Transport

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EMPEL SYSTEMS

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Project RUBICON
Future Autonomous Mobility

Session Chair, Steve Carroll

3rd February 2022

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PROJECT RUBICON – FUTURE AUTONOMOUS MOBILITY

Project Introduction

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PROJECT RUBICON – FUTURE AUTONOMOUS MOBILITY

Project RUBICON

ultRa dUraBle electrIC pOwertraiN

- Design of a powertrain for an autonomous passenger carrying vehicle that has very high utilisation and runs for ~1 million miles (or greater)

The Hypothesis

- Personal transport within a given city is provided as a service by small, autonomous electric vehicles that have high utilisation and acquire high mileages (~1m miles)
- The combination of no driver, high vehicle mileage and high utilisation makes the total cost of ownership and operation attractive, both economically and environmentally
- This means that it is a viable business and operational model which will compete with and displace conventional urban modes of transport

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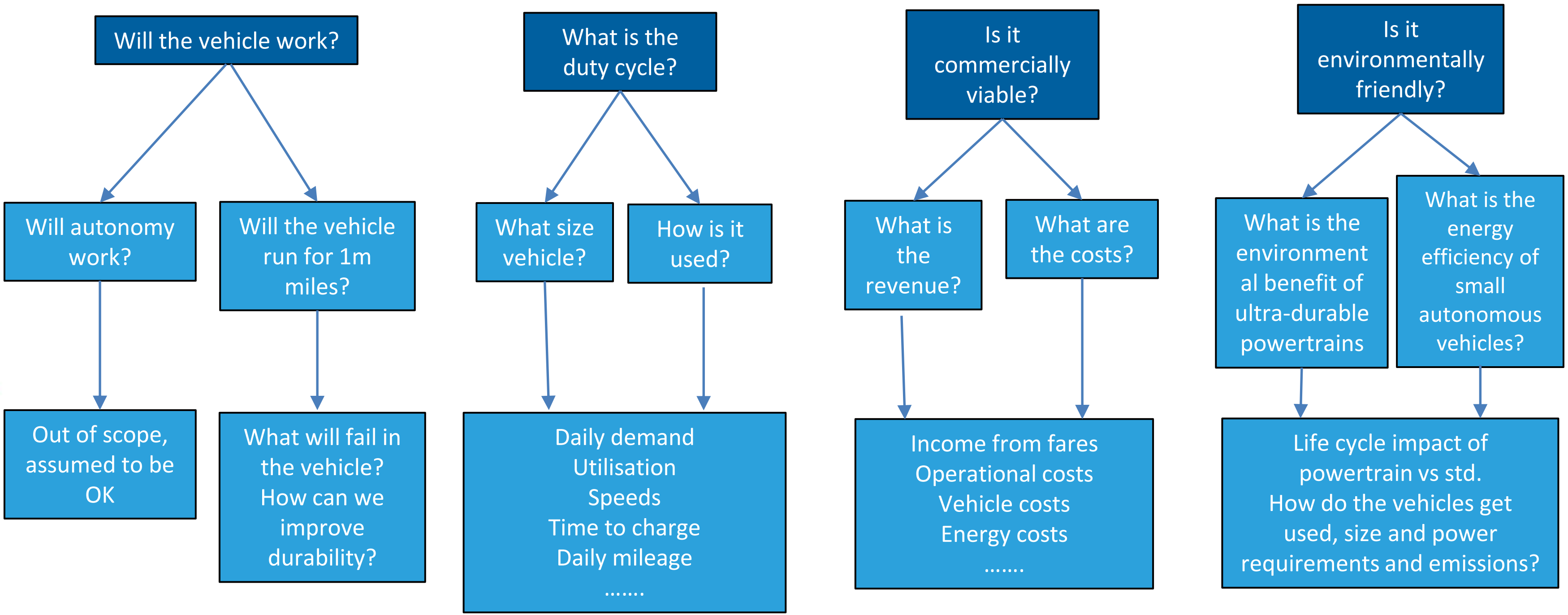
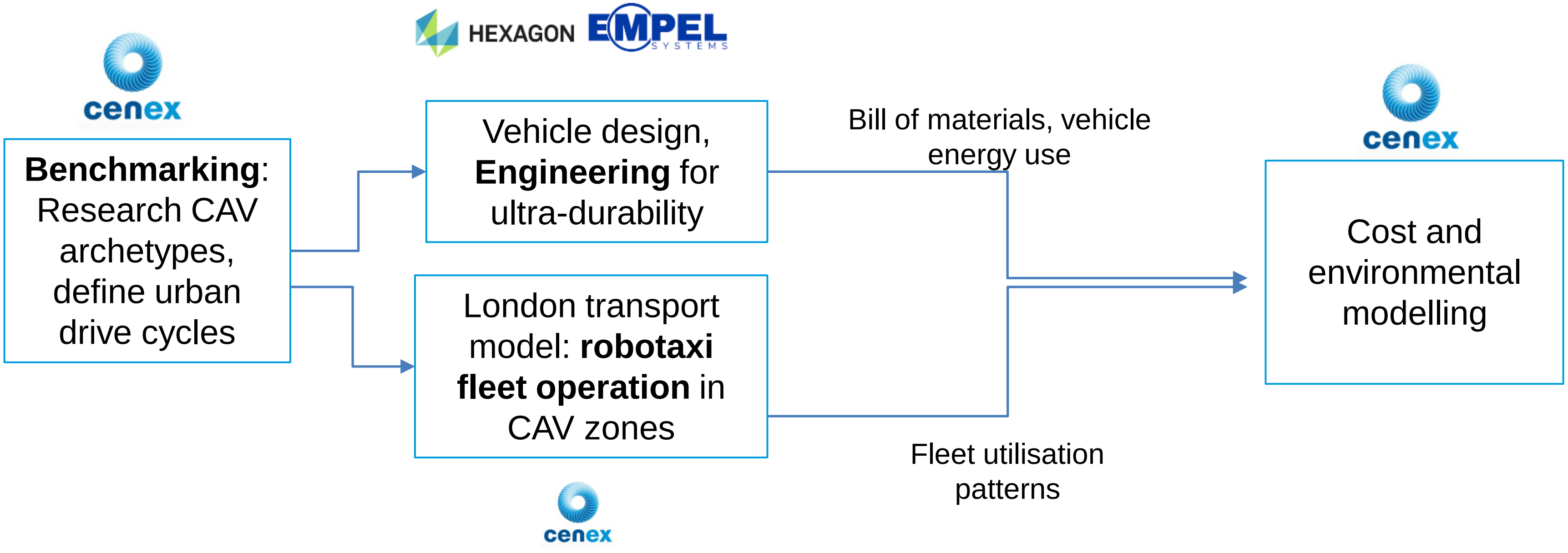
PROJECT RUBICON – FUTURE AUTONOMOUS MOBILITY

Is it viable?



Project RUBICON Workflow



Meet the Team

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- Durability assessment
- Component design
- Software development

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- Specialist support on motor design

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- Operational demands
- Business case
- Environmental case

Format of the Day

Duration	Topic	Lead
10 mins	Welcome and scene setting	Steve Carroll, Head of Transport, Cenex
15 mins	Engineering the case for ultra-durable CAVs	Barry James, Head of Research and Innovation, System Dynamics, Hexagon
15 mins	City demand for CAVs	Luis Ramos, Transport Planning Consultant, Cenex
15 mins	Business and Environmental Case	Victor Lejona, Modelling and Analysis Team Leader, Cenex
5 mins	Q&A & Close	All

Engineering challenges of ultra-durable powertrains for CAV applications

Barry James
Head of Research & Innovation

Global leader in **sensor**, **software**,
and **autonomous** solutions committed to

empowering an autonomous future

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Hexagon at a glance…

Hexagon digitizes the world

- Solutions for a wide range of industries including Electronics, Construction, Energy, Automotive & Aerospace
- 55% of net sales are software & services

R&D focused

- **10-12%** of net sales invested in R&D
- **3 800+** employees in R&D
- **3 700+** active patents

Global reach

- More than **20 000** employees in **50** countries
- Broad range of vital industries served

Strong financials

- **Around 3.8bn EUR** in net sales; 1/3rd from Americas, EMEA, Asia
- **25% operating margin**
- **6% CAGR sales growth 2015 - 2019**

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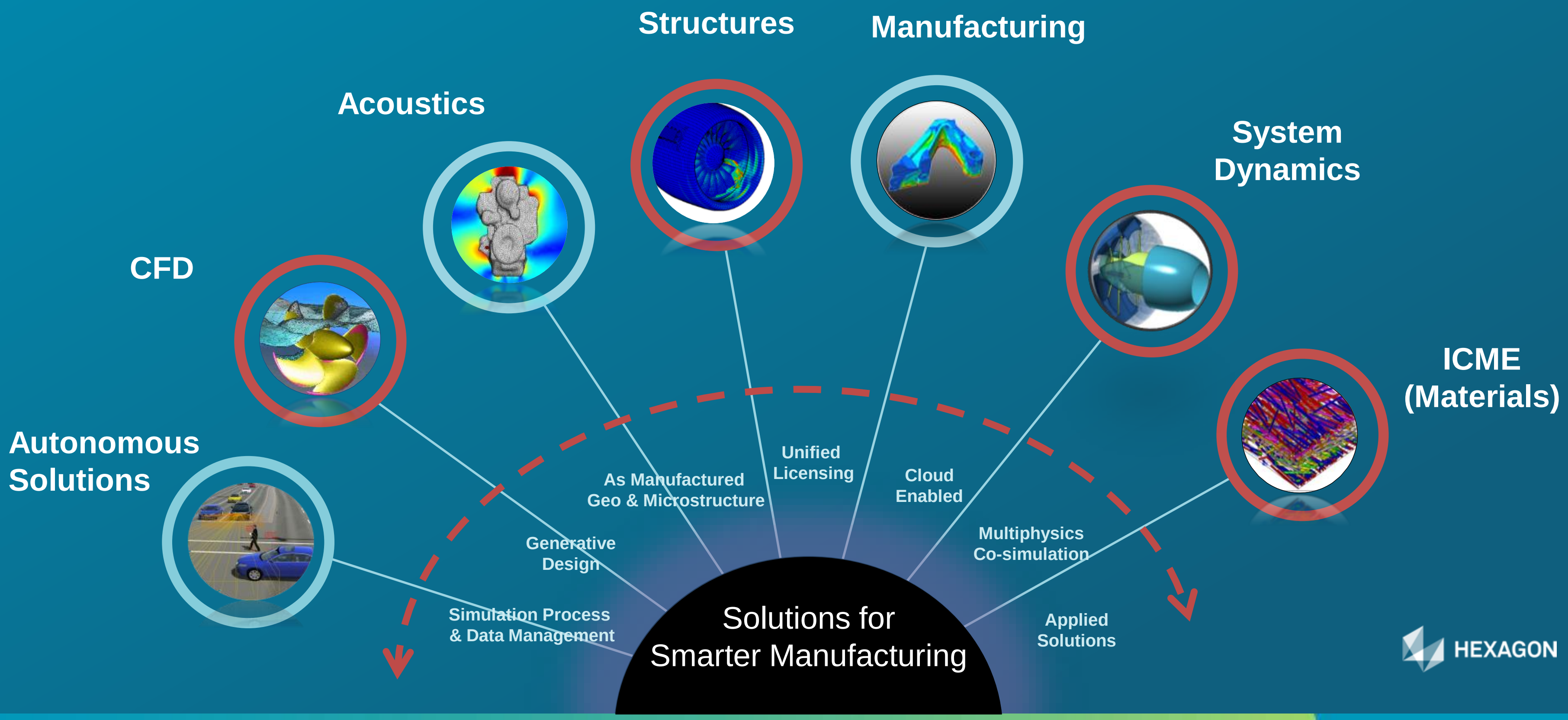
Hexagon’s portfolio of technology & software allow our clients to <u>Engineer a Better World</u>



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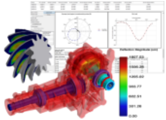
Applied Solutions

***Expertise in Electrification** : e-Mobility : e-Powertrain : Software Intensive Systems : I4.0*

Systems Engineering		• Whole lifecycle support • Architecture Definition and Concept Design • Dynamic System Modelling • Performance Analysis • Reliability Engineering • Functional Safety and Cyber Security • Process Improvement
Electro-Mechanical Engineering		• Electromechanical design, integration, manufacturing and testing • Rotating machines and transmissions • Lubrication and Cooling • Design Analysis and Optimisation (structural, thermal, co-sim etc.)
Electrical & Electronic Engineering	 	• Electronic systems design, integration, manufacturing and testing • Power Electronics, Inverters and MCUs • Electrical Machines • Control and Instrumentation (C&I) Systems inc Sensors and Actuators • Embedded Software and Controls Algorithm Development
Build & Test		• Manufacture, Integration and Testing • System and Subsystem verification – Including *Virtual Verification* – Digital Twins

Engineering a sustainable and ethical ePowertrain

Whole Lifecycle Analysis, Environmental impact reduction

At the ***vehicle level***, it is clear that there are three key factors which influence the ability to improve/reduce lifecycle (LCA):

1. **Vehicle size and mass**
2. **Vehicle range / Size of battery (assuming BEV)**
3. **Vehicle Lifetime impact/efficiency (relative to production impact)**

"Right sizing"

Reduce (higher reliability), reuse (modularity), recycle (material selection)

Interestingly, at the ***vehicle level,*** these factors are tightly coupled with total lifecycle costs (TCO). Therefore, reducing LCA also helps reduce the TCO.

