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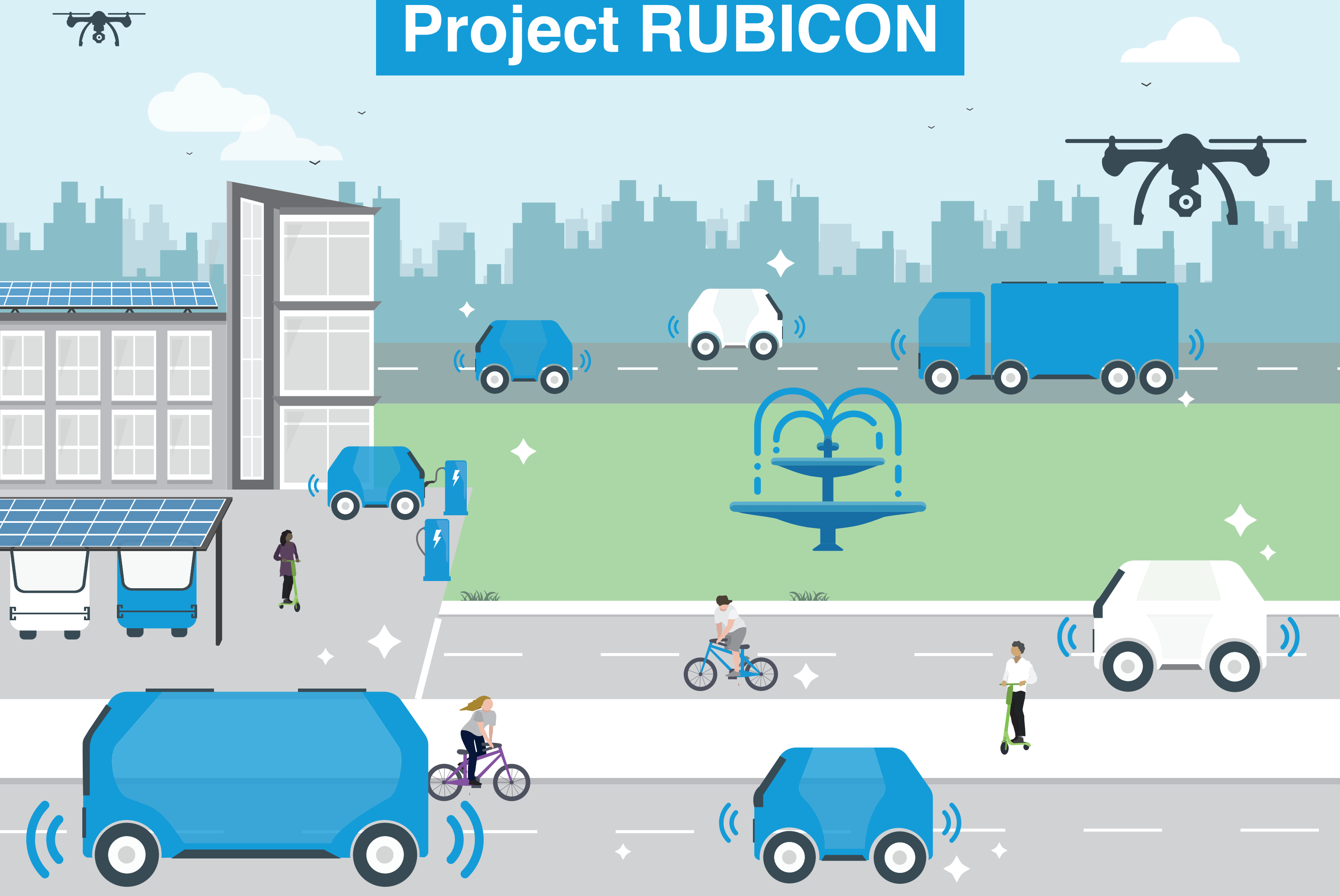
Future Mobility Insights: Ultra-durable Powertrains for Autonomous Vehicles

Project RUBICON



UKRI Innovate UK

EMPEL SYSTEMS

HEXAGON MANUFACTURING INTELLIGENCE

Romax TECHNOLOGY

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 vehicles 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.

The Innovate UK-funded project RUBICON (ultRa dUraBle electrIC pOwertraiNs) aims to design an ultra-durable powertrain for CAVs and investigate its commercial and environmental case in future deployment scenarios. This report summarises the results of a study looking at the typical CAV vehicle type, its duty cycle and potential deployment numbers in London and the commercial 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.

Assuming that CAVs will be heavily utilised in the future, offering mobility as a service in urban environments and achieving over 100,000 miles/year, they will require a powertrain able to withstand this intensive duty cycle over the vehicle's lifetime. **The project aims to answer several research questions.**

- **Is it possible to design a powertrain that can last over one million miles?**
- **Is the ultra-durable CAV concept commercially viable?**
- **Does it make sense from an environmental point of view?**

Executive Summary

Engineering Case

Current assumptions limit the anticipated life of a vehicle (time and distance) and this affects the engineering of the systems and components. It makes no commercial sense to invest time and resources to extend the life of a component way beyond the anticipated life of the vehicle.

A transformation to a highly utilised autonomous vehicle could transform all that. Systems and components would need to be engineered differently and the economic imperative could demand much longer life spans. With the right approach, it is anticipated that this will also yield advantages in terms of environmental impact across the life cycle of the vehicle.

Use Case

The project reviews future design concepts of CAVs by manufacturers, identifying two passenger carrying battery electric CAV archetypes suitable for this study: a 2-seater small pod and a 4 to 6-seater medium vehicle. This paper is focused on a level 4 (L4) small pod CAV. The reason is that L5 CAVs (full autonomy, able to operate under all conditions) are not expected to be deployed until at least 2035, while L4 CAVs are already being trialled and their deployment at scale is expected between 2025 and 2030. The operation of L4 CAVs needs to be restricted however to a certain geographical area (as part of their operational design domain or ODD), which we choose as an area in London with a similar size to current L4 CAV trials around the world.

Fleet Utilisation Model

Cenex developed a first-of-a-kind model to estimate the supply and demand of L4 CAVs in a number of areas of London, each equating to approximately 10 square miles. The model uses a ground-breaking methodology for estimating demand curves, and modelling duty cycles and business cases for CAVs in a city environment.

The model uses publicly available data on traffic statistics, vehicle occupancy and trip statistics depending on travel mode, purpose and region. The objective of this model is to understand how a fleet of certain characteristics (number, type and specification of vehicles) will be used in a certain area of a city when trying to displace certain types of trips (e.g. private car trips for commuting in North London). Based on our use case of L4 2-seater CAVs, deployed to displace private car trips, Cenex estimate that a highly utilised fleet (90% utilisation of non-parked time, comprising driving and charging) would require around 400 vehicles in one of our London L4 CAV areas. The vehicles would achieve annual mileages of over 100,000 miles/year (around 300 miles/day).

