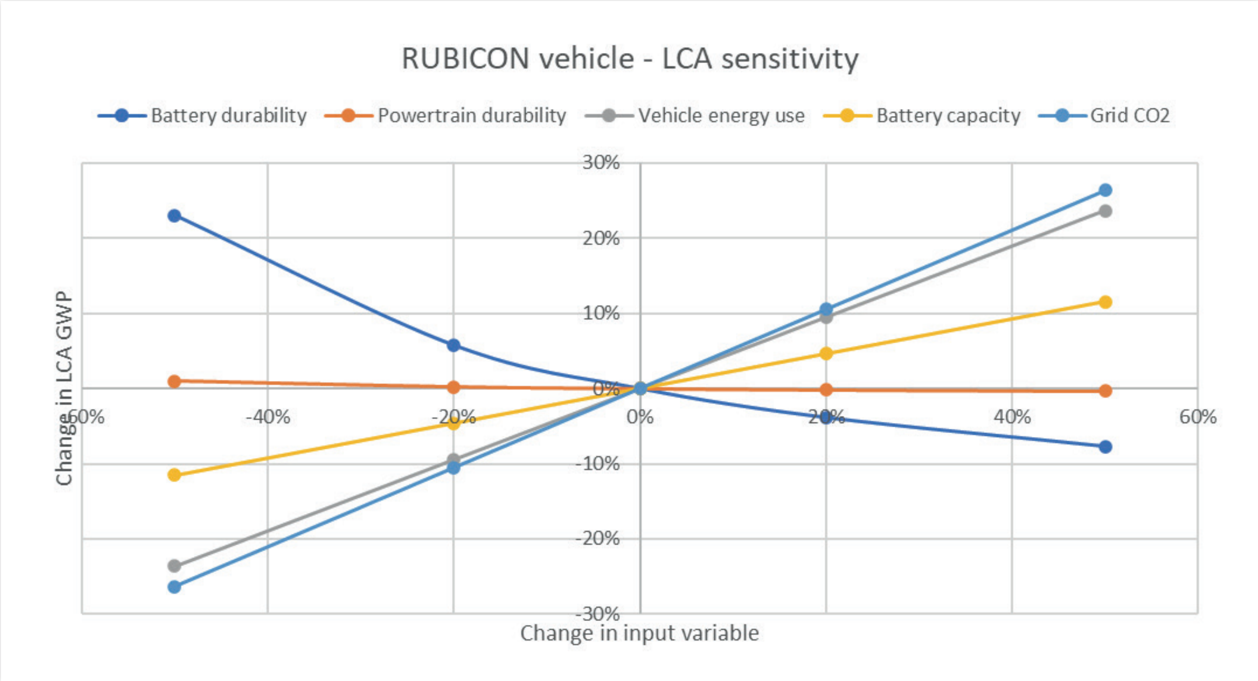
To reduce further the LCA impact of the RUBICON vehicle, we have explored possible future scenarios and performed a sensitivity analysis to identify the most impactful LCA variables.

