Potential Socio-Economic Impacts of Quantum Technologies in UK Transport

June 2024

Contents

Glossary

AI: Artificial Intelligence
BABS: British Airways Booking System
ML: Machine Learning
QML: Quantum Machine Learning
EV: Electric Vehicle
eVTOL: Electric Vertical Take-off and Landing
GNSS: Global Navigation Satellite Systems
GPS: Global Positioning System
QT: Quantum Technologies
QC: Quantum Computing
HPC: High Performance Computing
LiDAR: Light Detection and Ranging
NISQ: Noisy Intermediate Scale Quantum
FTQC: Fault Tolerant Quantum Computer
QS: Quantum Sensing
Quantum Comms: Quantum Communications
PQC: Post Quantum Cryptography
QKD: Quantum Key Distribution
QCaaS: Quantum Computing-as-a-Service
QRNG: Quantum Random Number Generation
MaaS: Mobility-as-a-Service
PoC: Proof-of-Concept
DSR: Demand Side Response

1.0 Executive Summary

1.1 Key Findings

The maturity of Quantum Technology varies greatly, with many technologies still in early development stages. However, the potential scale of the transformative impact of Quantum Technologies is vast. This report discusses material opportunities and potentially significant implications for the UK transport sector.

Key examples include;

1. Quantum Computers hold **unique computing potential**, processing (exponentially) large datasets that classical computers are not capable of processing. This could potentially solve a wide range of optimisation problems, across transport modalities – e.g. optimised traffic routing, cargo loading and staff scheduling.
2. Quantum Communications have the potential to provide **ultra-secure communication systems**, which becomes even more relevant in a "post quantum" world – i.e. when next generation, powerful quantum computers are able to decrypt existing communication channels. This level of security would not only prevent unauthorised access and manipulation of critical transport data but also minimise the costs associated with downtime and recovery from cyber incidents, thus maintaining the smooth operation of transport services and safeguarding passenger safety.
3. Quantum Sensing utilises the quantum properties of particles to create **high precision and sensitivity sensors, high accuracy timekeeping or imaging equipment**. These sensors could revolutionise transport sectors such as (underground) construction work, railway signalling, gas leak detection, autonomous vehicles and offshore drilling.
4. Quantum sensors could also enable **more precise navigation systems** that do not rely on satellite signals - which would be invaluable in environments where Global Positioning System (GPS) is unreliable or unavailable.
5. Powerful Quantum Computers could potentially be **integrated with existing High-Performance computers (HPC) and AI/ML models** – creating unprecedented computing power. These could solve a plethora of chemistry problems, advancing research into e.g. superior vehicles, batteries and essential building materials.

Inertia in adopting quantum technologies could pose several risks to the transport sector. Notably, there is a security risk that could potentially lead to economic disruption: if next generation quantum computers, operated by hostile actors, become able to hack existing encryption methods - and the UK would not be adequately prepared through the widespread adoption of quantum encryption methods.

Any attempt to quantify the potential socio-economic impacts of quantum technologies is inherently based on a multitude of assumptions. The challenge is that there are many different quantum technologies, which is itself an umbrella term for a wide set of emerging technologies relating to principles of quantum mechanics. All of which are at different stages of maturity, covering a plethora of potential use-cases, especially in the case of Quantum Computing which is a general purpose technology. Even if potential impacts have been quantified in specific research or industry papers, they are yet to be proven at (commercial) scale. However, based on available case studies and market research, we have **estimated a net value creation impact of £4-8bn by 2030-2035.** This is likely only scratching the surface, especially when quantum technologies would develop more rapidly than is currently expected, for example through the advent of AI technologies.

Illustrative value impact analysis

NB: the below table sets out examples of quantitative value impacts, for specific transport modalities. For example, personalised optimised traffic management through personalised re-routing is relevant for various transport modalities, yet the quantitative impact depicted focuses on a single modality.

NB: the analysis below is an oversimplification. However, we believe it serves as a good indicator of the potential magnitude of various impacts. All examples are based on known, quantified impacts (unless otherwise indicated).