Business Case

The economic analysis compared the cost and revenue breakdown of a human-driven taxi, a typical durability CAV and an ultra-durable CAV. The analysis shows that, if predictions of future robotaxi fares (in £/mile paid by passengers) were used to calculate the revenue for a fleet, human-driven taxis would incur a negative business case. The overhead costs for CAV fleets represent 65% of their total costs because, even though no drivers are required, a fleet business still requires staff, a trip booking system, marketing and land/office space. This figure rises to 89% in the case of a human-driven taxi fleet due to the driver costs. Considering all these costs plus the capital and operating expenditure of vehicles and chargepoints,

Executive Summary

it is estimated that CAV fleets can still make a profit of around £27,000/year per vehicle via taxi service revenue.

The assessment also shows that, although the ultra-durable powertrain adds 11% (£1,900) to the initial CAV cost, over 10 years the total cost of ownership for the vehicle is reduced by 7% (£8,300) compared to the normal durability CAV. The reason is that, for every ultra-durable powertrain replacement, the normal durability CAV. The reason is that, for every ultra-durable powertrain replacement, the normal durability powertrain needs to be replaced five or six times. The requirement to replace the lower durability powertrain every two years may appear unlikely; however, based on 100,000 miles per year this equates to a 200,000-mile replacement cycle.

For the human-driven taxi fleet to show a 3 to 5 years payback period off an initial investment, the fares would need to be similar to future predictions for human-driven taxi fares (£2.13/mile[16]). However, for the CAV fleets to have the same payback period, the trip fares would need to be much lower and similar to average UK total ownership costs for private cars (£0.68/mile).

A sensitivity analysis on the ultra-durable CAV fleet identified several key variables that have a major impact on its economic performance. The trip fare charged to passengers is key, and competition between mobility services in the future could lower these fares, hence decreasing the business profit. The percentage of miles driven with passengers is also very important, and so will be optimising strategies for collection of customers and trip routing. The salary of non-driving staff will also be critical, as will be the charging power even for small battery packs: the less time spent charging, the more time the vehicles will have to drive with passengers, or drive around looking for them or to demand hotspots.

Policy Implications

CAVs can help tackle road transport challenges via reduced congestion and emissions, increased safety, increased accessibility for marginalised groups and more space in the urban realm enabled by reduced road space and parking. Ultra-durable powertrains for CAVs help improve the business case for manufacturers and fleet operators. This would involve an accelerated CAV deployment timescale, with increased competition amongst city test beds and more focus on lifecycle emission reporting (manufacturing, use and disposal). Policymakers should be aware of these implications when planning ahead and preparing for potential at-scale deployment.

Next Steps

Following the duty cycle, demand and business case for CAVs presented in this paper, Cenex will undertake a life cycle assessment (LCA) and develop a geo-spatial operating model of the vehicles. The LCA will compare an ultra-durable CAV to a normal durability CAV. This will quantify emission savings due to the fewer powertrain replacements required in the ultra-durable vehicle, taking into account the whole life of the vehicle from manufacturing to end of life. The detailed geo-spatial model will be used to explore different scenarios in terms of BEV charging, trip sharing and transport demand on the CAV business case. The results from these exercises will be published in early 2022.

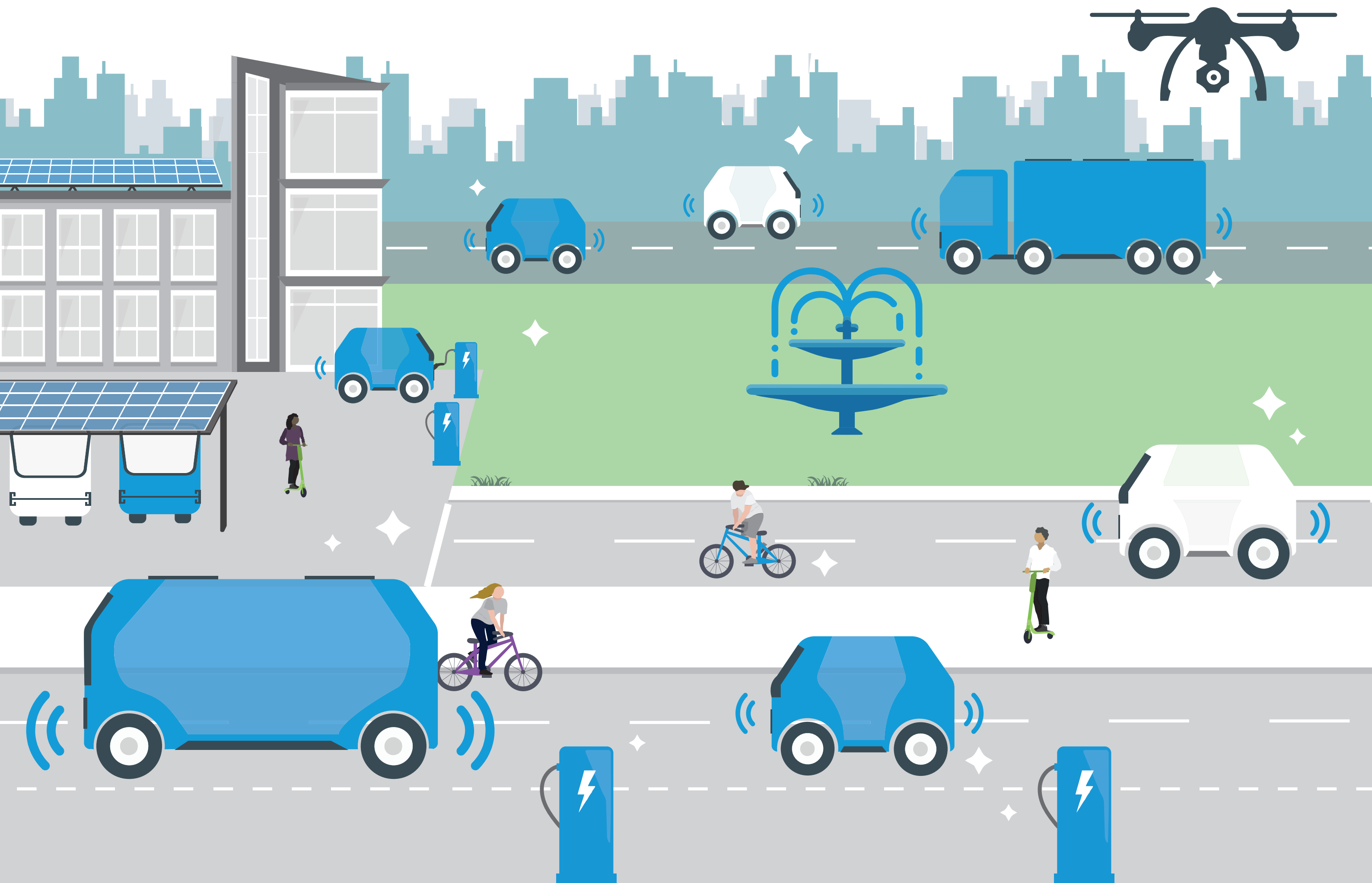
About Project RUBICON

Project **RUBICON** (ultR**a** d**U**ra**B**le electr**IC** p**O**wertrai**N**s) is 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 is targeted for its use in an autonomous passenger carrying vehicle that has very high utilisation and runs for more than one million miles.