The opportunity to influence the vehicle level factors ("right sizing") requires a detailed understanding of how vehicles are used compared to industry trends

➔ **Vehicle Use-case Analysis…**

Vehicle Use-case Analysis

Transport-as-a-Service/Connected and Autonomous Vehicle demand and cost modelling summary

- Based on UK Gov data — Department for Transport

- Around 62% of all car journeys only have 1 occupant (the driver) : this is dominated by commuting & business trips
- Around 88% of all car journeys only have up to 2 occupants or less
- 98% of commuting journeys have a maximum of 2 occupants

No of Occupants	Journey type							
	Commuting	Business	Education	Shopping	Personal business	Leisure	Holiday / day trip	All purposes
1	**89%**	**86%**	36%	52%	69%	56%	42%	**62%**
2	**9%**	11%	38%	36%	25%	26%	32%	**26%**
3	1%	2%	15%	7%	4%	11%	15%	7%
4	1%	1%	11%	5%	3%	7%	11%	5%

A brief look at BEV Archetypes…

Type	1 Small Pod / Microcar	2 Small Pod / A-segment	3 Medium Pod / B-Segment	4 Medium Car / C-Segment	*5 Large Pod*
Seats	2	4	5	5	*6*
Range	~ 90 km	~ 160 km	~400 km	~ 270 km	*~ 400 km*
Top speed	~ 45 - 80 km/h	~ 130 km/h	~ 135 km/h	~ 158 km/h	*~ 160 km/h*
Example vehicles in class	Renault Twizy, Citroën Ami	Dacia Spring, Fiat 500e	Renault Zoe (ZE50 R110)	Nissan Leaf (Acenta)	*VW Sedric (MEB based Concept)*
ROM Cost	7				

Courtesy Citroën

Courtesy Renault

Courtesy Dacia

Courtesy Renault

Courtesy Nissan

Courtesy VW

Overall Car Size: Energy Use

Yutong E10 (50 Seats)

- Energy Use → 2.8 kWh/mile
- Mass: 13200 kg
- With 25 passengers its equivalent to 25 single passenger Renault Twizy trips.

Renault Twizy
Range: 56 miles
6.1kwh battery
Energy Use → 0.11 kwh/mile
Mass: 450 kg

Tesla Model 3

- Range: 254 miles
- 54kWh battery
- Energy Use → 0.21kWh/mile
- Mass: 1645kg

Nissan Leaf

- Range: 168 miles
- 40kWh battery
- Energy Use → 0.24 kwh/mile
- Mass: 1650kg

LEVC LX

- Range: 80.6 miles
- 31kWh battery
- Energy Use → 0.38kWh/mile
- Mass: 2000kg

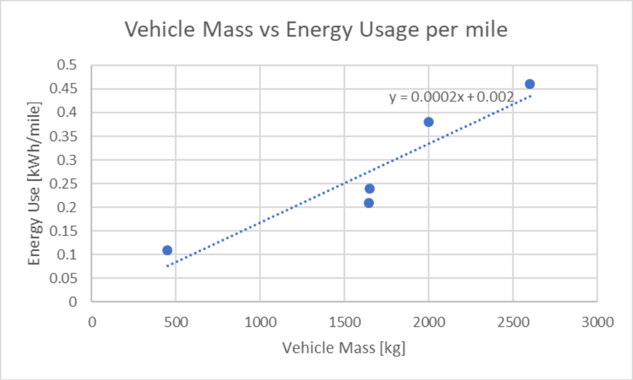
Rivian R1T

- Energy Use → 0.46 kWh/mile
- Mass: 2600 kg

Cake Kalk (with passenger) → 0.03 kWh/mile

Xiaomi Pro (with passenger) → 0.016 kWh/mile

xagonmi.com/romax



Conclusion:

EV powertrains are already quite efficient (+85%). We need to look at decreasing vehicle energy usage.

Every 1000kg of vehicle requires ~ 0.17 kWh/mile of energy use.

We want to use more energy carrying passengers, not carrying vehicles.

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Derived CAV/TaaS platform

Type	1 Small Pod / Microcar	Derived TaaS Platform	2 Small Pod / A-segment	3 Medium Pod / B-Segment	4 Medium Car / C-Segment	*5 Large Pod*
Seats	2	2	4	5	5	*6*
Range	~ 90 km	~ 100 km	~ 160 km	~400 km	~ 270 km	*~ 400 km*
Top speed	~ 45 - 80 km/h	80 km/h	~ 130 km/h	~ 135 km/h	~ 158 km/h	*~ 160 km/h*
Examples	Renault Twizy		Dacia Spring	Renault Zoe	Nissan Leaf	*VW Sedric*
ROM Cost	£7-15 k	£10-20 k	£17-28 k	£28 k	£20 k	> £30 k


Courtesy Citroën


Courtesy Renault


Courtesy Renault


Courtesy Dacia


Courtesy Renault


Courtesy Nissan

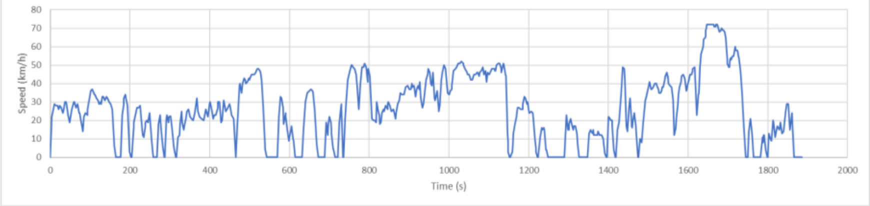
Courtesy VW

Cardinal TaaS Platform Requirements

- **Archetype 1 – Small Pod**
  - Loosely based on the physical size of the Citroën Ami
  - Occupancy: 2 people occupancy + luggage
  - Mass: 485 kg kerb weight, 705kg gross vehicle weight
  - Duty cycle derived from real-world data (on Nissan Leaf platform) – derived top speed and acceleration requirements
  - Top speed: 80 km/h (50 mph)
  - Acceleration: 0 - 80 km/h in 12 s
  - Range: 60 miles / 100 km
  - 23/24 hours availability (charge time ~ 1 hour)
  - 1,600,000 km durability (up from typical 300,000 km)

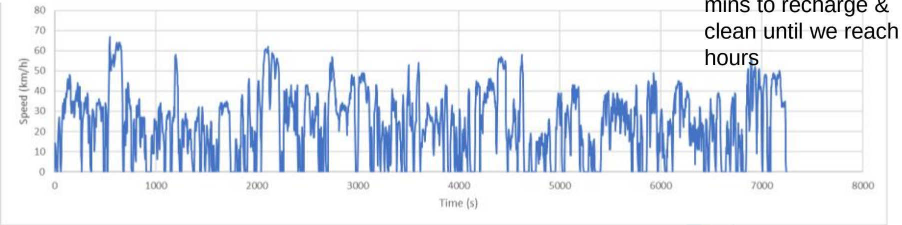
Courtesy Citroën

30 mins cycle Archetype 1



Full day cycle Archetype 1

Repeated cycles of 5 hours driving and 20 mins to recharge & clean until we reach 24 hours



E-Machine Reliability Improvement Opportunities

Simplified!

Bearing Current – induced magnetic fields – thermal events - Poor design

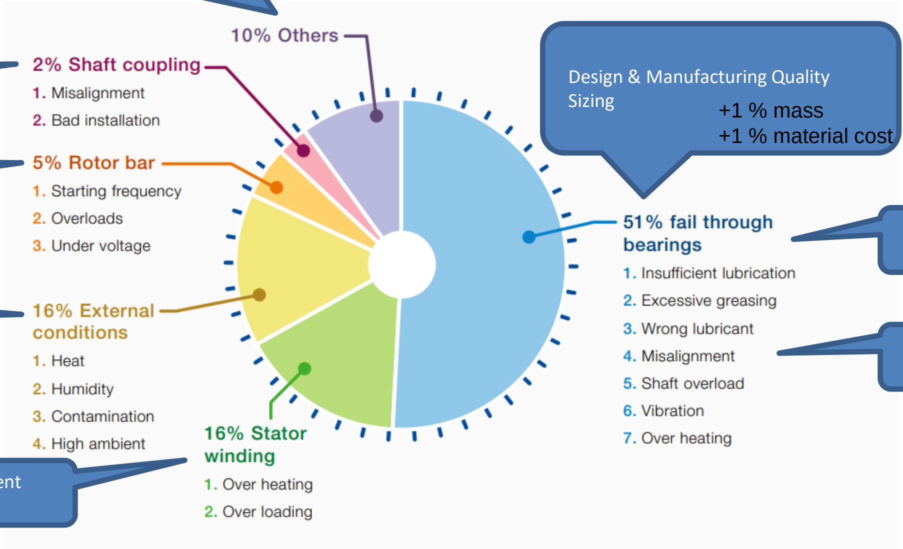
Manufacturing Quality

Control/Protection system failure or poor design

External Environment Thermals

Insulation/Material Breakdown

Internal Environment Thermals



Courtesy ABB, based on IAEA / NEMA data

Design & Manufacturing Quality
Sizing
+1 % mass
+1 % material cost

Internal Environment Thermals

External Environment Shock, Vibration

Manufacturing QA & tolerances

- Thermal induced failures ➔ Cooling System
- Electrical failures ➔ Control System
  - Increased monitoring vs Sensorless
- External Environment
  - Thermal induced failures ➔ Cooling Syste
  - Shock, Vibration ➔ Mounting Design and Manufacturing QA
  - Bearing ➔ Design/Selection and Manufacturing QA

Summary: E-Machine Failures are predominantly induced by their external environment/system or poor manufacturing.

Total quality assurance is achieved via the system-level (application of systems engineering).

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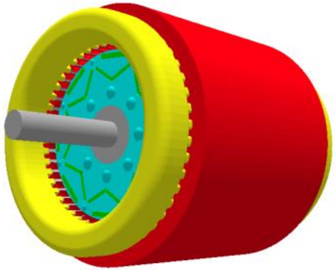
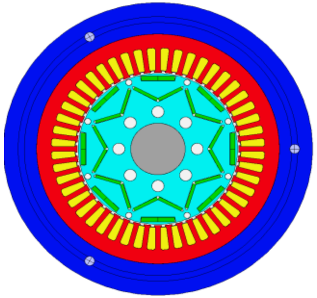
Investigating the benefits of motor over-sizing

- An ‘oversized’ motor flies in the face of conventional motor design, however when view with respect to the life cycle of an ultra-durable vehicle…..