Sensitivity Scenarios

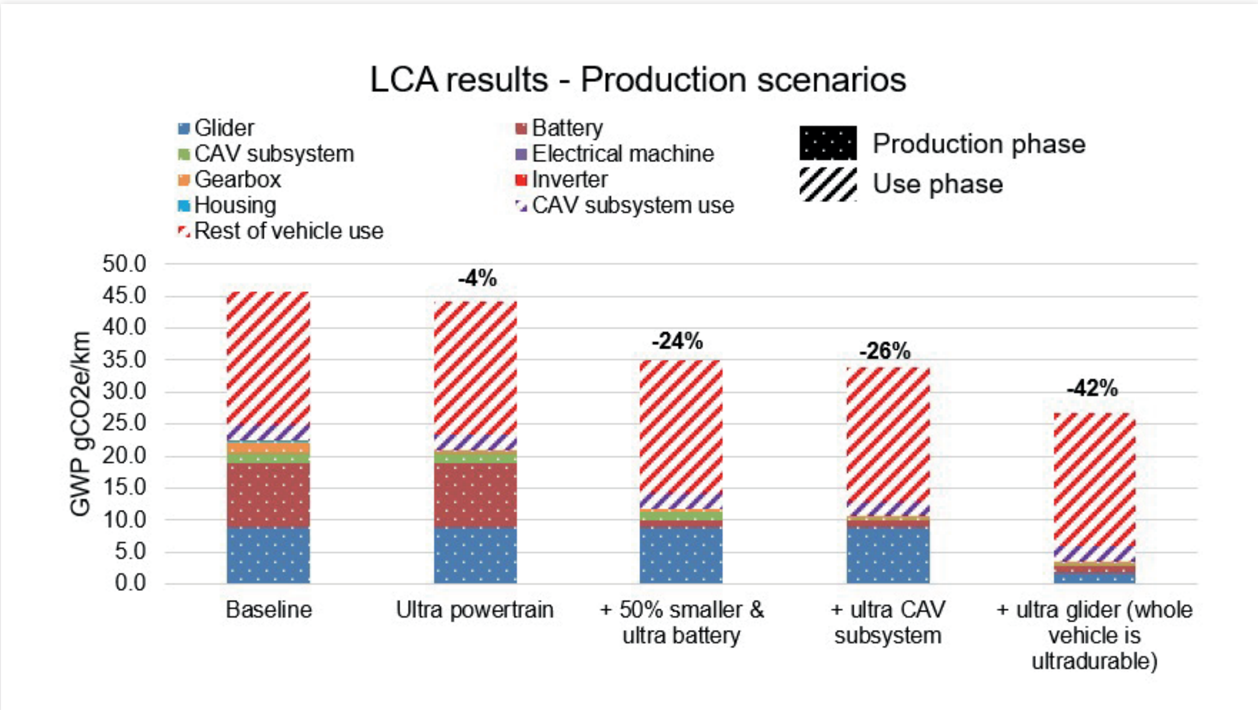
Regarding the production phase, there are two handles which we can vary: the durability of components and their size. In terms of the use phase, there are also two key variables that impact LCA: the energy used by the vehicle and the grid carbon intensity. In the **graph on the next page**, we have changed the values of these variables from their reference or initial values by the amount specified in the horizontal axis, and have observed the impact each of these have on the LCA GWP (vertical axis).

[17] Determining the environmental impacts of conventional and alternatively fuelled vehicles through LCA, Ricardo Energy & Environment, 2020.
[18] Bolin, Life cycle assessment, Carbon footprint of Polestar 2, 2020.

Environmental Analysis: Life Cycle Assessment (LCA)



The use phase variables (grid carbon and energy use) have a relatively large impact compared to the rest, while component durability and battery capacity (energy stored in kWh) have less impact, although still hold a relevant role in LCA. In the following two graphs, we analyse the effect of the production phase variables and the use phase variables separately, laying consecutive GWP reduction actions on top of each other to evaluate the extent of GWP reduction achievable with an improved RUBICON vehicle.



Environmental Analysis: Life Cycle Assessment (LCA)

Because battery and glider are the components that hold the largest weight in the production LCA, **making them ultra-durable enables a large reduction in GWP**. Moreover, battery capacity also has a large impact as per this and the previous graph, showing the importance of right-sizing vehicle components. A smaller battery does not only reduce the production GWP, but also the use phase GWP as we are not transporting the additional battery weight. A smaller battery would also involve the need to charge more often, which may not be a problem if there are enough rapid chargepoints available in future scenarios. Although the glider is subject to plenty of tear and wear given the large number of passengers these vehicles would be carrying, making some of its parts ultra-durable is achievable with further research in new materials and vehicle designs.