Current vehicle powertrains are typically designed for a lifetime of 150 to 300 thousand miles, 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 in order 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 is formed of Cenex, EMPEL Systems and Romax Technology. Cenex is providing CAV duty cycles and exploring the unique differences between future CAV archetypes and existing passenger vehicles. This involves 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 Romax's 30 years of experience in powertrain performance simulation, testing and design is allowing 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

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?
  - Might it be advantageous to include maintainability as a target for parts that are likely to fail?

- **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?
  - Does it make commercial sense to engineer an ultra-durable powertrain?

- **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?
  - Besides CO2 emissions, what other aspects of sustainability should be considered?

This paper reports on the project progress so far on answering some of these questions.

Engineering the Case for Ultra-Durable CAVs

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 as a result of 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 is the typical mileage durability of conventional powertrains. By then the vehicle is looking tired simply in terms of styling, and it is fully scrapped by the private owner. 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 see exactly what this economic and environmental advantage might be, and for this some detailed engineering design and simulation is required.

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.

The RUBICON project was able to identify gaps in engineering capability that are left by the standard business model, gaps that would need to be filled should the transport as a service (TaaS) model start to become a reality.

The ultra-durable powertrain consists of the gearbox, motor and inverter.

Engineering the Gearbox for Reliability

Electric vehicles do have gearboxes, but they are single speed or ratio gearboxes compared to the multi-speed ones in petrol or diesel vehicles. The conventional business model for passenger cars drives increasing power density, creating a smaller gearbox, light and cheap to manufacture. A larger gearbox makes little sense within the context of current business models: 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 TaaS vehicle that runs for substantially increased distances, especially when the total life cycle cost (economically and environmentally) is considered.

During the project, Romax Technology has modelled and simulated various gearboxes using its 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.

It has long been recognised that 'shock loads' have a major influence on gearbox durability. These are loads derived from driving over potholes, kerb climbing, etc. Experience has indicated that these are about twice the maximum motor/engine torque, and these events can limit the reliability of a gearbox.

Engineering the Case for Ultra-Durable CAVs

With this in mind, a dynamic model of the vehicle powertrain has been created and simulations carried out. This includes models for the road surface, tyres, suspension, driveshafts, gearbox, motor, inverter and battery. This allows the project to study the magnitude of such shock loads so that their effect on the gearbox reliability can be considered.

For human-driven vehicles, it has long been understood that a gearbox had to be designed to withstand the driving of the 'extreme' driver; the sort of driver that, although rare, would still place constraints on the design and engineering compared to most drivers. However, with a CAV, the opportunity exists to 'moderate' the torque demand at the motor, particularly when the most damaging cycles occur. The simulation model is being used to investigate how this could be used to limit the peak stress cycles and improve the reliability of the gearbox, potentially without an increase in manufacturing cost.

Further insight is possible. The term 'Digital Twin' has been used and misused in recent years, but Romax 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. The dynamic model created for the investigation of shock loads provides the ideal framework for a Digital Twin, with the aim that in the future such a model could provide insight into the reliability, operation and maintenance of the fleet of TaaS vehicles.

Engineering the Electric Motor for Reliability

Regarding reliability, it has long been hoped that replacing the internal combustion engine with an electric machine would increase vehicle reliability. However, 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 is being 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[4] temperature, which reduces the rate of winding degradation and hence improves durability. 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.

Engineering the Inverter for Reliability

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 Romax 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, cycling 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.

Our Use Case: Future Level 4 CAV Archetypes

Before explaining the vehicle demand and business case models, we need to define the boundary conditions of our study.

Vehicle Archetypes

Cenex reviewed the future archetypes of CAVs to understand the specifications of the vehicles that will be fitted with our ultra-durable powertrains. Current archetypes of CAVs are existing vehicles (typically saloon cars or minivans) that are retrofitted with CAV technology such as cameras, LIDAR, RADAR and ultrasound. However, the concept vehicles announced by several manufacturers to be released in the future are purpose-built battery electric vehicles (BEVs) with embedded CAV technology and a design that negates the presence of a driver. Because this project is researching future mobility, the study will focus on these future concept vehicles.

Several examples are shown below: the Renault EZ-POD (based on the existing Renault Twizy), the Volkswagen Sedric and the Renault EZ-GO.

Considering other concept future CAVs hinted by other manufacturers too, the CAV archetypes of the future can be broadly classified into two types: the 2-seater pod and the 4 to 6-seater CAV. Their typical specifications are shown in the table below.

Renault EZ-POD

Volkswagen Sedric

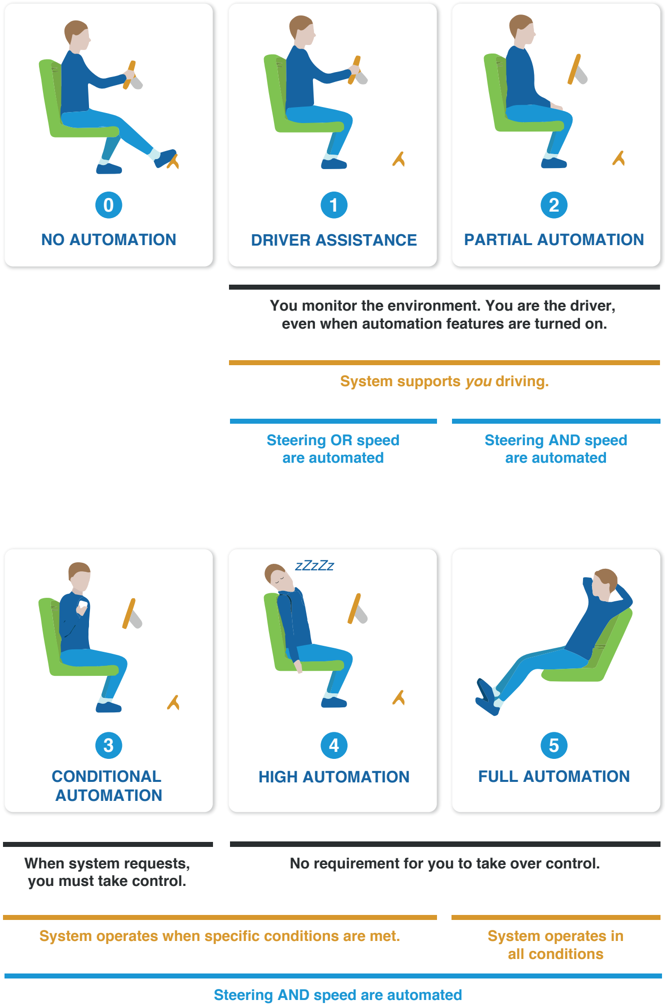
Renault EZ-GO

VEHICLE TYPE	EXAMPLE MODELS	SEATS	TOP SPEED	RANGE	BATTERY CAPACITY (kWh)	KERB WEIGHT (kg)[5]
Small Pod	Renault EZ-Pod	2	50 mph	50 miles	6	450
Medium CAV	Renault EZ-GO, VW Sedric	4-6	75 mph	250 - 300 miles	50	1,500