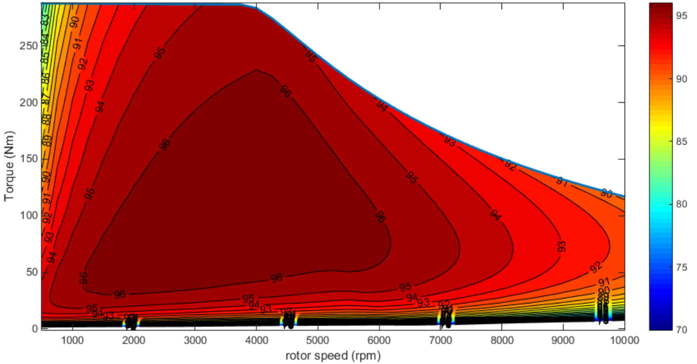
$$T = F\frac{D}{2} = \sigma \times \text{Area} \times \frac{D}{2} = \sigma\pi DL\frac{D}{2} = \frac{\pi}{2}D^2L\sigma = 2V_r\sigma$$

  - Increase motor size → lower flux density → lower current → lower resistive losses → **higher efficiency** (confirmed through simulation)
  - Lower resistive losses → less heat generation → lower operating temperatures → lower winding degradation → **improved durability**





– fficult to define, but in this case we selecte



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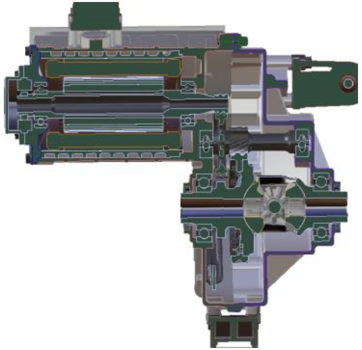
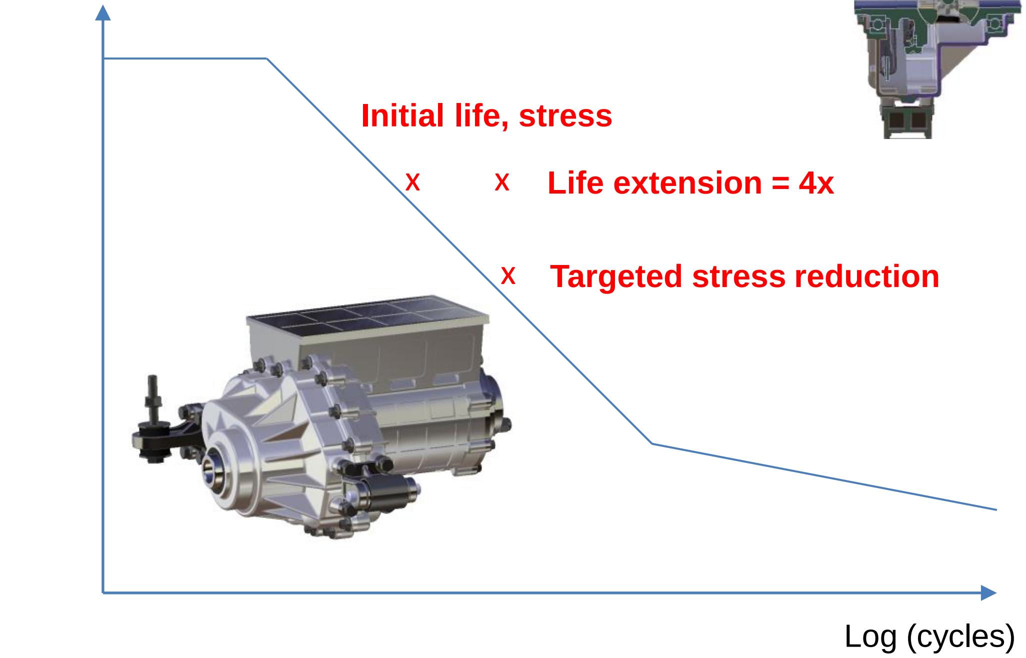
Designing a gearbox for ultra-durability



- Baseline TaaS gearbox designed according to ISO 6336 and benchmarked against gearboxes of existing vehicles in production and use

- A 4x increase in durability was targeted and the quantified increase in size was based on ISO 6336

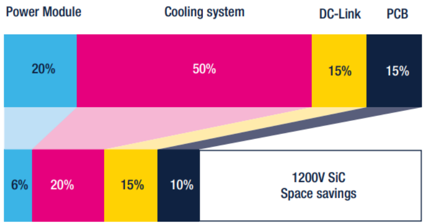
- Bearings were corresponding re-sized to give a ‘like-for-like’ level of reliability, indicating the penalty in the Bill-of-Materials for achieving ultra-durability



Power Electronics Reliability Improvement Opportunities

Simplified!

- Component Selection/sizing and Technology: IGBT vs SiC vs GaN

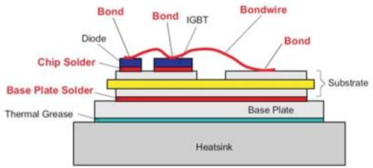


Courtesy ST

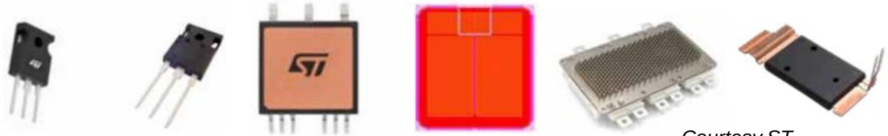
Parameter	IGBT	SiC
Chip Area	100%	20%
Conduction Losses	100%	~100%
Switching Losses	100%	~25%
Total losses	100%	~52%
Junction Temperature	100%	~98%

- Inverter:
  - \- 40% mass (approx.)
  - \+ 450% material cost (approx.)
  - Avg + 3% efficiency improvement
- System:
  - Savings afforded by increased efficiency and therefore potential battery reduction

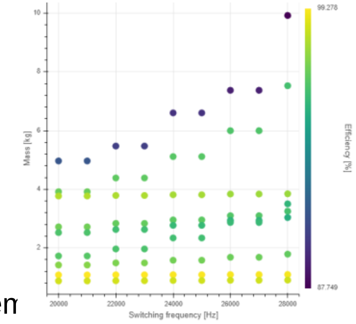
- Component Packaging : Thermal Management : inc direct immersion cooling



Courtesy EE Power



Courtesy ST



- Switching Frequency Optimisation: Multi-parameter sweeps
- Single point failure mitigation: Switching Devices – Multilevel Topologies cf Lower V/I devices
- Controller platform: microarchitecture, feature size, transistor tech, voting logic, diagnostics/prognostics implem
- Packaging / PEMS vs Hybrid,, Sn-rich solders and component mitigations inc Conformal coating

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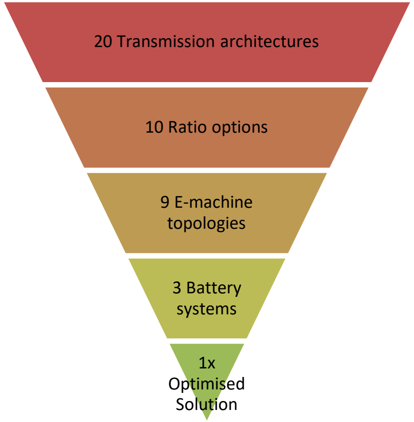
ePowertrain Architectural Development

Attributes we can influence at the ePowertrain level

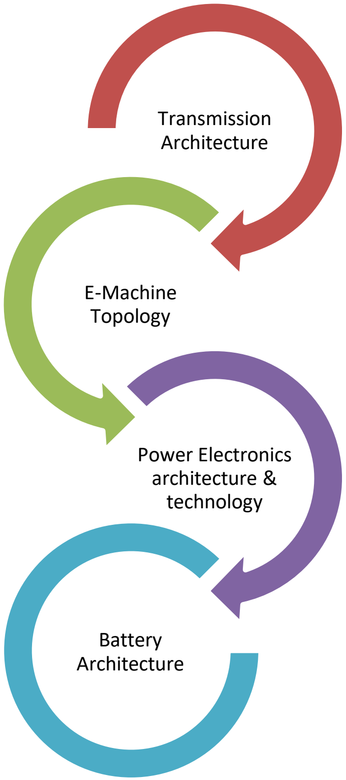
QuickE™ Rapid powertrain architecture assessment tool



1600 options (based on 1 motor, single speed transmission), rapid focussing down to 36 candidates…

- Topology
- Magnets
- Materials
- Efficiency

- Chemistry
- Voltage
- Layout
- Cooling
- BMS

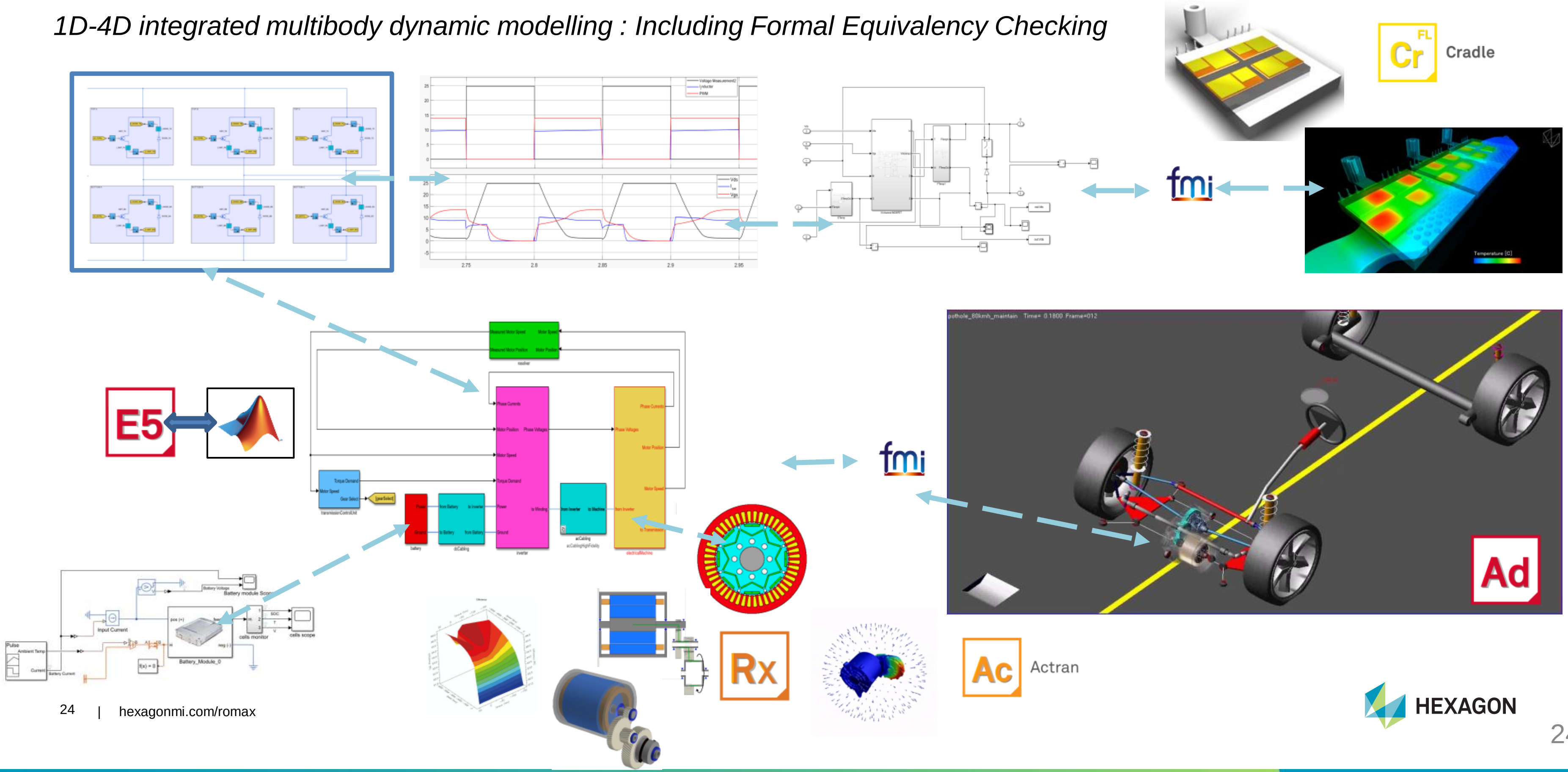


- Single vs Multispeed
- Ratio
- Stages
- Gears
- Lubrication
- Materials

- Power stage topology
- Power stage packaging/cooling
- Switching technology/component selection
- Switching frequency
- Motor Control Unit platform
- Diagnostics platform
- Software architecture

MBSE : Virtual Verification and Validation (V&V)

1D-4D integrated multibody dynamic modelling : Including Formal Equivalency Checking



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Bill-of-Materials derived by component and material for both versions

	Mass (Ultra-durable)	Mass (Standard)	% change
Gearbox & Motor Weight Include Housings	20.621	19.232	7.224
Gearbox Weight Include Housings	14.139	13.465	
Gearbox Weight Exclude Housings	6.518	5.994	

Gearbox Component List

UK-000703-AS-200	Housings	7.621	7.471
UK-000703-HG-106	GEARBOX HOUSING	1.346	1.291
UK-000703-HG-105	eMOTOR HOUSING	4.975	4.935
UK-000703-HG-202	eMOTOR COVER	0.288	0.25
UK-000703-HG-212	INVERTER COVER	0.255	0.255
UK-000703-HG-201	WATER JACKET	0.757	0.74
UK-000703-AS-203	Gear & Shaft Assemblies	2.382	2.339
UK-000703-GS-211	Intermediate Shaft with Output Pinion	0.320	0.315
UK-000703-GS-213	Gear, Input Wheel	0.268	0.259
UK-000703-BR-002	Idler Bearings	0.288	0.288
UK-000703-GS-210	Gear, Output Wheel	0.543	0.516
UK-000703-GS-209	Input Shaft with Input Pinion	0.707	0.705
UK-000703-BR-004	Input Bearings	0.254	0.254
7015-CC-214	Retaining Ring	0.002	0.002
UK-000703-AS-201	Differential Asembly	3.840	3.359
UK-000703-GS-202	Differential Housing	2.271	1.980
UK-000703-BR-003	Differemtial Bearings	0.706	0.615
UK-000703-GS-203	DIFFERENTIAL AXLE	0.129	0.112
UK-000703-GS-206	FOIL, DIFFERENTIAL PROTECTIVE CASE	0.011	0.010
UK-000703-GS-204	DIFFERENTIAL SIDE SHAFT BEVEL GEAR	0.458	0.399
UK-000703-GS-205	DIFFERENTIAL SPIDER BEVEL GEAR	0.178	0.155
UK-000703-SC-207	SPLIT DOWEL	0.003	0.003
7015-SC-236	BOLTS	0.084	0.084
UK-000703-AS-202	PARK LOCK ASSEMBLY	0.296	0.296
	SPRING, PLUNGER	0.011	0.011
	SPRING, LEAF	0.004	0.004
	SCREW	0.033	0.033
	ACTUATION ARM	0.011	0.011
	PIN, PAWL PIVOT	0.001	0.001
	SPRINT, PARK PAWL	0.110	0.110
	PARK PAWL	0.028	0.028
	PLATE, ACTUATION FRAME	0.028	0.028
	PLUNGER	0.044	0.044
	PLUNGER ASRM	0.022	0.022
	ROLL PIN	0.002	0.002
	WASHER	0.001	0.001
	WASHER	0.001	0.001