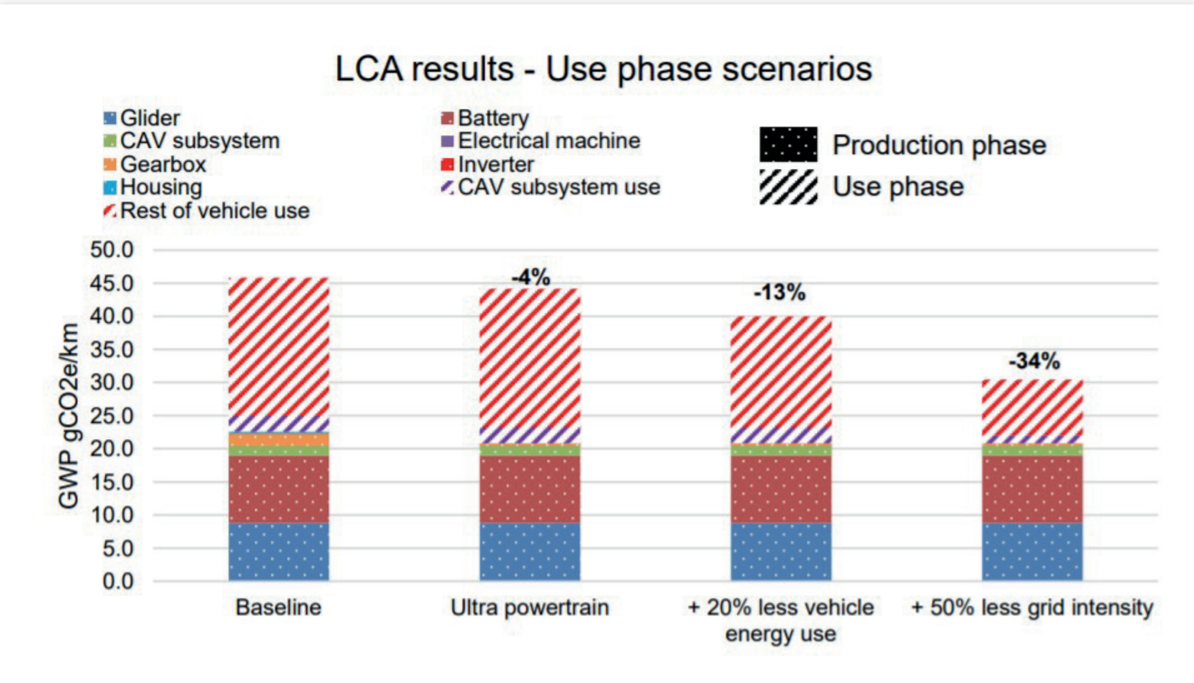
The impact of several use phase scenarios is shown in the **graph below**.

Using a low carbon energy source to charge these vehicles has a large impact in the LCA GWP. For example, a fleet charging from a depot with onsite renewable energy generation would significantly reduce their carbon footprint. Moreover, if the reduce their carbon footprint. Moreover, if the manufacturers of the RUBICON vehicle manage to make vehicle components more efficient, a further LCA GWP is achievable.

The largest GWP reductions are achievable when vehicles are designed with ultra-durability, battery right-sizing and high efficiency in mind, and additionally they are charged by a low carbon grid. When all our best case scenarios in the previous graphs are combined, we can achieve a **72% reduction in GWP** compared to the baseline vehicle.

Research question

So, is the RUBICON vehicle environmentally beneficial? If we compare it with other vehicles in the emissions vs cost chart presented earlier, the RUBICON vehicle ranges between 30 and 45 gCO2e/km (considering the range of scenarios presented), while the rest of vehicles are way above these values. Even small sized BEVs have a larger environmental impact because they are larger than our vehicles, as they can typically fit 4 or 5 people and have larger battery packs. Yes, **the RUBICON vehicle and its high utilisation TaaS operating model show a strong environmental case.**



Business Case Analysis

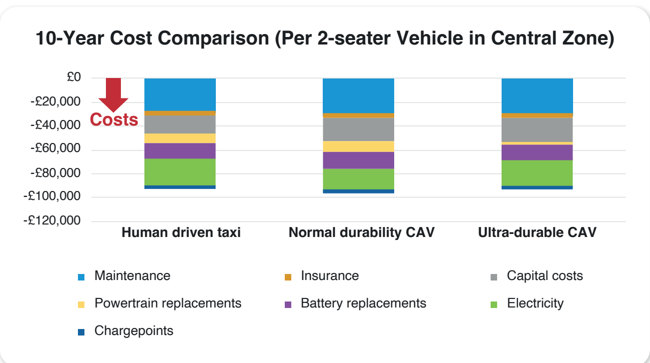
To make a fair comparison against other vehicles in the emissions vs cost graph, we need to consider the costs of the RUBICON vehicle from the passenger's perspective. We are answering this question: how much does a robotaxis fleet operator need to charge passengers in $/km for the fleet business to be reasonably profitable?