Transport modality *(impact only)*	**Value creation**	**Key assumptions**	**Illustrative impact**
	QC holds the potential to **optimise time-critical traffic management** tasks (e.g. personalised rerouting).	The UK loses £6.9bn annually due to traffic congestion. Fujitsu simulation indicated travel times may be reduced by 40%.	~£2.8bn (2019)
	QC can **optimise logistics networks** vs. relative best guesses (current practice).	2% (based on UK GDP) of global net value impact, estimate by BCG.	~£1.2bn (by 2035)
	Quantum Communication systems have the potential to **prevent cyberattacks** from adversary powers.	The estimated impact of a Global Navigation Satellite Systems (GNSS) outage on the UK transport sector is ~£700m per day (excluding impact on F&B sector and emergency services). Adjusted for inflation this amounts to ~£1.4bn by 2035. An illustrative 21-day outage (several weeks to fully restore) at 3% probability (in line with the National Risk Register) amounts to a ~£900m total impact.	~£900m (2035)
	QC can **optimise staff scheduling**, a major computational challenge.	The UK incurs ~£6.2bn of train employment costs annually. Early Hitachi case study suggests potential personnel cost savings up to 15%.	~£900m (by 2021)
	QC can **optimise global routing for aviation** industry.	2% (based on UK GDP) of global net value impact, estimate by BCG.	~£600m (2023)
	Quantum sensors can **prevent accidental strikes** as part of underground work.	~£2.4bn annual UK cost. Assumption of 10% potential effectiveness increase.	~£200m (2021)
	QC could enable **solving complex fluid dynamics** equations in aviation.	2% (based on UK GDP) of global net value impact, estimate by BCG.	~£200m (by 2035)
	Quantum sensors can **prevent erratic construction work** (being carried out in the wrong location).	~£1.5bn annual UK cost. Assumption of 10% potential effectiveness increase.	~£200m (2023)
	QC could **optimise autonomous vehicle** AI algorithm design.	2% (based on UK GDP) of global net value impact, estimate by BCG.	~£100m (by 2035)
	Quantum inertial navigation systems on aircraft could serve as **a reliable back-up to GNSS**.	2% (based on UK GDP) of global TAM, estimate by Citi Group.	~£100m (2024)

Illustrative value impact analysis

Transport modality *(impact only)*	**Value creation**	**Key assumptions**	**Illustrative impact**
	Quantum gravimeters could **reduce exploratory drilling** for energy & mineral exploration.	2% (based on UK GDP) on billions of global savings, estimate by Citi Group.	~£50m (2024)
	QC-enabled AI/ML techniques could proportionally benefit UK transport sector.	2% (based on UK GDP) of global net value impact, estimate by BCG. 3% (based on GVA) applied to total.	~£50m (by 2035)
	Quantum sensors potentially offer a r**ange of extreme precision applications**.	2% (based on UK GDP) of average global TAM estimate of $850m, a 2030 estimate by Citi Group.	~£10m (by 2030)
		Minimum value creation estimate: (by 2030-2035)	**~£7bn**
		Additional cost requirement estimate:	**~£1bn**
		Highly illustrative range: (by 2030-2035)	**£4-8bn**

Legend

Road Transportation

Rail Transportation

Air Transportation

Maritime Transportation

Table 1: Illustrative Value Impact Analysis

Not all socio-economic impacts are quantifiable. We have considered a range of socio-economic impacts that may provide "real value" yet are hard to directly translate into "utility", such as "quality of life". We also note that any analyses exclude opportunity costs, and do not provide policy recommendations as such.

1.2 What is next?

Predicting the trajectory of quantum technologies and determining which will lead the charge in the coming decades — the 2020s, 2030s, and 2040s — presents a formidable challenge.

Quantum technologies still face significant hurdles before they can outperform classical systems. Quantum computers struggle with environmental sensitivity, leading to errors and a lack of robustness. Similarly, quantum sensors and communications technologies must address their high sensitivity to environmental noise, impacting their stability and accuracy. Despite rapid advancements in quantum sensing for applications like magnetic field detection and navigation, challenges remain in device integration and the need for miniaturisation. Quantum communications, aiming for ultra-secure channels through quantum key distribution (QKD), also face scalability and integration challenges with existing telecommunications networks. Addressing these issues is crucial for the practical deployment of quantum technologies in fields such as vehicle-to-vehicle communications and traffic management systems, paving the way for innovations in autonomous vehicles and enhanced navigational systems. However, the surge in interest and investment in quantum technologies is focusing the necessary attention on these problems and suggests that they are not intractable.

The quantum field is swiftly advancing, marked by unpredictable breakthroughs and innovations. At a very high level, we see the following qualifiers;

1. **Quantum Computers:** whilst “hybrid” forms of QC are already available (i.e. integrated with existing, classical HPC systems) – fault tolerant QCs are expected to drive major impact throughout industries, with significant implications for UK transport sectors. Estimates as to when FTQCs become (commercially) available, range broadly between the next 5 to 40 years. Based on expert interviews, we expect that useful FTQCs, with “quantum advantage” versus classical systems for a range of practical applications, become available from ~2035 onwards.
2. **Quantum Sensing systems** are more likely to see near-term mass commercialisation. Many quantum sensing technologies have already demonstrated their advantages over conventional sensors used today, with magnetometers, gravimeters and accelerometers expected to be produced at scale in the next 5 years. The adoption of quantum radars is likely further out (post 2030).
3. **Quantum Communications:** While various quantum encryption systems are in advanced stages of development and some initial systems are already commercially available, it is generally expected that the majority will become available in the course of the next 5 years, in particular satellite-based quantum key distribution systems. Commercially viable quantum networks, advanced communication systems leveraging quantum principles to process and transmit information, are unlikely to become available before 2030. Post Quantum Cryptography algorithms, technically using classical rather than quantum properties, are already available and being implemented by pioneering organisations (e.g. incorporated in iOS by Apple).