Our Use Case: Future Level 4 CAV Archetypes

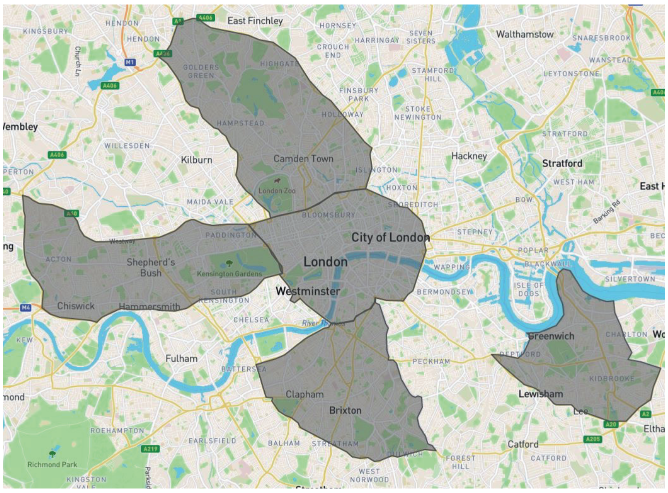
Level 4 CAVs

CAVs have different levels of autonomy depending on their interaction with the driver, other vehicles and the road infrastructure. The diagram below explains the different autonomy levels[6].



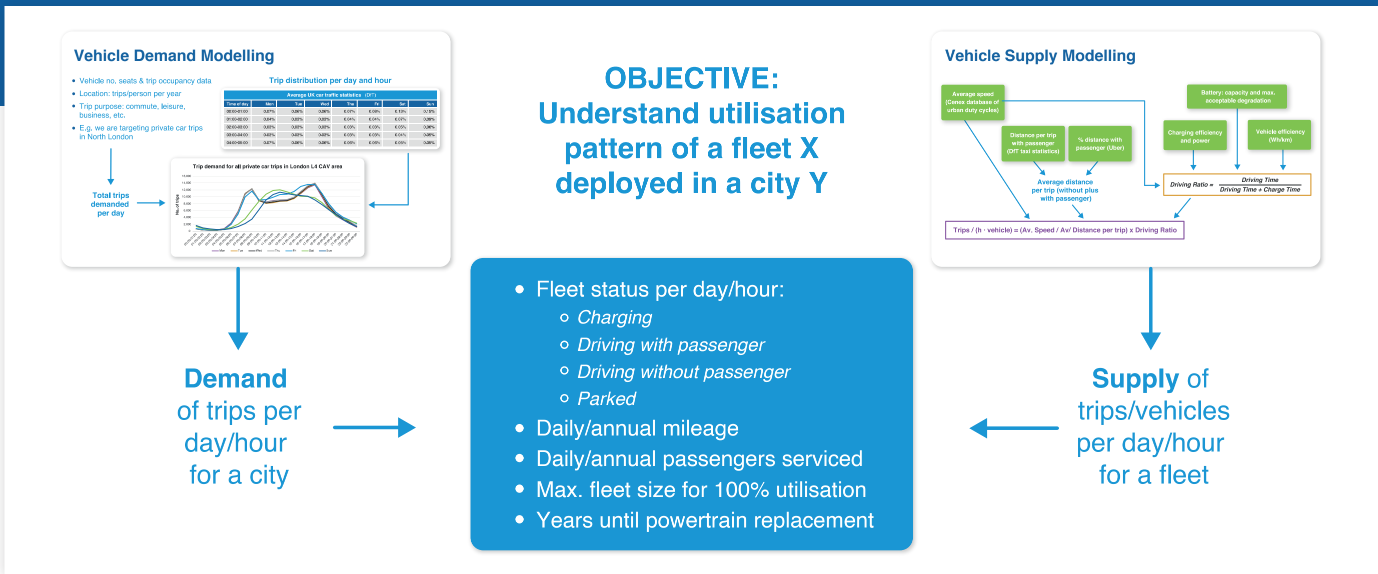
As explained in the diagram, both level 4 and 5 (L4 and L5) CAVs do not require any action from a driver at all. However, there is an important difference between these two autonomy levels: the operational design domain (ODD). The ODD is a range of conditions under which vehicles can operate, which are many: geographical area, time of day, weather, terrain, road features, etc. While L5 CAVs do not have an ODD, L4 CAVs do, meaning that they will potentially stop operating if they encounter a condition that is not defined within their ODD, such as heavy rain/snow or major changes in the road network.

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[7,8,9] which represents too long a horizon for our project. Our use case is therefore L4 CAVs, which have as one of their main ODD conditions their geographical area of operation. Current L4 CAV trials taking place in China and the USA have operational areas of 8 to 16 square miles. Therefore, we choose the following areas in London represented below, that have approximately this size. The main reasons for choosing London as our study city are the good availability of public data and its track record of attracting investment in new mobility technologies.



Fleet Utilisation Model

Once the use case and boundary conditions are set, we are ready to explain the methodology employed to develop our CAV fleet utilisation model. Before attempting to assess the business or environmental cases of CAVs, we need to understand how a fleet of certain characteristics will be used in a city or area with a certain population. To answer that question, Cenex has developed the model shown in the diagram below.



Our fleet utilisation model combines the demand and supply of trips and vehicles to calculate the average fleet status per hour, the mileage statistics, the number of passengers serviced, how small our fleet can be to achieve high utilisations, and how many years will our ultra-durable powertrains last. We will focus on the demand calculations first as shown in the diagram below.