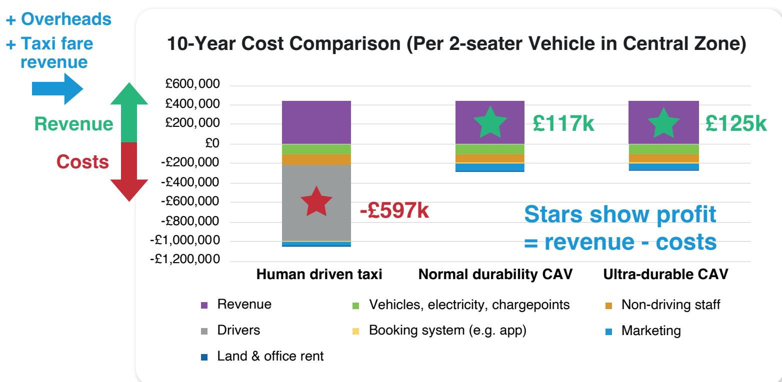
Business case elements: costs and revenue

The graphs below show the breakdown of revenue and costs per 2-seater vehicle in London's Central Zone after 10 years (representative of current UK vehicle life cycles). On the left, we can see the vehicle, electricity and chargepoints costs. On the right, we add on top of these costs all the estimated overhead costs and the revenue from operating a CAV taxi fleet normalised on a per vehicle basis. When comparing a human-driven taxi with a CAV (all of them BEVs), we assume that all drive the same annual distance, 111,000 km/year as per the transport model outputs explained previously, but the human-driven taxi would require multiple shift operation to achieve this.

The driver costs are a major portion of the human-driven taxi[19] due to the high distance the vehicles are operating, which highlights the benefit of high-mileage CAVs. The taxi fare used is £0.61/km for all three vehicles based on predictions of future robotaxi fares in London[20], as opposed to current London taxi fares of £4 to £5/km, hence the poor business case of human driven taxis. In the case of CAVs, the vehicle, electricity and chargepoint costs make up around 35% of all costs, the rest being overheads. Even though CAV fleets would not have driver costs anymore, there are still significant overhead costs to consider, such as non-driving staff (for vehicle cleaning, charging, fleet management, etc.)[21], a booking system (like an app plus its support system)[22], marketing (typically around 10% of revenue)[23], and the rent of an office and land to park/charge the vehicles[24]. For a human-driven taxi fleet, the overheads can make up to 89% of the costs mainly due to driver costs.

For more details on all business case assumptions, please refer to the previous RUBICON white paper[25]. We will focus now on the impact of several variables on the robotaxi fleet profit.





[19] £12/hour as the average taxi driver salary in London from the Economic Research Institute

[20] How disruptive will a mass adoption of robotaxis be?, UBS, 2017

[21] £1,100/year per vehicle for vehicle cleaning and supervision (CoMo) plus an assumed £50,000 annual salary with one non-driving employee for every 4 vehicles (as per Addison Lee company's statistics).

[22] Making the business case for a sustainable local car club: indicative costs for community groups, CoMo, 2018

[23] EverTransit

[24] £20/ft2 per year for industrial and office land rent in London, assumed 50ft2 per vehicle.