1.3 A Quantum Technologies Roadmap

The below high-level roadmap draws on numerous analytical reports from leading research institutions, providing a comprehensive outlook on quantum technologies' potential advancements and applications in the future, with a particular focus on the transport industry. It highlights quantum technologies that are expected to be further developed, and the key period in which the industry is likely to focus on these technologies. Please refer to part 1 of this report for more information on quantum technologies. The roadmap incorporates Technology Readiness Levels (TRL), a method for estimating the maturity of technologies using a scale from 1 to 9, with one being the lowest and nine being the highest level of technology maturity. This roadmap only shows existing estimates of development paths (e.g., atomic clocks are estimated to achieve TRL6 by 2030 - subsequently they may achieve TRL9 but no further estimates exist in current literature).

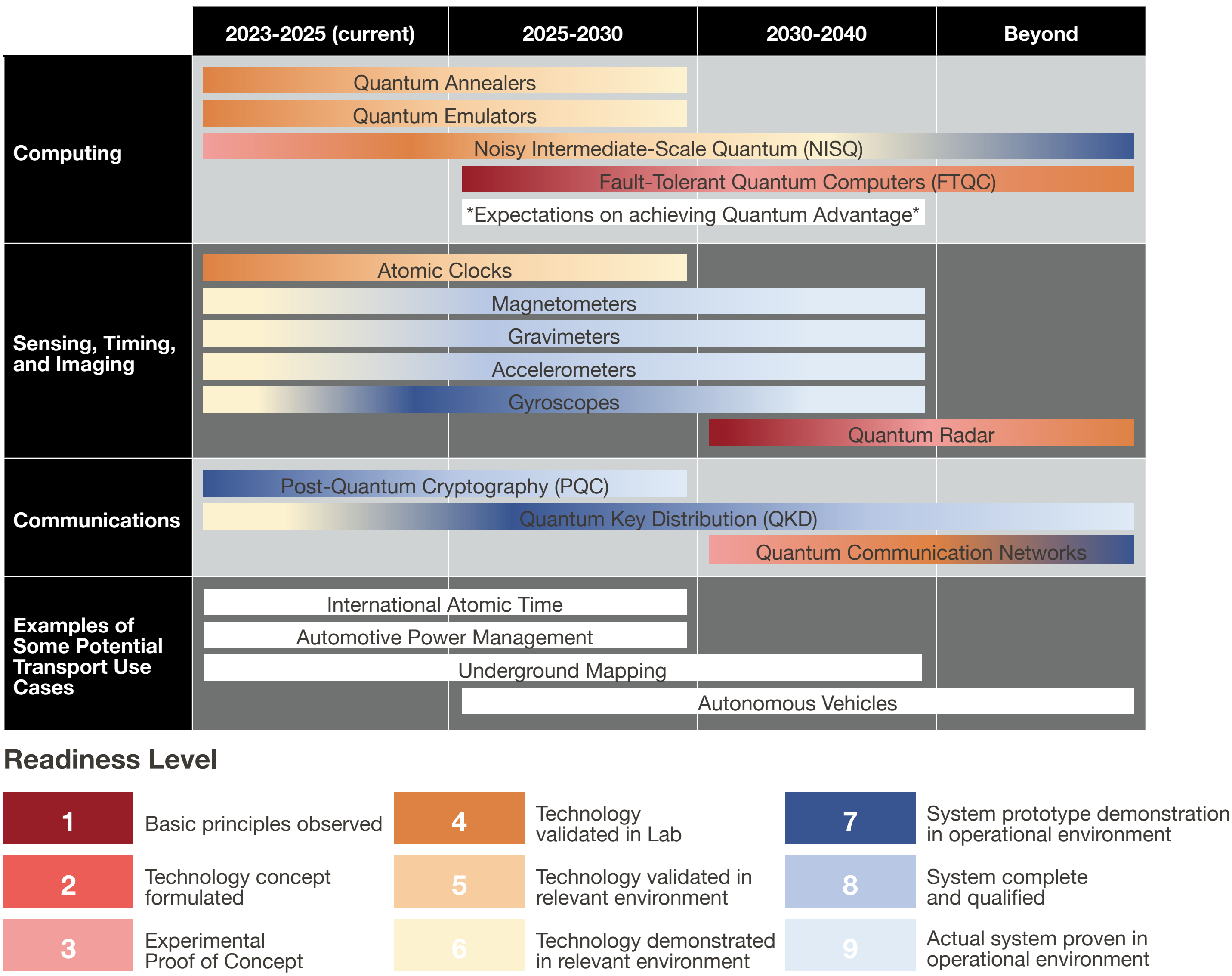
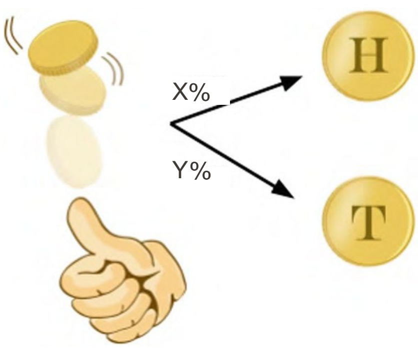