Trip Demand Calculations

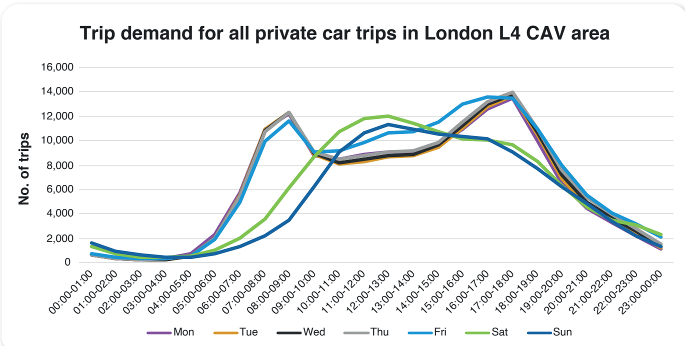
- Vehicle no. seats & trip occupancy data
- Location: trips/person per year
- Trip purpose: commute, leisure, business, etc.
- E.g. we are targeting private car trips in North London

Trip distribution per day and hour

Average UK car traffic statistics (DfT)

Time of day	Mon	Tue	Wed	Thu	Fri	Sat	Sun
00:00-01:00	0.07%	0.06%	0.06%	0.07%	0.08%	0.13%	0.15%
01:00-02:00	0.04%	0.03%	0.03%	0.04%	0.04%	0.07%	0.09%
02:00-03:00	0.03%	0.03%	0.03%	0.03%	0.03%	0.05%	0.06%
03:00-04:00	0.03%	0.03%	0.03%	0.03%	0.03%	0.04%	0.05%
04:00-05:00	0.07%	0.06%	0.06%	0.06%	0.06%	0.05%	0.05%

Total trips demanded per day



Fleet Utilisation Model

The number of trips required to meet a certain transport demand is calculated in the following way. The number of trips per person and per year by region and by trip purpose is obtained from the National Travel Survey (NTS)[10,11], from the Department for Transport (DfT). This number is then multiplied by the population in our study area, in this case a L4 CAV area in London of 10 square miles and 300,000 people. We then combine this result with NTS occupancy data per trip purpose[12] and the number of seats of our vehicle (a model input) to calculate the number of trips that can be potentially demanded from our fleet on an average day. This enables us to answer questions regarding specific travel modes and trip purposes, for example: "How many trips could we require from our 2-seater pod fleet to satisfy the demand of all commute trips by private car in my L4 CAV area?".

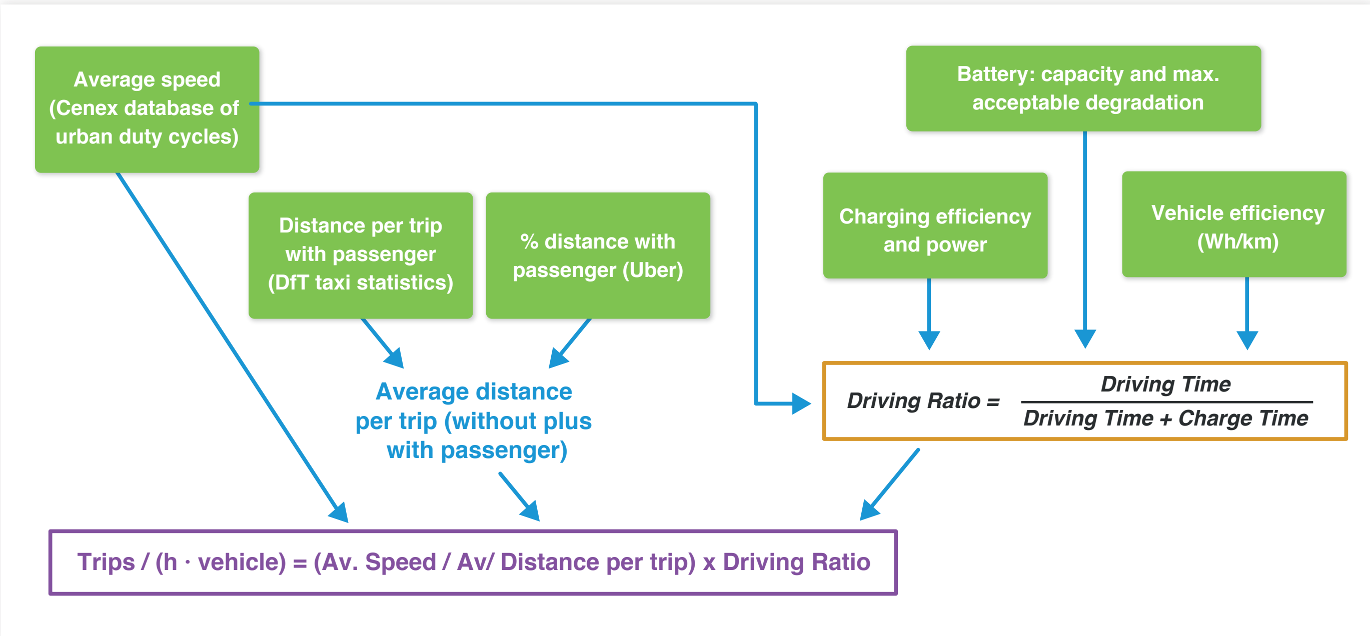
To add granularity to that figure, we then use road traffic statistics[13] from DfT to calculate the trip demand per day of week and time of day. That way we can obtain trip profiles like the ones shown in the previous diagram.

Trip Demand Calculations

We also need to understand how many trips our fleet can supply given certain vehicle specifications and drive cycle statistics. The diagram below explains how we do this.

Using Cenex's own database of urban drive cycles (trace of speed versus time), we develop bespoke drive cycles representative of the vehicle archetypes defined earlier. Their average speeds of 16 and 20 mph for the small and medium archetypes in a London operation are then used in the calculation. The total distance per trip is also input into the calculation, considering the typical UK taxi trip distance with passenger (DfT)[14] and the proportion of mileage with passenger[15]. Finally, the vehicle charging, battery and energy consumption specifications are used to calculate the ratio of time the vehicle can spend driving as opposed to charging.

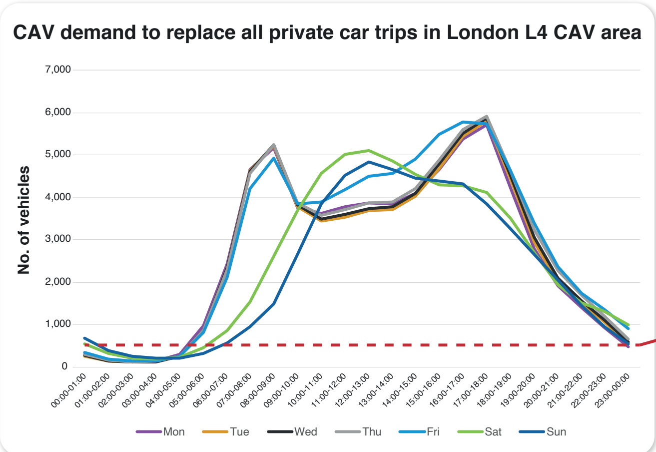
The combination of all these factors provides us with the number of paid trips per hour and per vehicle that our fleet can supply.

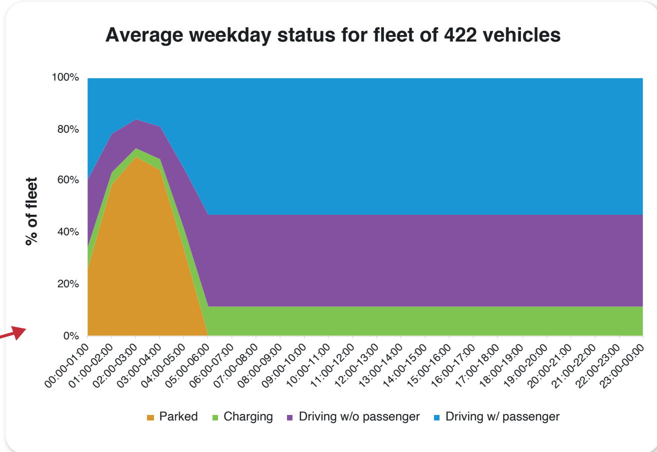


Fleet Utilisation Model

Model Outputs

When we combine the hourly total trips demanded from a certain area for specific trip purposes and travel modes with the hourly trips per vehicle that our fleet can supply, we come up with the number of vehicles per hour required. The graphs below show the example of a fleet of small pods aiming to replace as many private car trips as possible in one of our London L4 CAV areas (for this analysis it is irrelevant which specific area it is). The dotted red line represents the number of small pods in our fleet. The graph on the right represents the average fleet status for a weekday per hour.