[25] Future Mobility Insights: Ultra-durable Powertrains for Autonomous Vehicles, Project RUBICON; Cenex, Hexagon & Empel; September 2021

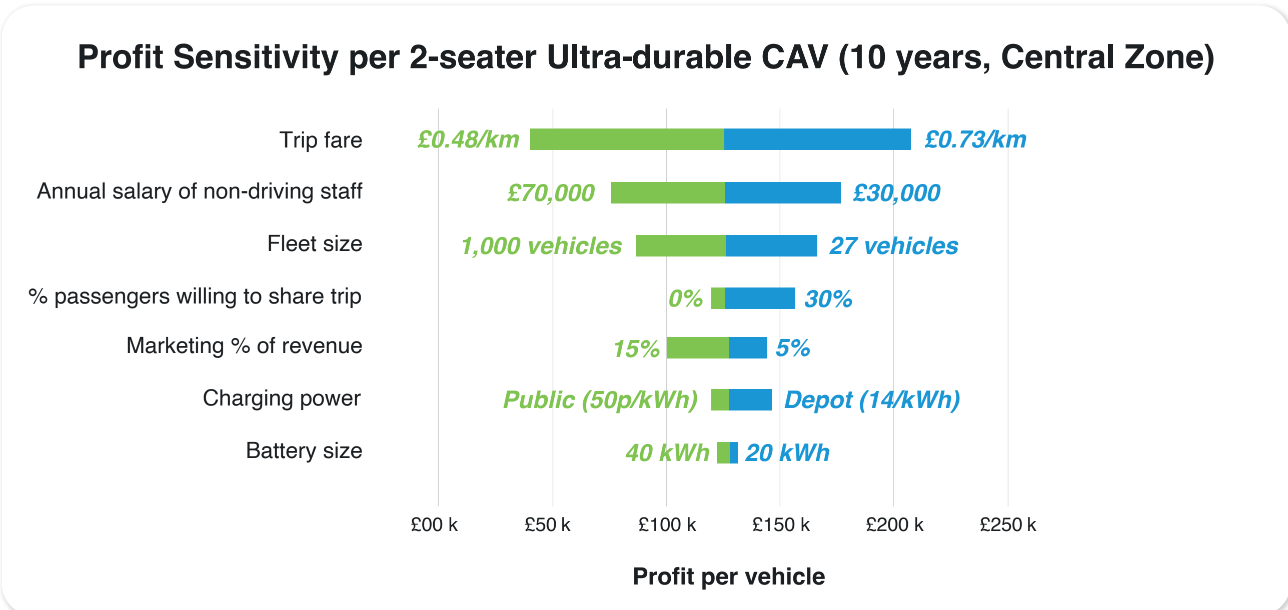
Business Case Analysis

Sensitivity analysis

We have performed a sensitivity exercise by identifying several independent variables that could have a relevant impact on the fleet profitability. Because this project is based on future predictions, performing a sensitivity analysis also allows to mitigate uncertainties on the values of certain variables. We have a core scenario in which all variables are kept at their medium value (approximate the average between the high and low values displayed on the chart); this constitutes the axis of the tornado chart shown below. We then change each of the variables one at a time from their low to high values while keeping the rest of the variables at their medium value. The extremes of the tornado represent the profit per vehicle after 10 years when each of the variables have the values indicated in the graph. This type of analysis enables to isolate the impact of each of the variables.

The analysis shows that:

- **Trip fare is one of the key variables** and its value needs to be carefully adjusted for the business case to work. The future competition between service providers could bring trip fares down, with consequences on the business case as per the graph.
- Another variable with high relevance is **salary of staff**, which will still be needed even without a driver in order to clean, charge and manage the vehicles and the business.
- **Smaller fleet sizes will be more profitable (on a per vehicle basis)** because vehicles will be more utilised and they will compete less for passengers amongst them.
- The higher the percentage of passengers willing to share a trip with strangers, the more optimised trip routing is (vehicles can pick up a second passenger on their way to drop-off the first passenger), reducing distance travelled with an empty vehicle.
- It is important to run an effective and efficient marketing system as it can affect annual profits by around £5,000 per vehicle.
- Depot charging (at 14 p/kWh) is more profitable than public charging (at 50 p/kWh)[26] because the initial investment in rapid depot chargepoints is quickly recovered by the cheaper electricity price. We assumed a price of £70,000 for dual-socket 150 kW chargepoints and a ratio of 6.1% of sockets to vehicles as shown in the transport modelling simulations.
- Battery capacity has a small impact on the business case but, as we showed in the LCA section, has a significant impact on GWP.