Image 1: Forecast of quantum computing, sensing, and communication technologies, readiness levels, and examples of use cases (2023 to 2040 and beyond)

2.0 Introduction

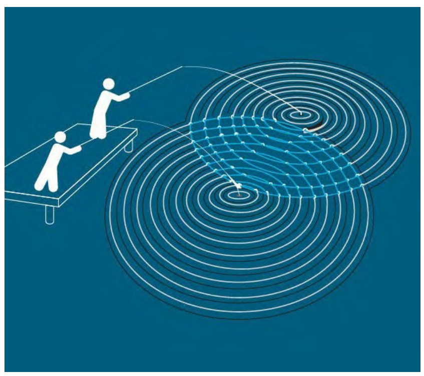
2.1 What are Quantum Technologies?

Quantum technologies can be defined as "technologies that utilise and/or measure particles or properties at the atomic and sub-atomic scale". They represent a class of technologies that work by using the principles of quantum physics, including superposition, interference and entanglement (see Image 2).



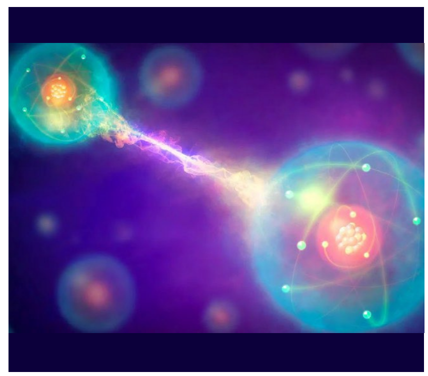
Superposition: The ability to exist in two different states at the same time.

Example: Imagine a coin spinning in the air. While it is spinning, it is not just heads or tails - it is both at the same time. This is like superposition in quantum physics, where particles can be multiple states at once.



Interference: Refers to the wave-like behaviour of particles, where the quantum states of multiple particles can interact and influence each other.

Example: Imagine two sets of ripples in a pond from two stones. Where ripples meet, they create bigger waves or cancel out. This is like interference in quantum physics, where particples act as waves that interact and influence each other.



Entanglement: Allow distinct subatomic particles to be bounded together no matter how distant they are.

Example: Imagine two balls located in two remote boxes. If one ball lights up, the other will instantly light up as well despite the distnce between them.

Image 2: Illustrations for Quantum Superposition, Interference, and Entanglement

Quantum technologies are promising advancements across the transport sector: for example through enhanced navigation, underground measurement, route optimisation, and many more use-cases outlined in this report. These technologies are not just theoretical – they are rapidly becoming practical tools with the potential to revolutionise all modes of transport.

2.2 Report Structure

Part 1 of this document provides high-level outlines of three key quantum technologies: (1) quantum computing; (2) quantum sensing, timing, imaging; and (3) quantum communications. The following sections summarise their principles, current state-of-the-art, practical challenges, and emerging applications for the UK transport sector.

Part 2 outlines in detail the potential socio-economic impacts of quantum technologies, specifically for the UK transport sector.

Part 1

3.0

Quantum Computing

What is a Quantum Computer?

Quantum computers process information radically differently by utilising principles from quantum mechanics. Quantum bits, or qubits, unlike classical bits that represent either 0 or 1, can exist in multiple states simultaneously. This unique capability allows quantum computers to perform various calculations simultaneously, potentially making them exponentially faster than classical computers for specific tasks (research is ongoing on whether quantum computers will be quadratically or exponentially faster, as well as how this might accelerate and improve the quality and accuracy of results).

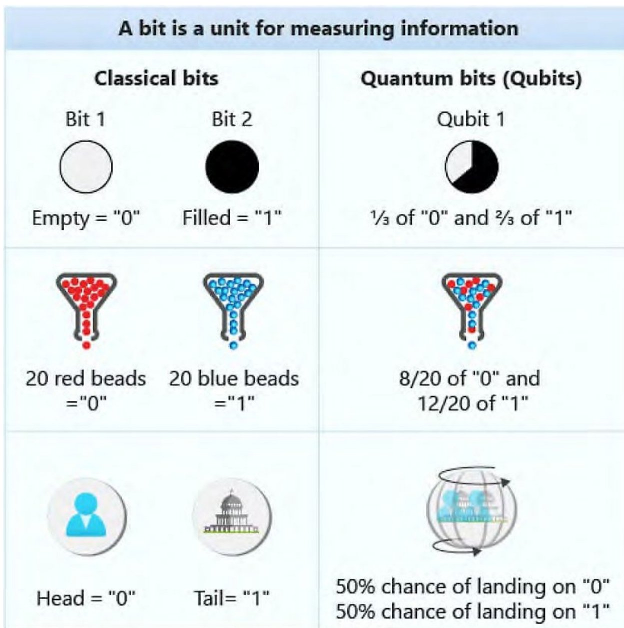


Image 3: Representations of classical bits vs quantum bits (qubits)

Types of Quantum Computers

Generally, there are three categories of quantum computers (QCs) today:

1. **Classical:** non-quantum computers that execute quantum algorithms, also called “quantum inspired” or “quantum emulators”.
2. **Analog:** QCs designed for specific quantum problems, such as “quantum annealing” and “quantum simulators”.
3. **Digital:** Versatile QCs which can potentially address multiple use-cases. These include Noisy Intermediate Scale Quantum (NISQ) and Fault Tolerant Quantum Computers (FTQC).