Motor Component and Materials List

Parts	Components	Material	Weight	Unit
Stator	Stator Lamination	M235-35A	2.627	kg
	Windings	Copper	1.439	kg
	Slot wedge	/	0.002	kg
Rotor	Rotor Lamination	M235-35A	1.641	kg
	Magnet	N42UH	0.288	kg
Total weight	Active Materials	/	5.997	kg

Inverter Materials List

Material	Weigth	Unit
Aluminium oxide	12.60	g
Aluminum	0.36	g
Brass	1.43	g
Copper	552.39	g
Diantimony trioxide	3.70	g
Doped silicon	0.97	g
Epoxy resin	29.00	g
Glassfiber	57.00	g
Gold (coating)	0.05	g
Low-alloy carbon steel	106.20	g
Nickel (coating)	4.35	g
Nylon	2.00	g
Polycarbonate	3.21	g
Polyethylene therephtalate (PET)	76.35	g
Polyphenylene sulfide (PPS)	62.00	g
Polypropylene	104.24	g
Polyurethane resin	53.21	g
Silicone adhesive	0.10	g
Silicone gel	34.85	g
Solder (95.5Sn/3.8Ag/0.7Cu)	14.60	g
Tin	13.21	g
Zinc (coating)	2.25	g
Zinc oxide	1.35	g
Other mixed composites (%Brass, %	166	g

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City demand for CAVs

Luis Ramos

Transport Planning Consultant

Why modelling?

TCO and LCA analyses in the project require inputs extracted from a real-world operation of the fleet. These are:

- *Optimal fleet size for different utilisation targets*
- *Annual travel distance*
- *Average trip distance*
- *Share of total distance driven "in service"*
- *Average speed 'in service'*
- *Energy consumed per vehicle*
- *Maximum number of vehicles recharging simultaneously*

Model requirements

- *The modelling platform to be employed in the study must be able to analyse each vehicle in the fleet individually throughout a typical day of operation, extracting duty cycles and operation data, in short time intervals.*
- *The base model, of Greater London, must be validated to observed congestion data.*
- *Immense Fleet was selected as the most suitable platform, as it meets all requirements.*

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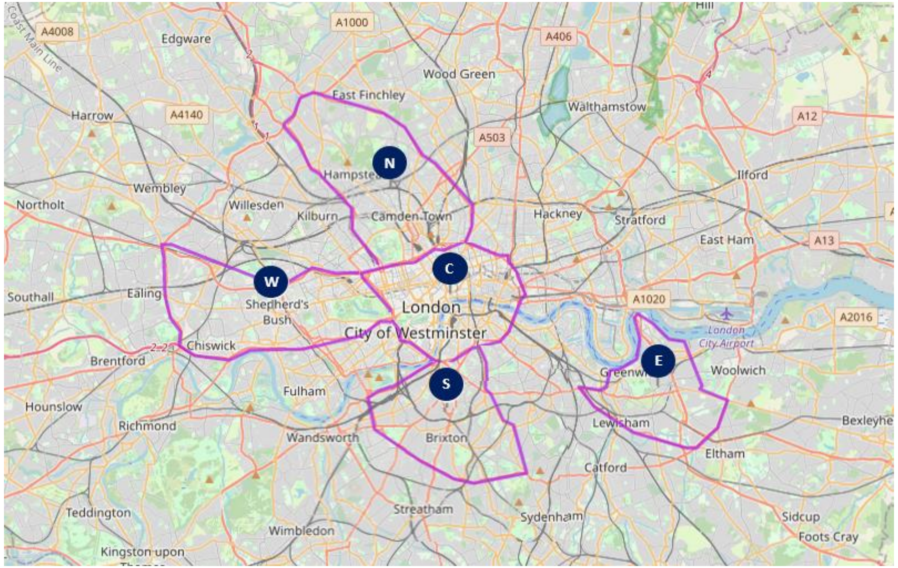
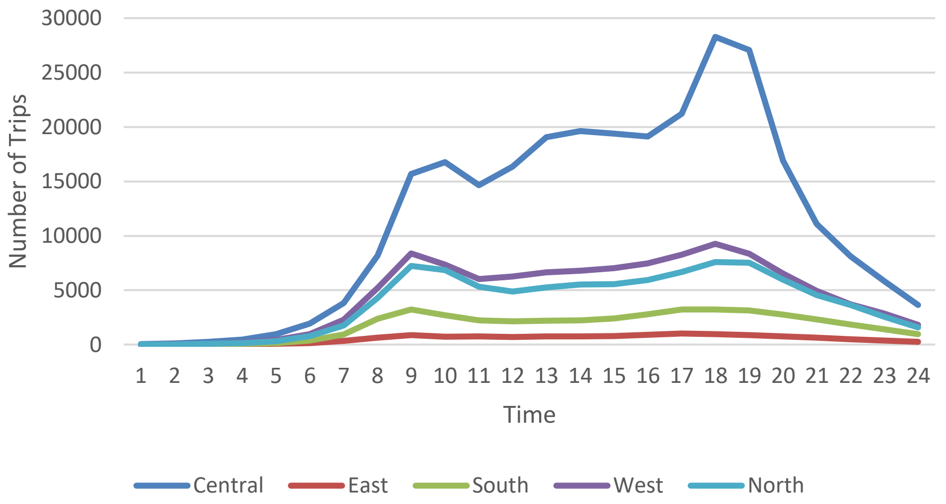
Model Extents and Duration

- *Five areas in Greater London: Central, North, East, South and West.*
- *All models were run for 24 hours.*
- *A typical weekday base model (Wednesday) was used.*



Trip Demand

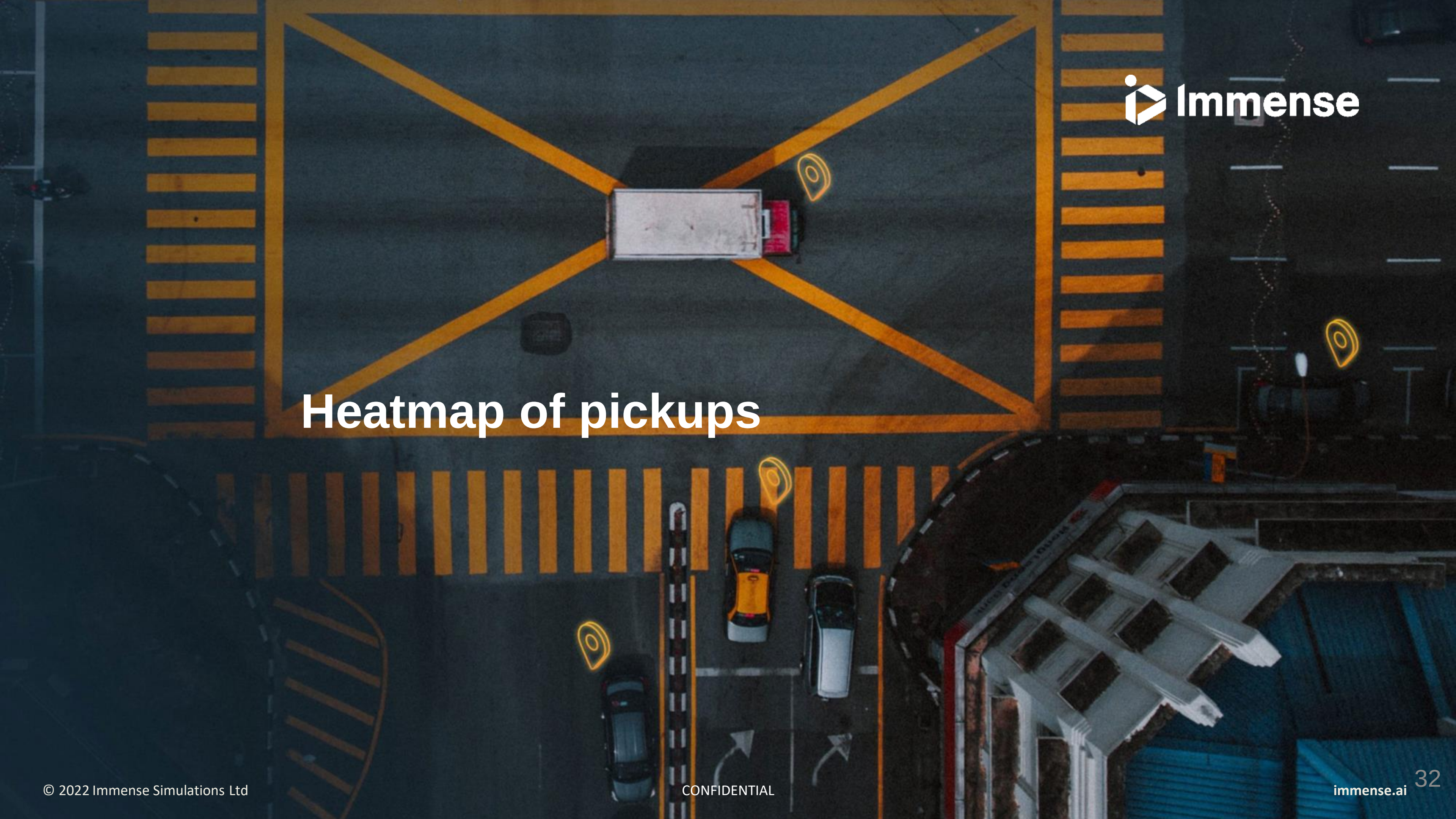
- *Demand from mobile phone data.*
- *Contains origin-destination coordinates and time of the day.*
- *Data from DfT on passenger per trip was incorporated.*



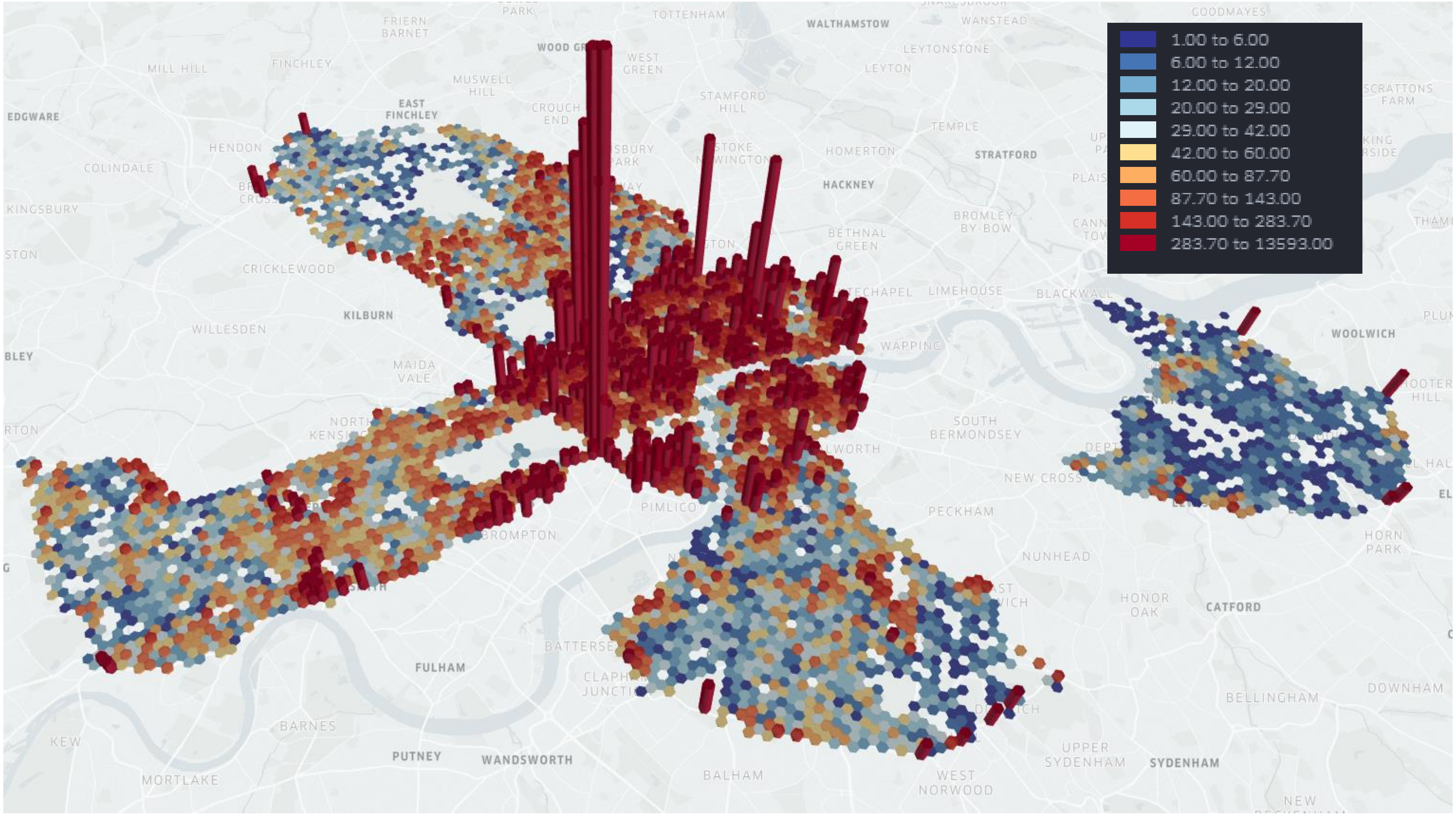
Methodology

- *To mitigate the uncertainty over future scenarios, a sensitivity testing approach was employed.*
- *Three variables were identified as the most relevant to the study.*
- *All permutations of these variables were tested, resulting in 60 scenarios per zone (300 total).*