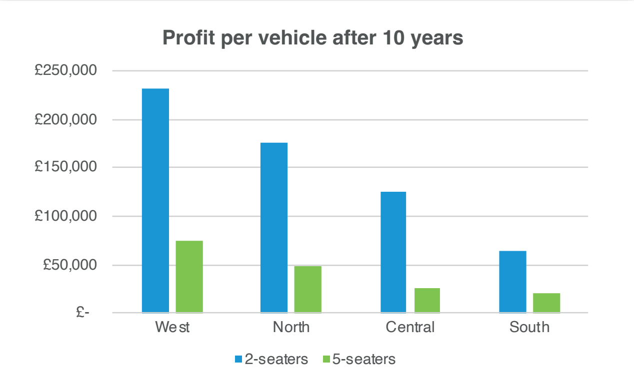
[26] Depot charging price reflective of typical UK industrial energy prices. Public charging price reflective of typical UK rapid charging costs.

[27] Confidential industry quotations.

Business Case Analysis

Difference between zones and vehicle types

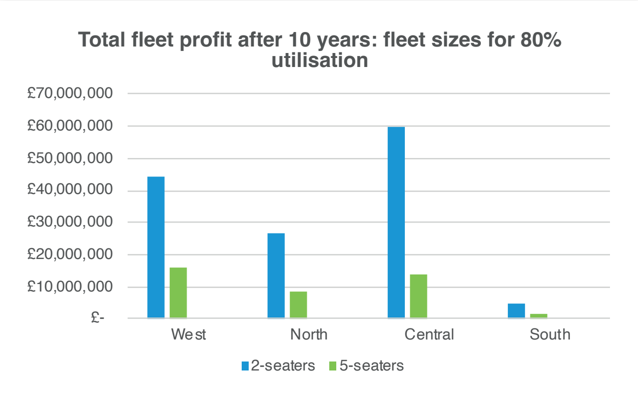
The graph below shows the profit per vehicle after 10 years for 50 vehicles in the baseline scenario (axis in the 'tornado' chart show previously) for the two vehicle types analysed in the transport model and for different CAV zones.



The **5-seater vehicles are 72% less profitable than the 2-seater ones** for two reasons. Firstly, their higher capital cost caused due to their larger batteries and gliders. Secondly, their higher energy use because of their higher weight from these larger components. Moreover, the fact that 88% of private car trips in the UK have two or less passengers means that the 5-seater vehicles are carrying empty seats around most of the time, causing an inefficient use of energy. These results further justify the choice of the 2-seater vehicle archetype for the RUBICON vehicle design.

Even though the Central zone has the largest trip demand, the West and North zones provide larger profits per vehicle. This is because, as per the transport modelling results, the annual distance for fleets with high utilisations (more than 80%) is higher in these zones, resulting in higher distances carrying passengers.

The following graph shows the total profit for the whole fleet when we assume a fleet size such that vehicle utilisation is 80%. These fleet sizes are labelled in the graph. Note that these fleet sizes assume fleets formed purely by one vehicle type (e.g. in the West, either a fleet made of 218 five-seaters or a fleet made of 191 two-seaters).



Although the Central zone was the third one in the profit per vehicle ranking, it is the first one in the total profit ranking. This happens because of the very large trip demand in the Central Zone, which allows for relatively large fleets of around 500 vehicles with 80% vehicle utilisation rates, as opposed to 150-200 vehicles in the West/North zones.