Quantum computers today are categorised as Noisy Intermediate Scale Quantum (NISQ) devices. NISQ computers have limited qubits (from dozens to thousands), lack full error correction, and suffer from short coherence times and imperfect operations, leading to errors. NISQ devices can solve some problems classical computers can handle, as well as some unique quantum problems, allowing them to work in a hybrid form with classical computers. Fault-Tolerant Quantum Computing (FTQC) represents advanced quantum computers, that will in the future perform reliable calculations, not suffering from limitations faced by NISQ-era QCs today. FTQC requires sophisticated error correction techniques, which are complex and costly, and not expected to be available for another 5-10 years. Until then, we are in a “hybrid era” where NISQ systems are used alongside High-Performance Computers (HPC), which currently offers the optimal benefits of the available QC technologies. This report generally refers to Quantum Computing as hybrid NISQ/HPC.

Quantum Computing and AI

Quantum Machine Learning (QML) can significantly benefit the transport industry by combining the strengths of quantum computing with machine learning. QML has the potential to accelerate various machine learning applications, leading to more efficient and accurate models. For instance, QML can optimise route planning, enhance traffic management, and improve predictive maintenance for transport vehicles. Despite the challenges in scaling quantum technologies, companies have been further developing this approach. For example, US-based SandboxAQ employs AI techniques to enhance the precision and efficiency of quantum sensors, and Finland-based Quantrolox is developing ML-based software to maximise quantum computer uptime. This integration of QML in the transport sector can lead to smarter, more efficient transportation systems.

What does it mean to reach “Quantum advantage”?

Quantum advantage is the point at which a quantum computer will perform a set of calculations that are practically impossible for a classical computer to achieve in a reasonable amount of time. This concept is a crucial milestone in quantum computing, marking the transition from theoretical to practical superiority over classical computing in specific tasks. In 2019, Google claimed to achieve quantum supremacy with their 53-qubit Sycamore quantum processor by solving a problem in 200 seconds, that would have taken 10,000 years for a classical computer. This was later contested by IBM, showing it was possible to solve the problem with a classical computer by changing the parameters used by Google, proceeding to solve the problem in 2.5 days. While this shows that the solution was quantum superior, the particular problem solved did not bring any “real-life” applicability and has therefore been contested as proof of quantum advantage.

3.1 Practical Challenges

The development of quantum computers involves some critical technical barriers. Based on expert interviews, we expect that useful FTQCs, with "quantum advantage" versus classical systems for a range of practical applications, become available from ~2035 onwards (see Table 3).

Technical Barriers	Error rates and Quantum Decoherence	• Susceptibility to environmental interference • Challenges in maintaining coherence over time
	Scalability	• Difficulty in scaling up qubit count • Exponential complexity increases with more qubits
	Quantum Error Correction	• Complexity in developing effective correction techniques • Need to correct errors without disturbing the quantum state
	Physical Requirements	• Extreme conditions like very low temperatures required • Costly infrastructure, e.g., dilution refrigerators needed
	Software and Algorithms	• Challenge in developing fully utilisable algorithms • Lack of advanced software and programming tools
	Integration with Existing Systems	• Technical difficulties in hybrid QC/HPC integration • Development of complex algorithms for hybrid platforms

Table 2: Technical barriers for Quantum Computing

The development of quantum computers involves some critical technical barriers (see Table 2).

3.2 Potential for Transport

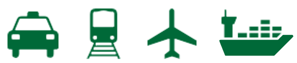
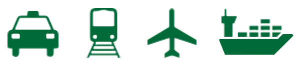
Quantum Computing holds transformative potential for the transport industry by offering computational power far exceeding that of classical computers for certain problems.

This leap in processing capability could revolutionise various aspects of transportation, from optimising logistics and supply chain management to enhancing the design and material science behind vehicles, batteries and infrastructure. QML could potentially be a key asset for optimising route planning, enhancing traffic management, and improving predictive maintenance for vehicles, leading to smarter and more efficient transportation systems. Quantum algorithms could solve complex optimisation problems—such as route planning and traffic congestion management—more efficiently, leading to significant reductions in travel time and fuel consumption. Additionally, quantum computing's ability to analyse large datasets can improve transport modelling and predictive maintenance for transportation systems, minimising downtime and extending the lifespan of critical infrastructure.

Quantum Computing harbours the potential for significant computational capabilities, which, in turn, could offer answers to some of the most pressing challenges faced by the UK transport sector today and positively contribute to achieving strategic goals outlined under the UK Transport Vision 2050. The technology could promote improvements across the entire transport value chain, from vehicle manufacturing through energy efficiency to optimised travel options for the end-user. Data-driven industries within the transport sector, such as logistics, are prime candidates for transformation in a "post-quantum" world.