- **422 vehicles for 90% utilisation**
- **293 miles/day (per vehicle)**
- **107,000 miles/year (per vehicle)**
- **70 passengers/day (per vehicle)**
- **11m passengers/year for whole fleet**
- **9 years to 1m miles (powertrain life)**

Because the objective of project RUBICON is to have vehicles with high mileage and utilisation to reduce the environmental and financial costs per mile, we aim to have a relatively small fleet that is demanded almost all the time. In this case, in order to have a 90% average utilisation (defined as non-parked time, i.e. either driving or charging), we would require a fleet of around 400 small pods in each of the L4 CAV areas defined earlier.

The fleet would be fully utilised except between midnight and 6 am, when up to 70% of the vehicles could be parked. To mitigate this low night-time demand, the vehicles could be used for deliveries if designed appropriately, or as a grid balancing asset via vehicle to grid (V2G), and these could be subjects of further research in the future. The vehicles would accumulate mileages in excess of one million miles in less than 10 years, hence the requirement for an ultra-durable powertrain. Moreover, this relatively small fleet would service over 10 million passengers per year. If the fleet was larger, the utilisation would drop and the annual mileage would decrease too, reducing the commercial and environmental case for the application.

Fleet Utilisation Model

Model Limitations and Mitigation

It must be noted that this is a relatively simple Excel-based model that uses average UK transport statistics to calculate general trends in potential CAV demand. As such, it has several limitations:

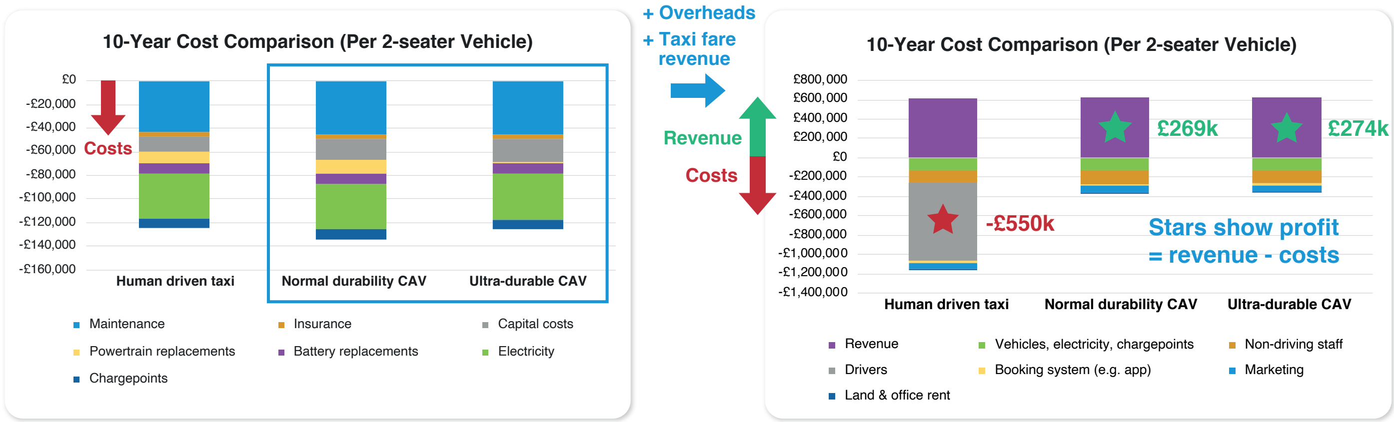
- Lack of geographical granularity: to understand trip demand hotspots
- Lack of 'per vehicle' granularity: to understand the behaviour of different vehicles within the fleet
- Charging schedule: it cannot implement a smarter charging strategy where vehicles prefer to charge during night-time, when the trip demand is lower
- No possibility of trip sharing amongst strangers if their origin and destinations align appropriately

The project presented an opportunity for Cenex to mitigate these limitations with a more refined and geo-spatial transport model. This refined modelling allows us to simulate a range of charging, trip-sharing, fleet size and vehicle archetype scenarios, to ultimately answer the question: "For the environmental and business cases to work, how does the future need to look like?". The results of this modelling work will be published in early 2022.

Credit to Immense Simulations

Business Case Analysis

Now that we have right sized our fleet for high operating utilisations, we will analyse its economic performance. For the business case analysis, we select the small 2-seater pod as the preferred vehicle. The main reason is that the average UK car occupancy is 1.6 people (including the driver) and 88% of trips have 2 or fewer people (including the driver)[11]. We select a 10-year ownership period as representative of current UK vehicle life cycles, and because this is approximately the life expectancy of our ultra-durable powertrain. Please note that, when referring to the ultra-durable powertrain, we consider the motor, gearbox and power electronics, but not the battery (as discussed below). However, it is recognised that this approach to ultra-durable design might reasonably be applied to the battery pack and other vehicle systems.



Breakdown of Costs and Revenue

The graphs below show the breakdown of revenue and costs per vehicle. 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 mileage, 107,000 miles/year as per the fleet utilisation model outputs explained previously, but the human-driven taxi would require multiple shift operation to achieve this.

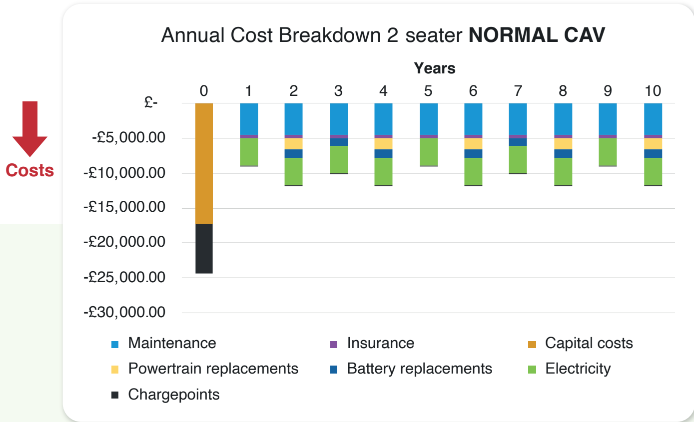
The driver costs are a major portion of the human-driven taxi[16] due to the high mileages the vehicles are operating, which highlights the benefit of high-mileage CAVs. The taxi fare used is £0.98/mile for all three vehicles based on predictions of future robotaxi fares in London, as opposed to future taxi fare predictions of £2.13/mile[17], hence the poor business case of human driven taxis in this case. 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.)[18], a booking system (like an app plus its support system) , marketing (typically around 10% of revenue)[20],