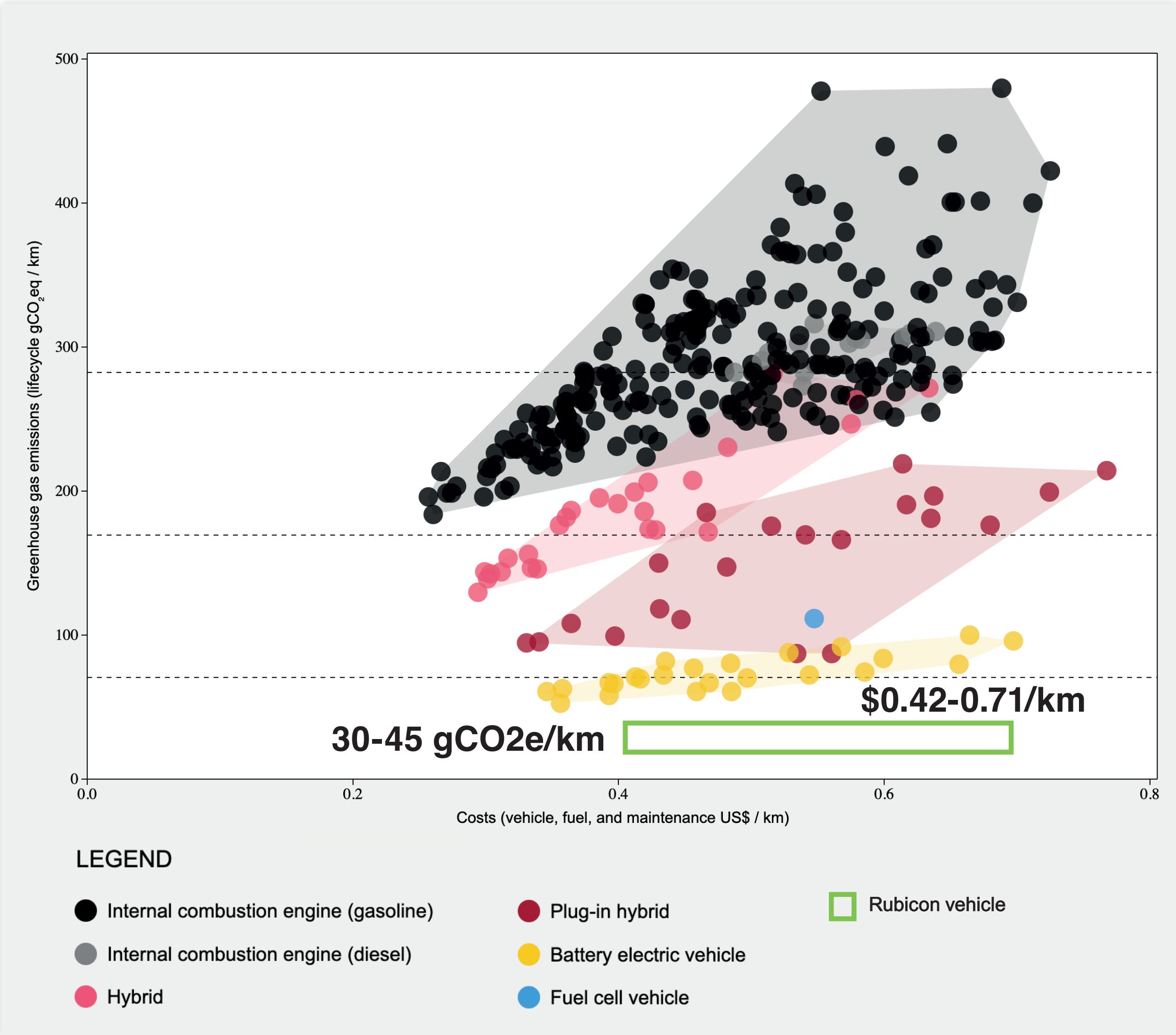
The transport modelling has shown that there is an optimal ratio of 5-seater vehicles that allows to maximise the total fleet size while keeping a high vehicle utilisation. This ratio is somewhere around 25% of 5-seater vehicles in a fleet. However, **this ratio is not the optimal from a business case perspective.** Taking the Central zone as an example, a 25% ratio of 5-seaters allows to have 540 vehicles in the fleet while keeping an 80% vehicle utilisation. In this case, the total fleet profit would be £54.1m. However, if we have a fleet purely made of 2-seaters, this would allow to have 470 vehicles while keeping an 80% vehicle utilisation, providing a profit of £59.6m (10% more). Even though we would have a smaller fleet size, **it still pays off to have only 2-seater vehicles because of their far better business case per vehicle compared to 5-seaters.**

Business Case Analysis

Research question

So, does the RUBICON vehicle provide a compelling business case for both fleet operator and user? Under the range of different scenarios, the robotaxis fare would be between $0.42/km and $0.71/km. This would ensure a far smaller fare for users than current taxis while maintaining a good economic case for a fleet operator, who would payback their initial investment in 3 to 5 years.