In the current NISQ era, Quantum Computing applications tend to be limited to niche, one-off experiments (commonly achieved through quantum-annealing technologies or hybrid high-performance supercomputers leveraging Quantum Computing components), although ongoing experiments in the industry well illustrate the scale and diverse use cases of the technology. See below table for an overview of key applications that are potentially relevant.

Application	Transport Mode Relevance	Case Study (Real World Experiment)
Personnel		In 2021, Japan's Hitachi leveraged quantum-integrated systems to automate and optimise staff scheduling operations.
Scheduling		In 2021, Germany's Deutsche Bahn partnered with Cambridge Quantum to explore how QC can improve rail traffic.
Mobility-as-a-Service		In 2021, the Government of New South Wales engaged Q-CTRL to develop quantum algorithms for shared mobility challenges.
Traffic Management		Volkswagen has worked with D-Wave since 2017 to develop a quantum-driven traffic management system.
Supply Chain		D-Wave developed supply chain route optimisation algorithms for DENSO and Toyota Tsusho Corporation. Potential to improve demand forecasting so carriers can better allocate and locate assets in the correct markets (e.g. intermodal rail containers and chassis)
Logistics & Shipping		IBM is researching several QC use cases in logistics, including last mile delivery, disruption management, fulfilment optimisation and maritime routing. Potential to optimise in-warehouse resources (e.g. forklifts, forklift drivers) against near-term projected truck arrivals.
Fleet Optimisation		In 2023, IBM partnered with SavantX to leverage the Eagle computer to develop fleet optimisation solutions for trucking.
Autonomous Vehicles		In 2023, Hyundai and IonQ partnered to interpret sensor data from autonomous vehicle sensors using quantum computing.
New Transport Modes		Pasqal will use its dual quantum system to optimise routes for low-altitude air traffic to ensure safety of flying cars and drones.
Disaster Response		D-Wave worked with Marikina City authorities to develop quantum-annealing algorithms for disaster response.
Aviation		In 2022, IonQ and Airbus signed a collaboration agreement to develop quantum aircraft loading algorithms.
Machine Learning		In 2023, Airbus and BMW Group launched a Quantum Computing Competition to tackle their most pressing mobility challenges, including QC and ML.
Battery Design		Ford is using quantum computing to develop new batteries in collaboration with Quantinuum.

Application	Transport Mode Relevance	Case Study (Real World Experiment)
Fuel Efficiency		Mercedes-Benz is researching quantum computing benefits in battery design and fuel efficiency (with IBM and Google).
Biofuel Costs		Multiverse used a digital twin and quantum optimisation to boost the efficiency of green hydrogen production.
Manufacturing & Automation		BMW is working with Pasqal to enhance its manufacturing by using QC for metal forming applications modelling.
Aircraft & Vehicle Design		Boeing is working with IBM to leverage QC in aircraft design and in developing new materials for aircraft.

Legend

 Road Transportation  Rail Transportation  Air Transportation  Maritime Transportation

Table 3: Applications for Quantum Computing in transport

4.0 Quantum Sensing, Timing, and Imaging

Quantum sensing, timing, and imaging represent essential advancements in the field of quantum technologies, focusing on developing precision and sensitivity beyond the capabilities of classical instruments. At its core, quantum sensing utilises the quantum properties of particles to measure physical quantities with extraordinary accuracy, and in some cases to overcome major barriers faced by classical instruments.

Quantum Sensing

Quantum sensing utilises the principles of quantum mechanics to achieve measurements of physical quantities with unprecedented accuracy and sensitivity. By exploiting the unique properties of quantum states, such as superposition and entanglement, and the phenomenon of interference resulting from these properties, quantum sensors can detect and measure phenomena that are otherwise undetectable by classical methods.

Overall, quantum sensing is based on manipulating and measuring quantum states in particles or systems, such as photons, electrons, or atoms. These quantum properties include superposition, entanglement, and interference (see Table below).

Quantum property	Use in sensing
Superposition	• Enhances measurement precision by averaging over multiple quantum states
Entanglement	• Boosts sensitivity • Reduces noise impact
Interference	• Utilised for precise measurements • Key in quantum interferometers

Table 4: Quantum properties and phenomena and their use in quantum sensing

Types of quantum sensors

Quantum sensors can generally be categorised into general sensing (e.g., atomic interferometers, nitrogen-vacancy centre sensors, accelerometers, gravimeters, magnetometers), imaging-oriented (e.g., photonic quantum sensors, quantum LiDAR (Light Detection and Ranging), quantum radars), and timing-oriented (e.g., atomic clocks).

Quantum Timing

Quantum timing leverages quantum mechanical phenomena to measure time with unprecedented accuracy and stability. By utilising principles such as energy level quantisation in atoms and the properties of particles such as photons, quantum timing devices outperform traditional clocks. This precise measurement and control of quantum states, involving superposition, entanglement, and quantum interference, is crucial for applications in navigation, telecommunications, and scientific research.