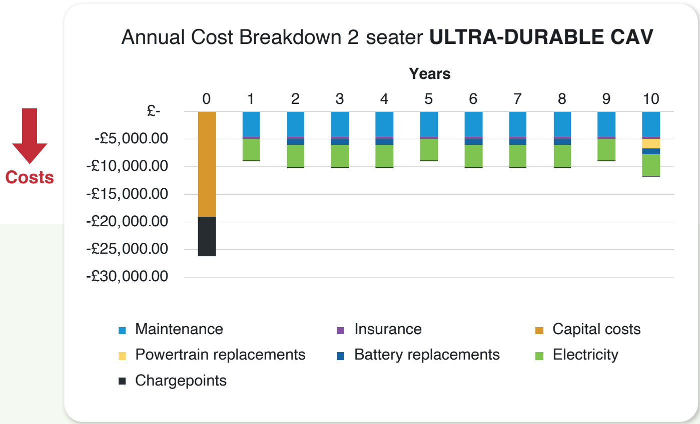
Business Case Analysis

and the rent of an office and land to park/charge the vehicles[21]. For a human-driven taxi fleet, the overheads can make up to 89% of the costs mainly due to driver costs.

The cost of repairing and replacing vehicle interiors is included in the maintenance costs on a per mile basis. These costs could potentially be higher for the CAVs compared to human-driven taxis due to increased vandalism (because of the absence of a driver and hence perceived surveillance, although cameras are likely to be present). However, it is difficult to quantify these additional costs and we do not envisage this factor making a relevant difference to the total business case, therefore we do not include these additional costs. Assuming vehicle interiors need to be replaced more often in high utilisation duty cycles like ours, an interesting proposition would be to design the base of the vehicle as a platform with wheels and ultra-durable powertrain separately from the top of the vehicle with chassis and interior. This proposal would enable replacement of the top part of the vehicle easily and more frequently than the bottom part. This could constitute a good opportunity for future research.

Due to their better business case, we focus on the normal and ultra-durable CAVs now and we compare their cost breakdown (excl. overheads) over the 10-year ownership period as per the graphs below.





The ultra-durable powertrain adds 11% (£1,900) to the initial investment in capital costs. However, the normal CAV requires 5 powertrain replacements along its lifetime, while the ultra-durable CAV only requires one. The calculation assumes a 150,000-mile lifetime for the normal powertrain and a 1m mile lifetime for the ultra-durable one[22]. After 10 years, this involves an overall vehicle cost saving of 7% (£8,300).

Cenex uses an in-house battery degradation model that considers both cyclical[23] and calendar[24] ageing to calculate useful life depending on charging power, charging type (AC or DC)[25] and thermal management (liquid or passive cooling)[23]. We can observe how the battery still needs to be replaced 6 times in both vehicle types, because designing an ultra-durable battery is out of the scope of this project. However, this poses an interesting opportunity for further research, as extending the life of batteries could provide a positive environmental and business case for ultra-durable CAVs.

Business Case Analysis

Fleet Business Model

We now scale up the 'per vehicle' business case to analyse a whole fleet of 422 small 2-seater pods, as per the CAV demand model example shown previously for a 90% utilisation in a London L4 CAV area. With an annual mileage of 107,000 miles and a trip fare of £0.98/mile, the table below shows what the business case would look like after 10 years.

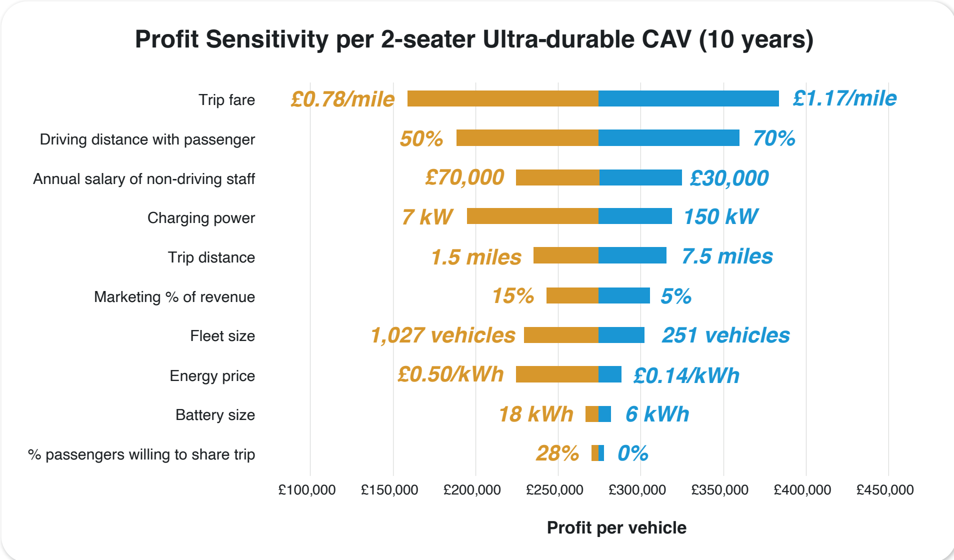
	Human driven taxi	Normal durability CAV	Ultra-durable CAV
Vehicles, electricity and chargepoints	*£53 m*	*£57 m*	*£53 m*
Overheads	*£437 m*	*£97 m*	*£97 m*
Total costs	£490 m	£154 m	£150 m
Revenue	£266 m	£266 m	£266 m
Profit	**-£224 m**	**£112 m**	**£116 m**
Annual investment return	**N/A**	**7%**	**8%**
Payback (years)	**N/A**	**2.6**	**2.4**
Trip fare for 3 year payback (£/mile)	£2.25	£0.90	£0.86
Trip fare for 5 year payback (£/mile)	£2.05	£0.69	£0.66
Trip fare for 10% annual return (£/mile)	£4.27	£1.17	£1.14

As previously explained, the human-driven fleet provides a negative business case using robotaxi fares due to the high overhead cost coming mostly from driver salaries. However, the CAVs provide reasonable paybacks to the initial investment using predictions of future London robotaxi fares[16].

Cenex then calculate the trip fare that the fleet would need to charge in order to have a 3 to 5 year payback, and a 10% annual investment return. The 3 and 5-year payback fares for the human driven taxi are similar to future taxi fare predictions of £2.13/mile[16]. The 3 and 5-year payback fares for the CAVs are in line with the average UK total cost of ownership for a medium car, which is £0.77/mile for a petrol car and £0.68/mile for a BEV[26]. This means that a robotaxi service aiming to achieve a reasonable investment payback could compete with private car ownership. If the investment goals were more aggressive and we tried to achieve a 10% annual return, then the trip fares would need to be higher and potentially not competitive with other robotaxis services or private car ownership.