Going back to the emissions vs cost graph, **the RUBICON vehicle is in line with BEV private car ownership costs.** This graph is the Carbon Counter tool[28] developed by the MIT, which presents mainstream vehicles in an emission versus cost graph and classifies them by powertrain as shown below. However, our vehicle has a **lower carbon footprint and increased convenience** due to the elimination of certain ‘barriers to entry’ that private car ownership presents: learning and being able to drive, capital expense of buying a car and a chargepoint, finding and paying for a parking place, the stress of driving and parking in a busy city etc. These barriers are currently considered acceptable due to the large cost advantages of private car ownership ($0.3/km to $0.7/km) over current taxis ($5.5/km). But if our cost projections of robotaxi services materialise, then there is a clear and propelling business case.



[28] https://www.carboncounter.com/#!/explore, methodology detailed in Miotti et al., Personal Vehicles Evaluated against Climate Change Mitigation Targets, Environmental Science & Technology 2016. Tool costs and vehicles updated in 2021.

Study Conclusions

Engineering for ultra-durability

- Despite 100 years of designing passenger cars for private ownership and low utilisation, it is possible to design a vehicle for much higher utilisation and, subsequently, higher durability, even using current technologies.
- It is likely that various technological advances will act in unison to facilitate this advance. CAVs will eliminate many of the shock loads that exist in human-driven vehicles, the availability of large amounts of data will facilitate the development of Digital Twins that monitor the reliability of vehicles, and the deployment of CAVs as part of a fleet makes the use of these Digital Twins easier.
- In developing the building blocks that will support these CAV-based Digital Twins, benefits will arise in the short term for conventionally driven vehicles, leading to improved outcomes in terms of durability, cost and the environment.

Fleet operating patterns

- If fleets are right-sized to demand levels and placed in the right areas of a city, it is feasible to achieve high annual distances in excess of 100,000 km.
- If only passenger services are to be provided, high utilisation levels can only be achieved in some areas of a city with very small fleets. Further research should explore alternative overnight applications for CAVs such as goods deliveries.
- For high vehicle utilisation targets of more than 80%, fleets can be in excess of 100 vehicles in several London zones (e.g. around 500 vehicles in Central London).
- Some (< 25%) 5-seater vehicles are needed in the fleet to service trips of 3 or more passengers. Having more 5-seaters does not yield benefits and increases energy requirements.

Environmental assessment

- New mobility as a service transport models encourage the operation of highly utilised vehicles in order to reduce the environmental impact per passenger and increase fleet profits. At the same time, highly utilised vehicles call for ultra-durable vehicle designs to avoid replacing components frequently.
- If we make all components of the RUBICON vehicle ultra-durable we can achieve a 42% reduction in GWP against the baseline vehicle.
- If, on top of making the vehicle ultra-durable, we make the vehicle highly efficient and power it with a low carbon grid we can achieve a 72% reduction in GWP against the baseline vehicle.

Business case

- Based on the sensitivity analysis, the top three factors that most impact the business case are trip fares, non-driving staff salary and fleet size.
- A fleet of robotaxis can provide reasonable payback periods for the fleet operator of 3 to 5 years when vehicle utilisation is high (> 80%), with the right fleet sizes and areas of operation. The reason is that costs not only originate from vehicles, energy and chargepoints, but also from plenty of overheads: non-driving staff, app, marketing, land, offices, etc.
- The cost for a RUBICON vehicle passenger is similar to private car ownership prices. However, this comes at a) lower emissions and b) an increased convenience regarding the elimination of barriers (learning and being able to drive, capital expense of buying a car and a chargepoint, finding and paying for parking).

You can find out more about our research projects, along with downloading a range of free, public reports, from our website:

www.cenex.co.uk

Cenex
Holywell Building
Holywell Park
Ashby Road
Loughborough
Leicestershire
LE11 3UZ

Tel: 01509 642 500
Email: info@cenex.co.uk
Website: www.cenex.co.uk