Variable	Value
Infrastructure	Public
	Depot
	Public (reduced availability)
Split between 2-seaters and 5-seaters	100% 2-seaters, 0% 5-seaters
	75% 2-seaters, 25% 5-seaters
	50% 2-seaters, 50% 5-seaters
	25% 2-seaters, 75% 5-seaters
	0% 2-seaters, 100% 5-seaters
Willingness to ride-share (% of all trips)	0%
	10%
	20%
	30%



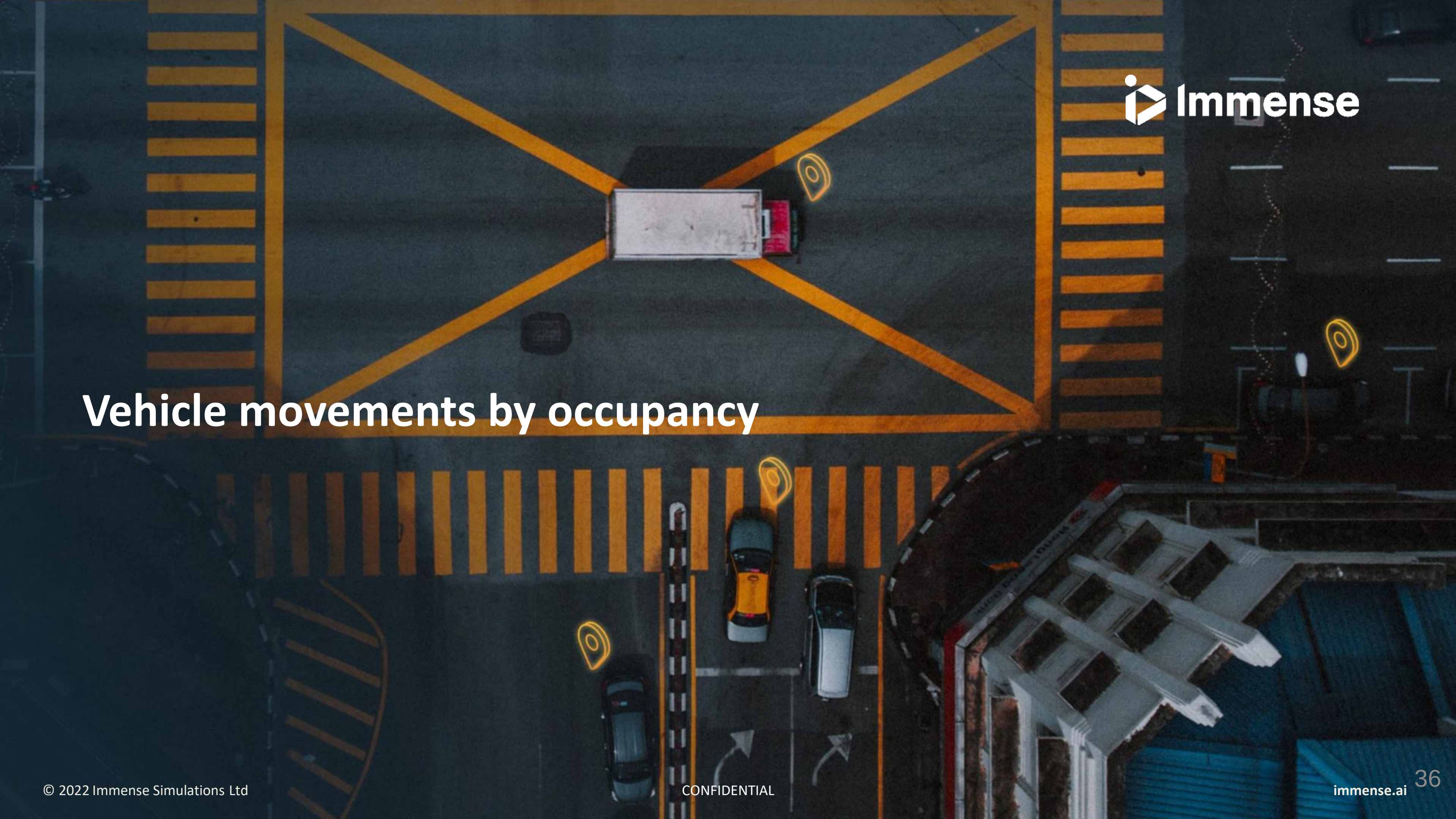
Heatmap of pickups


1.00 to 6.00
6.00 to 12.00
12.00 to 20.00
20.00 to 29.00
29.00 to 42.00
42.00 to 60.00
60.00 to 87.70
87.70 to 143.00
143.00 to 283.70
283.70 to 13593.00

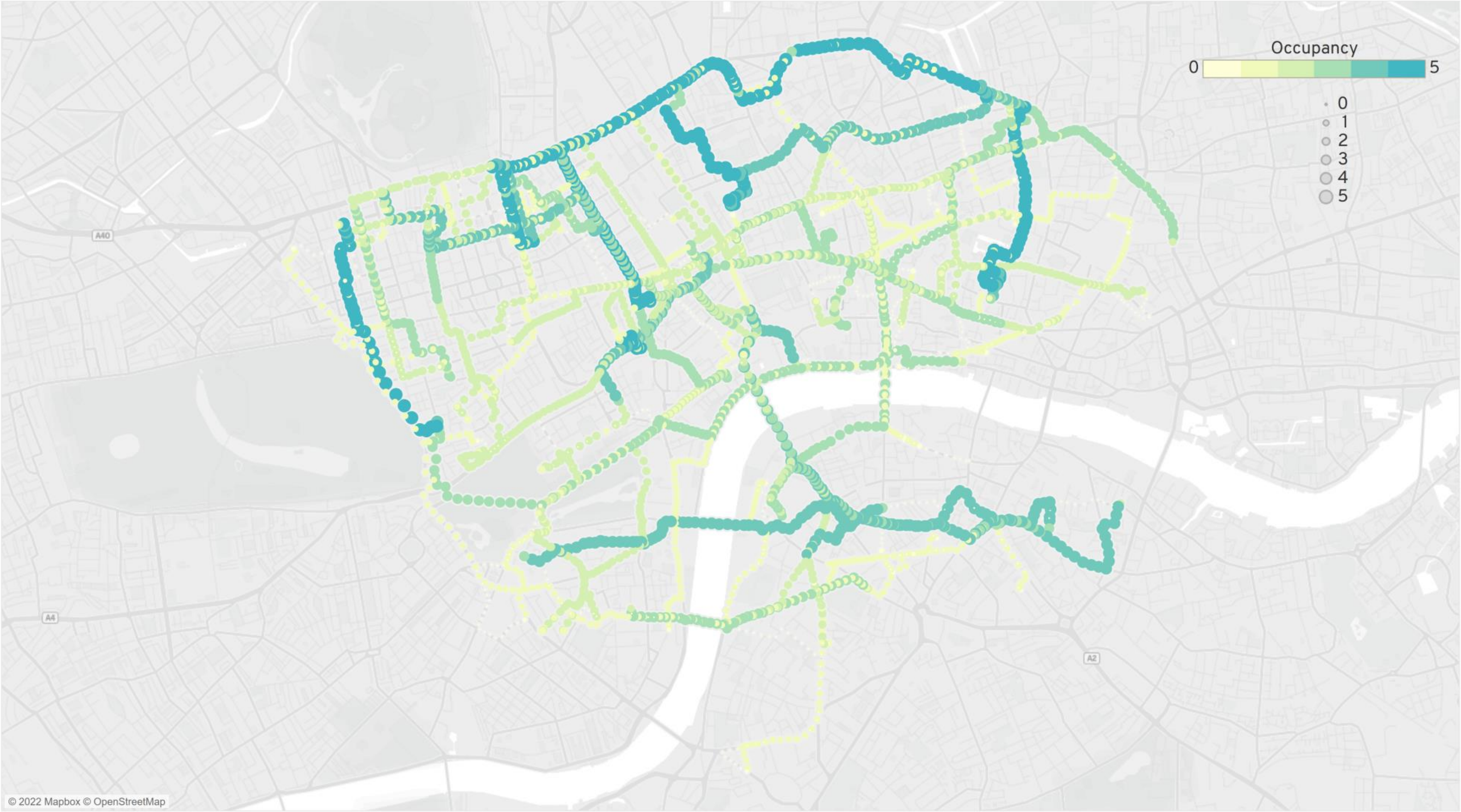
Immense

Vehicle movements by state

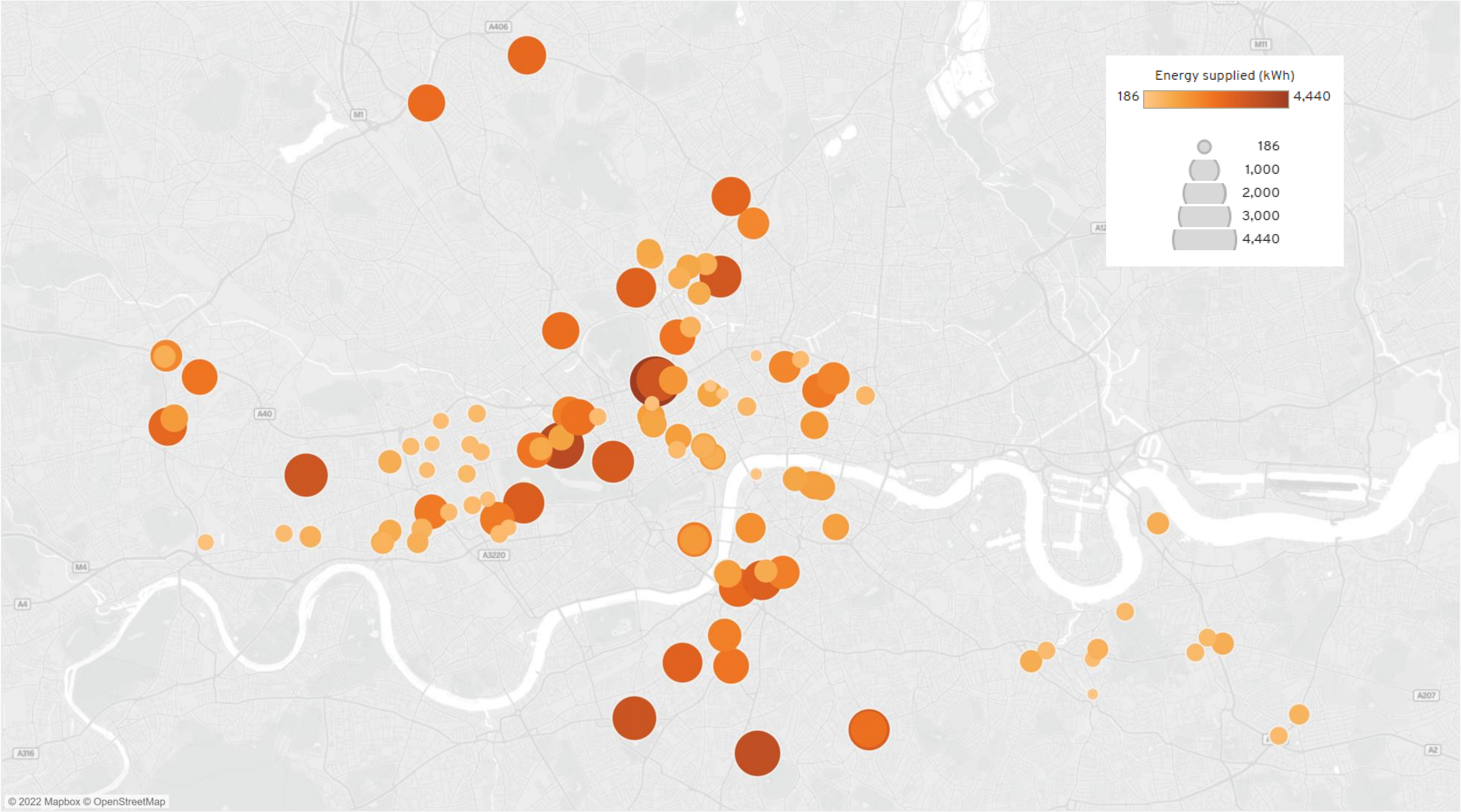

KING'S CROSS
PENTONVILLE
SHOREDITCH
SOMERS TOWN
ST LUKE'S
FINSBURY
CLERKENWELL
HOLBORN
ST CLEMENT DANES
SOHO
SOUTH BANK
MAYFAIR
ST JAMES'S
SOUTHWARK
BOROUGH
VICTORIA
03/24/2022
8:01:06 AM
IN_SERVICE
ON_CALL