Business Case Analysis

Sensitivity Analysis



To finish the business case analysis, Cenex perform a sensitivity exercise by identifying 10 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 central scenario in which all variables are kept at their medium value; this constitutes the axis of the tornado chart shown above. 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.

The analysis shows that the 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. The driving ratio with passenger (shown as % of total mileage) is also very important, as just a +/- 10% variation can have a large impact on the profit. It would therefore be very interesting to improve algorithms to optimise the strategies for pick-up and drop-off of passengers to minimise 'dead' mileage (this will be further explored in the refined transport modelling exercise explained previously).

There are other variables with high relevance for the business case, such as salary of staff, which will still be needed even without a driver in order to clean, charge and manage the vehicles and the business. Moreover, we note that charging power has much more importance than battery size, as even small battery sizes can benefit from rapid charging. The less time the vehicles spend charging, the more time they will have to drive around looking for passengers, driving to passenger hotspots or driving them to their destination. The impacts on battery degradation due to rapid or ultra-rapid charging would still need to be accounted for, and this could pose an interesting topic for further research.

Another variable that we could include in the sensitivity analysis is the potential 'pay as you go' road user pricing that governments may introduce to mitigate congestion and make up for the tax shortfall caused by the switch to electric vehicles[27]. We do acknowledge that road pricing could be a possibility, but there are not good enough predictions to quantify this. Moreover, it will be applied to all vehicles and not just CAVs, so there will not be a difference in business case between different types of vehicles. Therefore, we have decided not to include this variable in the analysis.

Policy Considerations

A detailed discussion of the broader policy implications of CAVs is outside the scope of this report. In this section we briefly outline some topics that policymakers should consider, with a focus on the potential implications of accelerated development of ultra-durable powertrains.

CAVs can help tackle many of the challenges associated with road transport:

- Vehicles will have zero tailpipe emissions and will therefore reduce greenhouse gas emissions which contribute to climate change, and pollutant emissions which contribute to poor air quality.
- By reducing the number of privately owned conventional vehicles on the road, CAVs can help alleviate congestion.
- CAVs will be expected to increase the safety of passengers and other road users.
- CAVs can increase access to mobility for marginalised groups including the elderly, disabled, and those on low incomes.
- By reducing demand for road space and parking, CAVs can help planners reallocate space in the urban realm to encourage active travel.

As this report outlines, the development of ultra-durable powertrains for CAVs will help improve the business case for manufacturers to build these vehicles, and for their deployment by fleet operators. This would have several policy implications:

- Improving the business case for CAVs may accelerate the timing and rate of deployment. Policymakers should be aware of this and be proactive in their engagement with potential suppliers and end users.
- An accelerated timescale will present near-term opportunities for cities to be test beds for CAV services, and there may be competition between cities to attract technology trials.
- Ultra-durable powertrains can help overcome concerns about the lifecycle (manufacturing, use and disposal) sustainability of CAVs. Policy makers should encourage technology developers to measure and report lifecycle greenhouse gas emissions. Likewise, policy makers should aim to create targets/requirements based in lifecycle (and not just operating) emissions.
- L4 CAVS have a limitation in that they must be restricted to a defined geographical area. However, this is an advantage from a policy perspective, as their use can be restricted to a desired area via a geofence. For example, although in this report we consider deployment in central London as a generic use case, it could be advantageous to prevent their operation here, to reduce competition with public transport.
- If ultra-durable CAVs allow operators to provide a cheap and convenient car service, this may reduce use of active travel and public transport. Policy makers should be aware of interplays between different policy objectives.

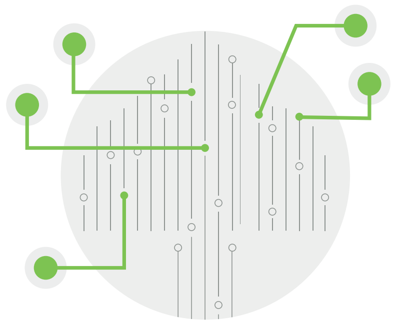
L5 CAVs (full autonomy, able to operate under all conditions) are not expected to be deployed until at least 2035. L4 CAVs are at early trial stage, and operators may seek to deploy these services at scale in cities in the 2020s. National and local policymakers should ensure they are abreast of the latest developments in CAV technology, and are proactive in preparing for potential deployment, to maximise potential benefits and minimise any negative impacts.

Next Steps

Life Cycle Assessment and Geospatial Transport Model

Cenex will perform a life cycle assessment (LCA) of an ultra-durable CAV compared to a normal durability CAV once the design of the powertrain is finalised. Cenex will use data provided by project partners Romax Technology and EMPEL Systems on bill of materials (BoMs) for powertrain components and on vehicle energy consumption based on their simulations. Data from non-powertrain components will be derived from public literature. The study will quantify emission savings due to the fewer powertrain replacements required in the ultra-durable vehicle and the improved efficiency of the ultra-durable powertrain, taking into account the whole life of the vehicle from manufacturing to end of life.

Cenex will also perform a detailed geo-spatial analysis of the transport demand within our London L4 CAV areas using bespoke software. The objective of this task is to explore different possible future scenarios in terms of charging, trip sharing and transport demand. The results from this exercise and the LCA will be published in early 2022.



Completing the Picture

As has been stated, RUBICON proposes a hypothesis concerning the viability of autonomous taxis being able to provide TaaS transportation within the urban environment. For this to be confirmed, it would have to be shown that there are cost and environmental advantages to such a business model.

The steps to complete the picture will be to assemble the data from the previous sections into a combined analysis to compare the performance of the TaaS vehicle against current production vehicles. The hypothesis will be shown to be valid if:

- The economic model shows an advantage over current vehicles in production. We operate in a free market and the consortium believes that working with the market rather than against it is the best way to achieve societal change that protects the environment.
- The total life cycle environmental impact is less than for current vehicles in production, and those being designed. Whilst the economic imperative dominates, it is anticipated that society will increasingly focus its attention on the environmental impact of any industry. Any demonstrable advantage in terms of sustainability will enhance the commercial chances of that solution.

About

Cenex

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Independent non-profit experts in low emission transport research and consultancy headquartered in Loughborough (UK), with presence in Edinburgh, London, Amsterdam, South Korea and Barcelona. We accelerate the shift to low emission transport and energy solutions by delivering projects that support innovation and market development.

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Hexagon is a global leader in sensor, software and autonomous solutions. We are putting data to work to boost efficiency, productivity, and quality across industrial, manufacturing, infrastructure, safety, and mobility applications. Romax, part of Hexagon's Manufacturing Intelligence division, provides world-leading solutions for the design, analysis, testing and manufacture of gearboxes, drivetrains and bearings.

EMPEL Systems

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EMPEL Systems is at the forefront of creating new electric propulsion technologies that deliver higher performance, efficiency, and value achieved through development of an innovate modular, multi-voltage, scalable integrated e-motor and inverter product family.

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