Quantum Imaging

Quantum imaging exploits quantum mechanics principles, including entanglement, to capture information with higher precision than traditional methods. By leveraging the peculiarities of quantum states, it can enhance the spatial resolution of imaging, offering new capabilities in observing phenomena at unprecedented scales. In essence, Quantum imaging utilises quantum light sources for high-resolution imaging of fragile objects.

For example, consider the challenge of conducting non-invasive diagnostics on critical infrastructure, such as bridges or railways. Traditional imaging methods are constrained by their resolution, obtaining fewer structural details that would be critical for early fault detection. Through entanglement, quantum imaging can help enhance the imaging precision resolution. This means that they can detect micro-level structural defects or analyse materials that are not discernible with classical imaging technologies. Quantum imaging can reveal atomic-scale anomalies in infrastructure, enabling enhanced predictive maintenance.

4.1 Practical Challenges

The development of quantum sensors, timing and imaging, presents some challenges in the form of technical barriers: Table 5 presents a non-exhaustive list. We note that whilst there are practical challenges, early trials are underway and enabled by existing infrastructure: e.g. existing inspection trains are able to carry heavy equipment including prototype quantum sensors, even before they have been fully miniaturised. Of all QT, quantum sensing, timing and imaging technologies are most likely to see near-term mass commercialisation.

Technical Barriers	Quantum coherence maintenance	• Susceptibility to environmental noise and decoherence • Requires advanced isolation and error correction
	Entanglement Distribution	• Challenges in maintaining entanglement over long distances • Requires reliable quantum repeaters
	Temperature requirements	• Necessity for cryogenic temperatures for some sensors • Increases complexity and cost
	Integration with classical systems	• Compatibility issues with existing infrastructure • Data interpretation and processing challenges
	Precision maintenance for timing	• Achieving and sustaining extreme precision • Vulnerability to environmental perturbations
	Scalability	• Miniaturising without losing accuracy • Integrating into diverse systems
	Frequency stability	• Ensuring long-term stability of the clock’s frequency output for quantum timing

Table 5: Technical barriers for Quantum Sensors

4.2 Potential for Transport

Quantum sensors, timing and imaging, utilise principles of quantum mechanics to achieve unprecedented sensitivity and precision in measurement, making them vital for the transport industry's future.

These sensors can detect minute changes in gravitational fields, magnetic fields, and other environmental factors with far greater accuracy than classical sensors. This capability is transformative for navigation, allowing for more precise positioning and mapping without reliance on satellite signals, which is crucial in environments where GPS is unreliable or unavailable. Furthermore, quantum sensors can enhance the safety and efficiency of autonomous vehicles by providing detailed information about their surroundings, enabling better decision-making and obstacle avoidance. They also hold promise for optimising traffic flow and infrastructure maintenance by accurately monitoring conditions in real-time. Another key application area is the asset management of below ground assets (e.g. pipes and cables), with an incomplete and inaccurate asset inventory driving major costs for the transport sector. Quantum sensors such as magnetometers and gravitometers can play a critical role in preventing damage and construction delays, and enabling proactive asset maintenance through remote condition monitoring.

Although a meaningful number of the potential applications is in development stages, ongoing research and experiments highlight the broad and impactful range of use-cases that quantum sensors could provide in the transport industry. Table 6 shows a non-exhaustive list of these applications.

Application	Transport Mode Relevance	Case Study (Real World Experiment)
Reduction of Signal Failures	Road, Rail, Air, Maritime	Imperial College researchers are currently exploring quantum sensing applications for London's TfL.
Optimised Maintenance	Road, Rail, Air, Maritime	QT-PRI explores quantum gravity sensor market potential against existing geotechnologies, collaborating with RSK, Atkins, Network Rail, and the University of Birmingham.
Accurate Navigation	Road, Rail, Air, Maritime	Airbus is currently exploring and developing the use of quantum sensing technologies to enhance navigation systems.
Underground Infrastructure Detection	Road, Rail	In 2022, the University of Birmingham pioneered use of a quantum gravity sensor to detect a buried structure outside of laboratory conditions, offering a "new lens into the underground."
Reduced Reliance on GNSS	Rail, Air, Maritime	Imperial College is exploring implementation of quantum sensors in lieu of signalling systems to improve safety and reliability in the London TfL and reduce existing reliance on GNSS in challenging conditions.
Battery Charge Estimation for Electric Cars	Road	A research team from the Tokyo Institute of Technology, headed by Professor Mutsuko Hatano, has created a diamond quantum sensor that can accurately estimate battery charge within 1% accuracy while measuring high currents. These compact sensors are capable of detecting currents in the milliampere range, making them well-suited for automotive applications.
Underwater Imaging	Maritime	Imaging in turbid water conditions is hard. Quantic, in the UK, is supporting research and trials on using quantum sensors for achieving clear imaging even at multi-meter distances. This could help in offshore installation inspection and terrain mapping and hence navigation.
Underground Sensing	Road, Rail	UK-based Delta G raised £1.5 million in 2023 to commercialise its quantum sensors. This company aims at building a 'Google Maps for the underground' for 'complex subsurface and unseen locations' and claims it has 'produced the world's first field-proven quantum sensor for gravity gradiometry'.
Ultra precise Diagnostics	Road, Rail, Air, Maritime	Bosch is aiming to integrate quantum sensors onto chips for medicine and mobility, including ultra-precise navigation and vehicle diagnostics.