Vehicle movements by occupancy

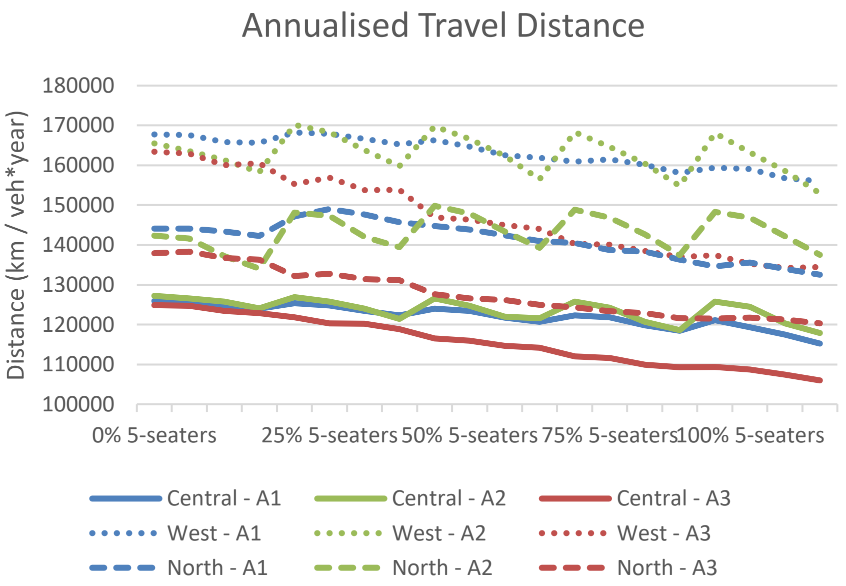

Occupancy
0
5
0
1
2
3
4
5
A40
A4
A2
© 2022 Mapbox © OpenStreetMap

Energy supplied


Energy supplied (kWh)
186
4,440
186
1,000
2,000
3,000
4,440
© 2022 Mapbox © OpenStreetMap

Outputs

Model outputs provide a range of values under different operational environments, as well as trends to understand how sensitive each output magnitude is to the input variables.



Outputs: Utilisation

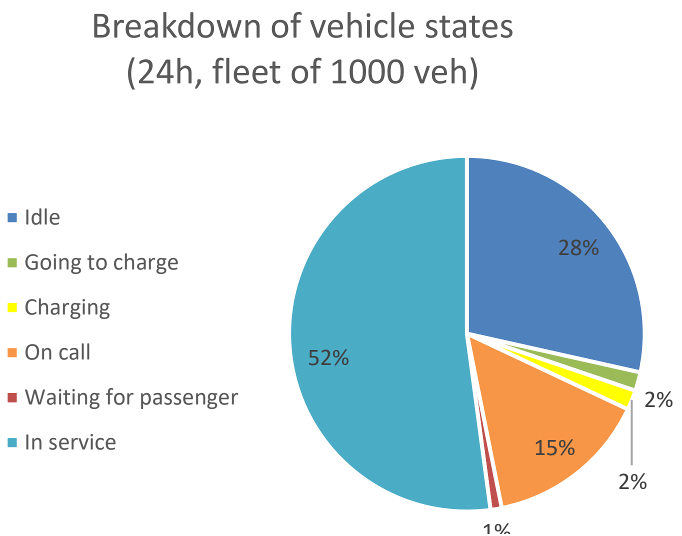
Optimal fleet sizes for several utilisation targets were estimated.

High utilisations (90-95%) require small fleets in most zones due to low overnight demand. Optimal fleet sizes are much higher when utilisation targets are reduced to 80%.

	Utilisation target			
	95%	90%	85%	80%
Central	30	92	216	495
East	1	3	12	30
South	4	12	27	80
West	10	29	79	207
North	5	20	57	165

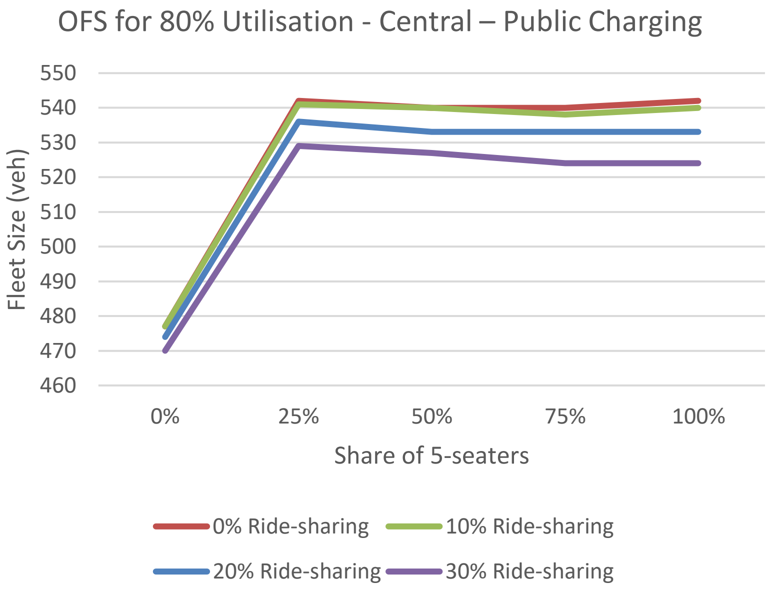
Outputs: Utilisation

With large fleets over the OFS (e.g. 1000 veh), utilisation drops as there is not enough overnight demand.



Outputs: Utilisation

- *In all zones and model scenarios (charge and ridesharing), the highest optimal fleet sizes for any utilisation target are seen in scenarios where there is a combination of 2-seaters and 5-seaters.*
- *Without 5-seaters in the fleet, some trips cannot be serviced and customer demand is effectively lower.*



Outputs: Travel Distance

- *Average annual travel distance per vehicle are high in zones of high demand (utilisation): Central, West and North.*
- *They are significantly lower in areas of modest customer demand: South and East.*

	Average Annual Distance (km/veh)
Central	120,488
East	32,009
South	90,028
West	157,736
North	137,462

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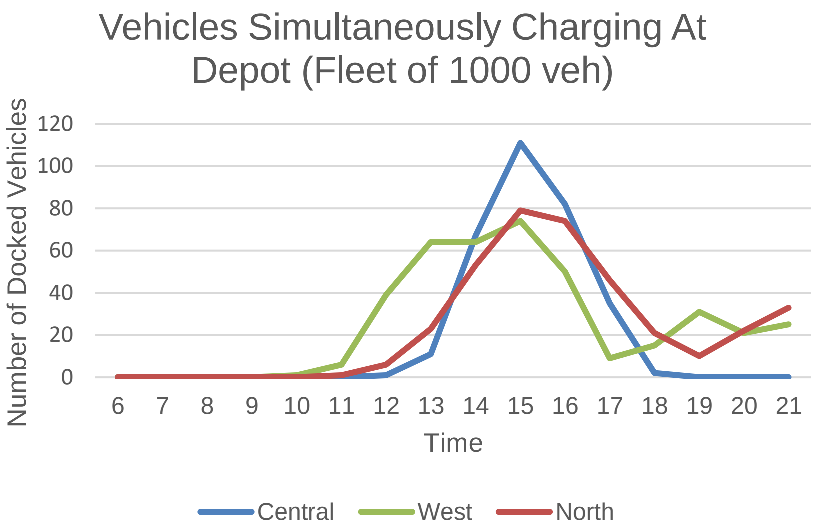
Outputs: Chargepoint Requirements

- *The maximum number of vehicles simultaneously charging at depot was estimated.*
- *Peak in the afternoon to be efficiently managed.*

	Number of vehicles (Fleet size optimised for 80% utilisation)
Central	44
West	15
North	12



Outputs: Energy Requirements

Energy requirements are dependent on traffic conditions of each zone, utilisation and fleet composition (share of 5-seaters).

	Average Daily Energy Requirements (kWh/veh)
Central	57
East	15
South	43
West	75
North	65

Outputs: Conclusions

- *It is feasible to achieve high annual mileages. It is important to right-size the fleet to demand levels to maximise utilisation.*
- *If only passenger services are to be provided, high utilisation levels can only be achieved with very small fleets. Explore alternative overnight applications (parcel deliveries?)*
- *For a utilisation target of 80%, fleets can be in excess of 100 vehicles in several zones (over 400-500 in Central London).*
- *Some (<25%) 5-seaters are needed in the fleet to service trips of 3 or more passengers. Having more 5-seaters does not yield significant benefits and increases energy requirements.*

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Thank you for listening

Luis Ramos

Transport Planning Consultant

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Project RUBICON – Cost & Environmental Analysis

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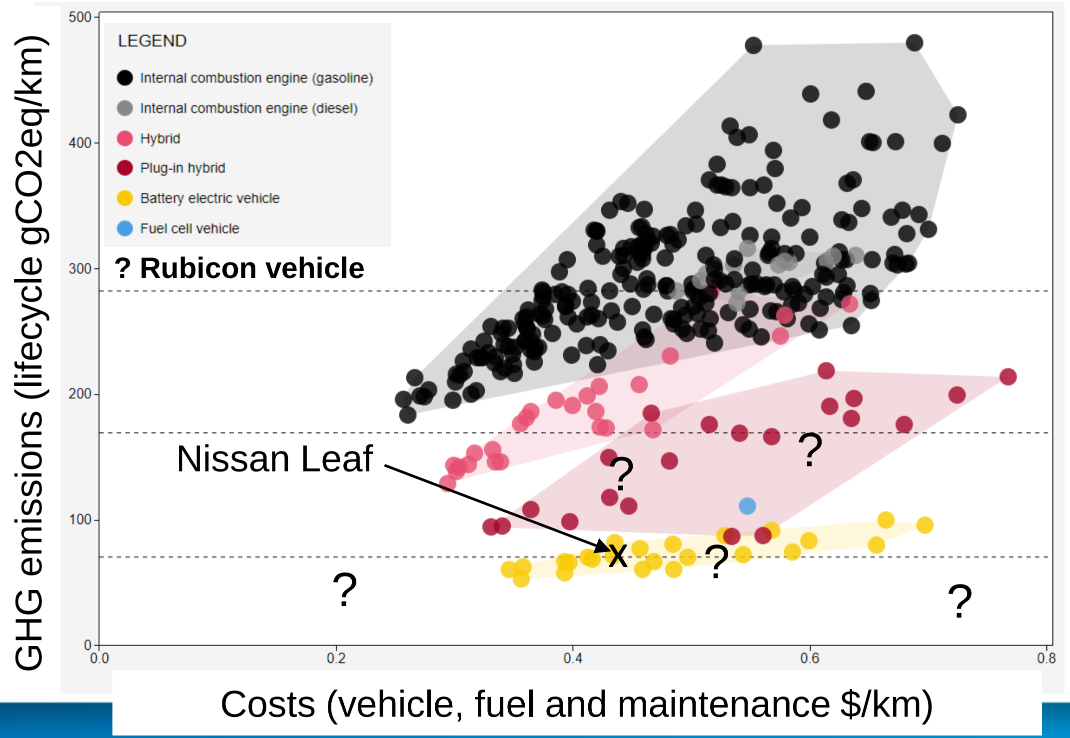
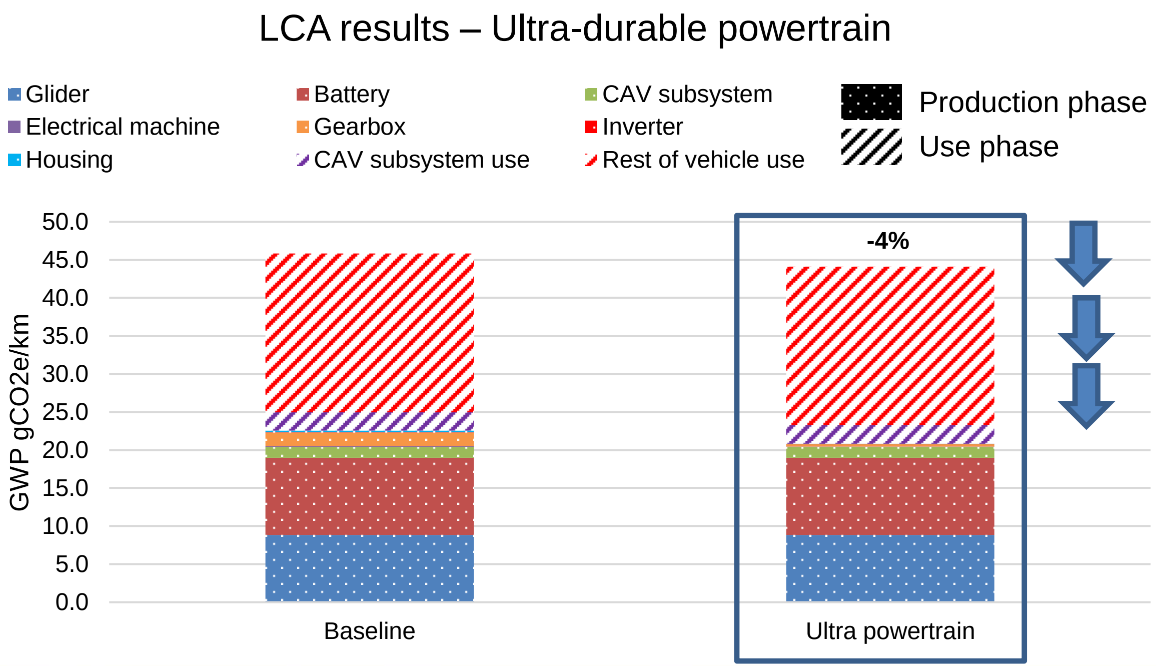
RUBICON Vehicle in the CO2 vs Cost Graph



- Carbon counter tool* by MIT places vehicles by their LCA GHG emissions and their costs
- Aim: to place our vehicle in this graph **as close to the origin as possible**
- RUBICON vehicle: 2-seater autonomous car with ultra-durable components
- We ‘copied’ the assumptions in this tool to enable like-for-like comparison

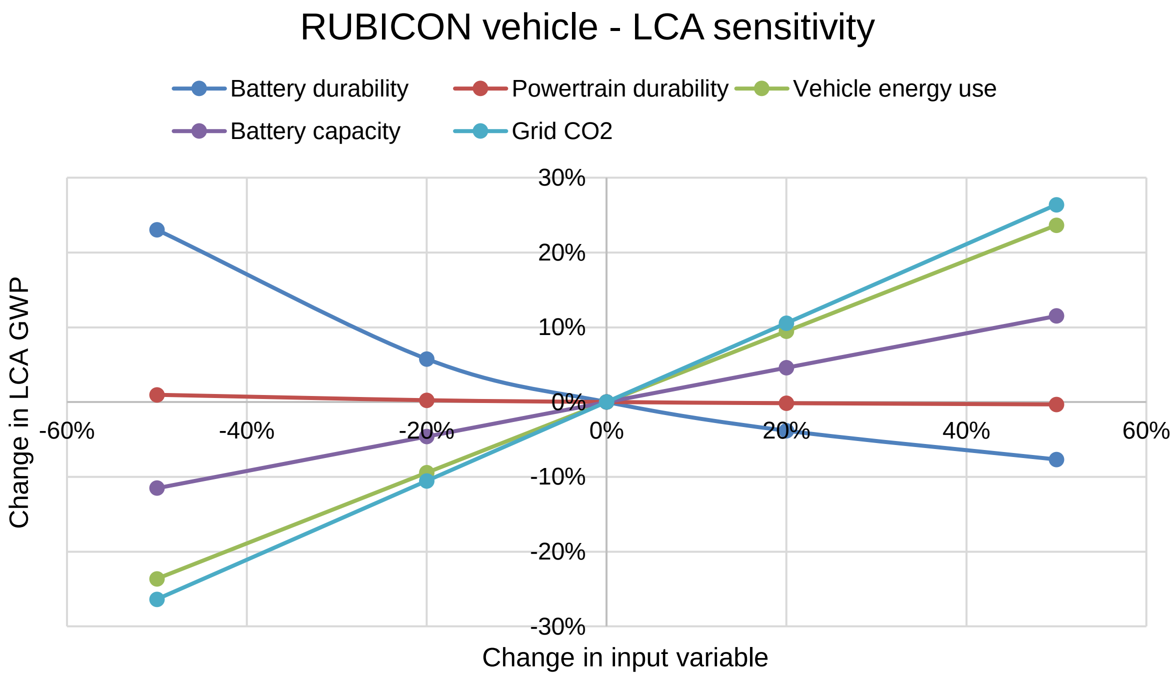
* https://www.carboncounter.com/#!/explore

LCA Results from RUBICON Vehicle



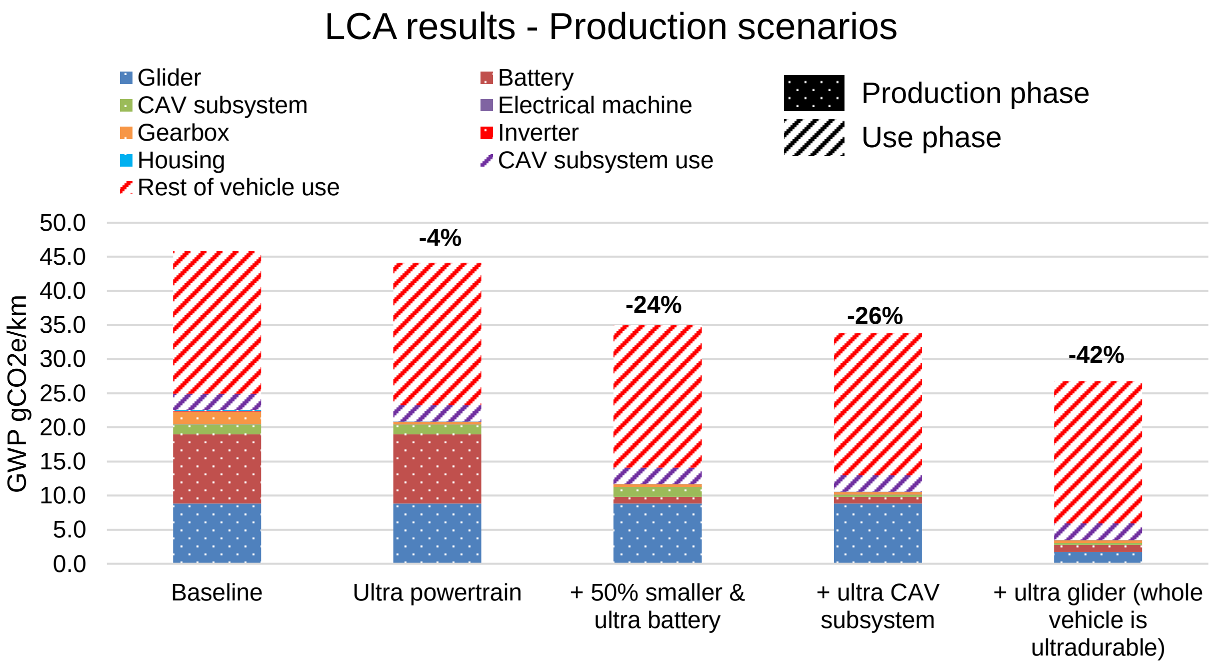
- LCA considered production and use phases using bill of materials from Hexagon & Empel, and literature data for non-powertrain components
- **High utilisation, mileage and charging patterns** used as per Immense transport model
- Increased durability of powertrain yields 8% reduction in production GWP and 4% in total GWP

LCA Sensitivity



- Production phase handles: **component durability & battery capacity**
- Reference: powertrain 1m miles, battery 200k miles & 30 kWh
- Use phase handles: **vehicle energy use, grid carbon intensity**
- Reference: 90 Wh/km and 194 gCO2e/kWh

LCA Sensitivity – Production Phase



- Increasing powertrain & battery **durability** and reducing its size has large impact
- Increasing **glider lifetime** important but more difficult to make ultra durable due to tear and wear (ideal scenario)

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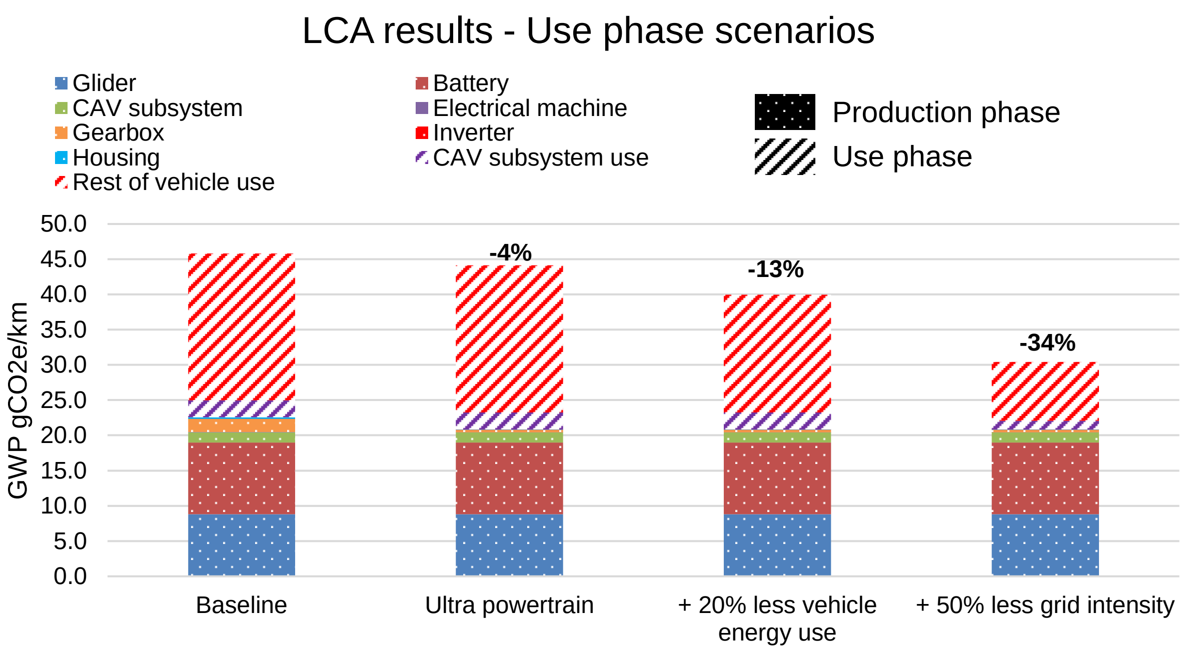
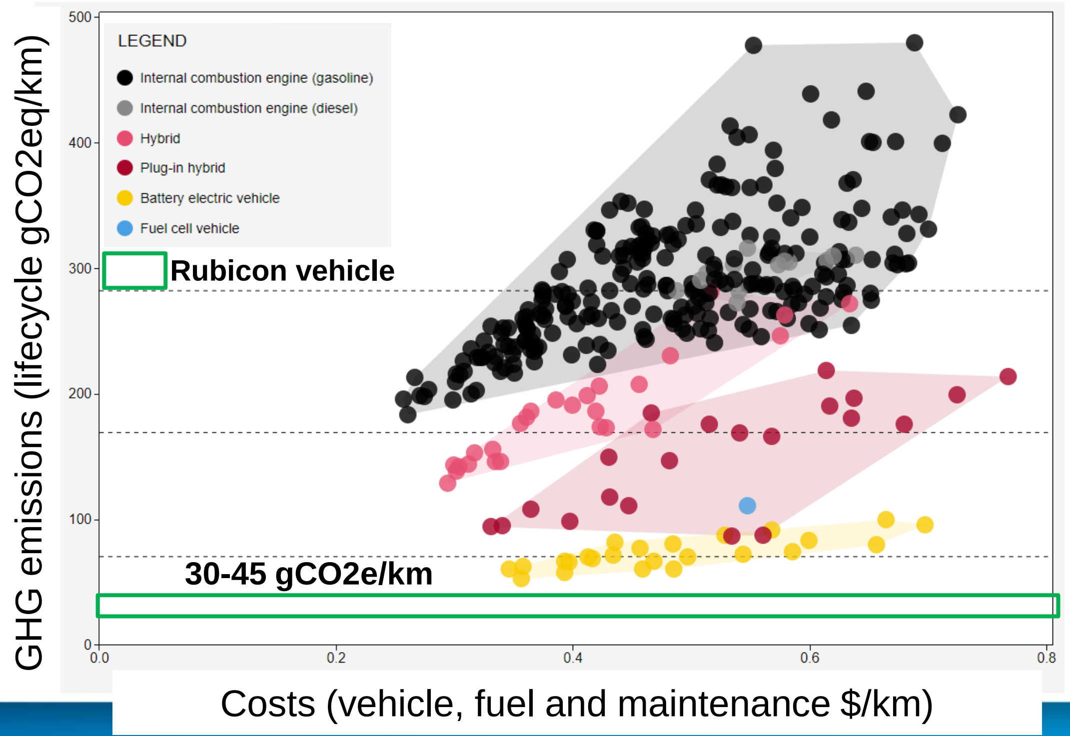
LCA Sensitivity – Vehicle Use Phase



- Biggest impact from **grid carbon intensity**, e.g. onsite renewable generation for fleets
- Biggest factor where manufacturers influence is reducing **vehicle energy use**
- Way to go: highly efficient and durable powertrains powered by small & durable batteries charged by low carbon grid = **72% reduction**

RUBICON Vehicle in the CO2 vs Cost Graph



- **Below BEVs**, even small-sized vehicles
- Now to determine location in horizontal axis: vehicle costs
- Cost from the perspective of a user: how much fleets charge customers in $/km to be profitable, and how does that compare to private car ownership

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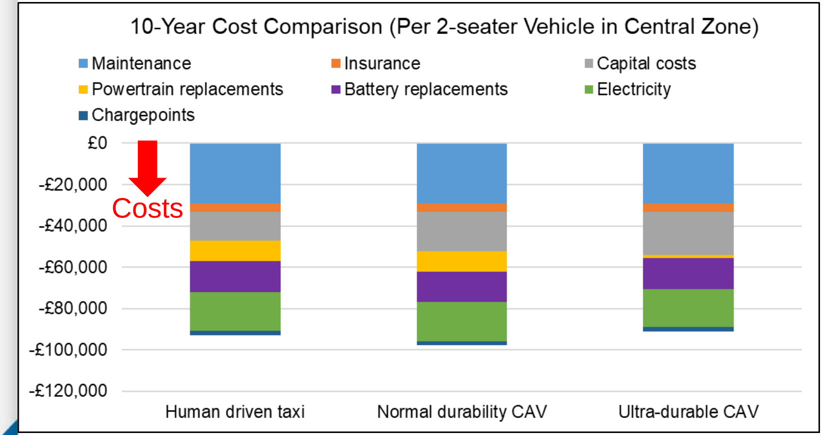
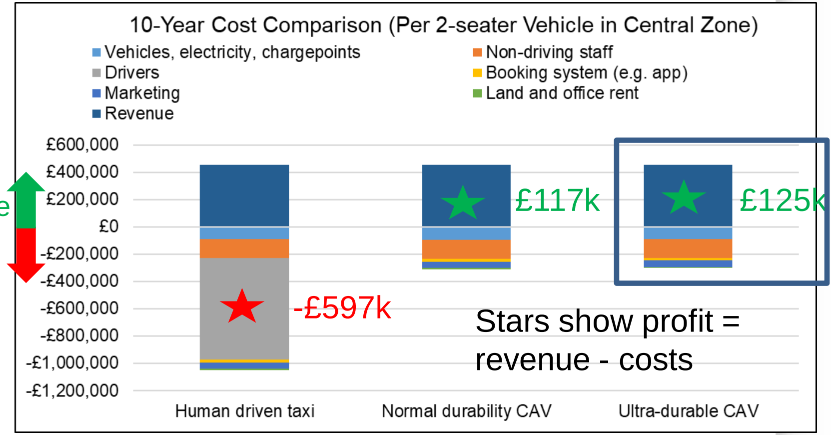
Cost and Revenue Breakdown



+ Overheads
+ Taxi fare revenue



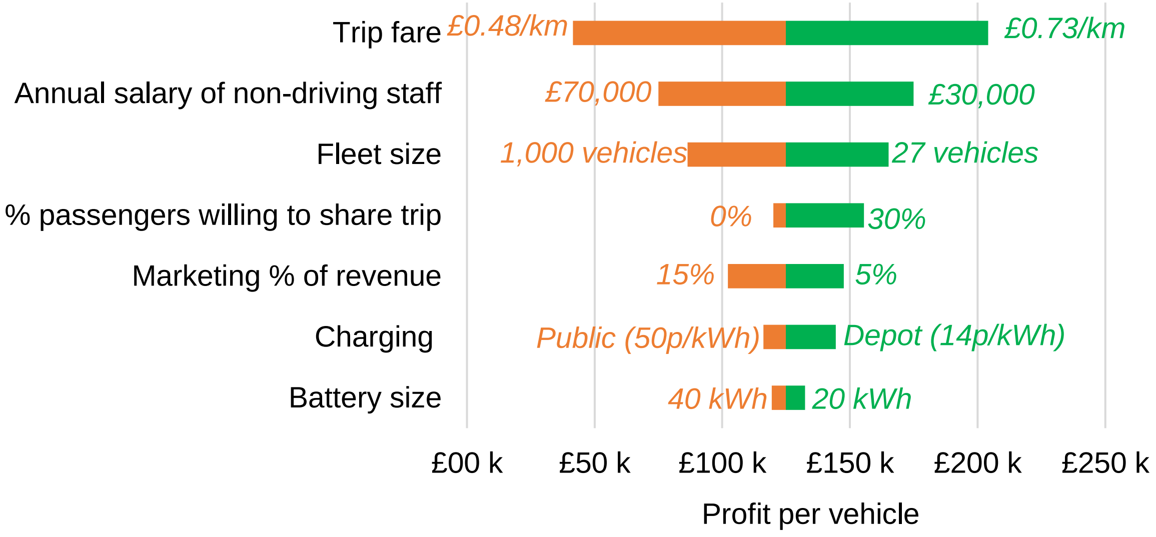
- **High utilisation, mileage and charging pattern** used as per Immense transport model
- Driver costs = £12/hour as average London taxi driver salary (1)
- Taxi fare revenue = **£0.61/km** as prediction of robotaxi fare in London (2)
- Human driven taxis present negative profit because current London fares are higher (£4 to £5/km)

(1) Economic Research Institute
(2) UBS, How disruptive will a mass adoption of robotaxis be?

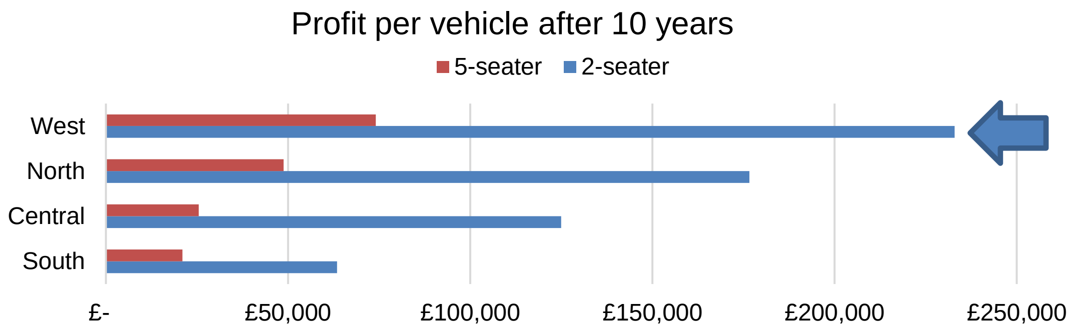
Business Case Sensitivity in Central Zone

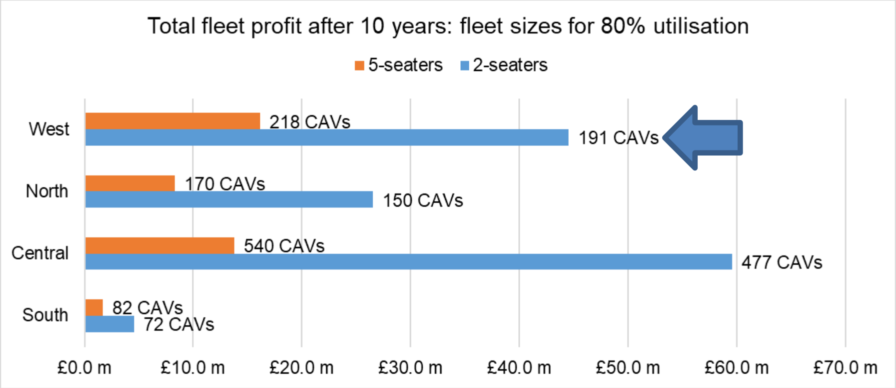
- Key technical and economic independent variables chosen
- The ‘axis’ of the tornado shows the **profit per vehicle after 10 years** when all variables have the medium value (‘core scenario’)
- We then vary one variable at a time from low to high, **while keeping the rest of the variables in their medium values**: each of the tornado extremes are also the 10-year profit

Profit Sensitivity per 2-seater Ultra-durable CAV (10 years, Central Zone)



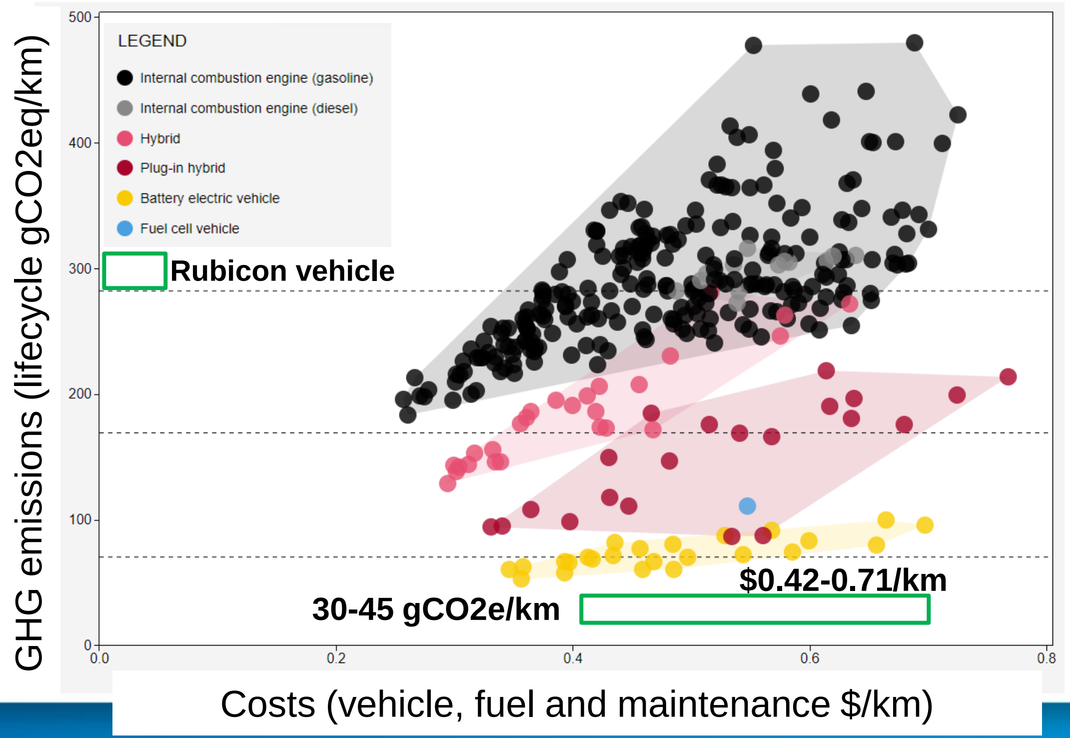
Business Case per CAV Zone





- East zone excluded because it only allows for very small fleets with high utilisation
- 5-seaters are less profitable due to higher capital cost and higher energy use
- Even though Central zone allows for biggest fleet size, profit/vehicle is higher in West zone
- Central zone still has highest overall profit, followed by West

RUBICON Vehicle in the CO2 vs Cost Graph



- Sensitivity analysis on most profitable zone per vehicle (West)
- For a fleet's initial investment to pay back in 3 to 5 years, they would need to charge customers $0.42-0.71/km
- In line with private car ownership prices, but with increased convenience and at a lower carbon footprint

Conclusions

- New mobility as a service models encourage highly utilised vehicles, which call for ultra-durable vehicle designs
- Making all components ultra-durable provides 42% reduction in GWP
- Adding on top highly efficient vehicles coupled with low carbon grid we can achieve 72% reduction in GWP

- Business case highly impacted by trip fares, staff salary and fleet size
- Cost for robotaxi customer is similar to private car ownership prices, but with increased convenience and at a lower carbon footprint
- Fleet of robotaxis is only profitable in high vehicle utilisation scenarios and zones, because of overheads (not just vehicles and energy, also staff, app, marketing, land, etc.)

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Thank you for listening

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Lowering your emissions through innovation in transport and energy infrastructure

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Thank you for listening

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