Legend

Road Transportation

Rail Transportation

Air Transportation

Maritime Transportation

Table 6: Potentially relevant applications for quantum sensing in transport.

5.0 Quantum Communications and Security

What are Quantum communications?

Fault-Tolerant Quantum Computing (FTQC) has the potential to decrypt RSA encryption, posing a potential cybersecurity threat to digital infrastructure. There is also the "harvest now, decrypt later" tactic, where encrypted data is collected now, to be decrypted at some point in the future using FTQCs.

These risks can be mitigated by leveraging quantum communication systems, which represent an advancement in the way information is transmitted and secured, leveraging the principles of quantum mechanics for the transmission process. Development efforts in quantum communications aim to design hardware, software, tools and communication protocols to exchange quantum information among multiple distant users, reaching levels of speed and security that are impossible with current technologies.

In practice, this means that any attempt to intercept or eavesdrop on a quantum communication can be detected by the legitimate parties involved, ensuring an unprecedented level of security in data transmission.

Types of Quantum Communications' technologies

Quantum communications involve a range of technologies that are focused on building secure communications leveraging the properties of quantum mechanics. They can be categorised into hardware – the physical devices needed to perform the communications (e.g., Quantum Random Number Generators or QRNGs, quantum repeaters, photon detectors, quantum transmitters and receivers, quantum dots and trapped ions), protocols – the set of rules or procedures that govern the transmission, encryption, and decryption of information using quantum states (e.g., Quantum Key Distribution and Quantum Secure Direct Communication), and methods (such as achieving true randomness in encryption through QRNGs).

Two key concepts are Post-Quantum Cryptography (PQC) and Quantum Key Distribution (QKD).

Post-quantum cryptography (PQC) uses classical properties and technologies to develop mathematical problems, which are difficult for quantum computers to solve. It secures communications against quantum computers, which could break many current encryption schemes. Unlike traditional methods relying on the computational difficulty of problems, PQC is based on problems resistant to quantum attacks. The US is pushing its federal agencies to implement PQC protocols, transitioning systems to the National Institute of Standard and Technology (NIST) PQC standards by 2035. The private sector is following this example, e.g. Apple announced a post-quantum cryptographic protocol called PQ3 for iMessage in February 2024.

Quantum key distribution (QKD) secures communication by using quantum mechanics to distribute encryption keys, leveraging quantum properties of particles (photons). Any attempt at interception changes the quantum state, alerting parties to the breach. This method offers security based on physics, making it immune to decryption by quantum computers. However, QKD systems are susceptible to attacks, such as the Quantum Man-in-the-Middle Attack on the calibration process. Terrestrial QKD methods are also limited by atmospheric losses and in-fibre attenuation. To overcome these challenges, integrating satellites with advanced optical technologies offers a promising solution for long-distance quantum encryption.

5.1 Practical Challenges

The development of quantum communication technologies faces some critical technical barriers. While various quantum encryption systems are in advanced stages of development and some initial systems are already commercially available, it is generally expected that the majority will become available in the course of the next 5 years. Table 7 presents a non-exhaustive list of the practical challenges.

Technical Barriers	Hardware development	• Diversity of applications necessitates a broad range of hardware, each tailored to specific requirements
	Miniaturisation and integration	• Focus on reducing the size of quantum devices and integrating essential components like electronics and optics • Key for enhancing the usability and scalability of quantum technologies, especially in trapped ions and ultra-cold atoms
	Environmental noise and malicious interventions	• Development of control techniques is crucial to protect quantum systems from environmental noise and security threats • Ensuring the integrity and functionality of quantum technologies in practical settings requires robust protection measures

Table 7: Technical barriers for Quantum Communications

5.2 Potential for Transport

Quantum communications harbour the potential to enhance data security, efficiency, and reliability.

Quantum communications harbour the potential to enhance data security, efficiency, and reliability. As the transport sector integrates more autonomous vehicles and smart infrastructure, the need for secure communication technologies increases. Quantum communication systems (e.g. QKD) and post-quantum cryptographic algorithms (PQC) offer enhanced encryption to protect sensitive data against cyber threats. These technologies can improve real-time data exchange for vehicle coordination, traffic flow optimisation, and emergency response, making transportation systems safer and more efficient. Adopting quantum communication technologies could provide a competitive edge in safety, privacy, and operational efficiency for the transport industry.

Application	Transport Mode Relevance	Case Study (Real World Experiment)
Protection of critical real-time data	Road, Rail, Air, Maritime	Airbus is participating in the European Quantum Communications Initiative (EuroQCI) which is driving implementation of an ultra-secure communication infrastructure, resistant to classical and quantum attacks, based on QKD for the protection of European (EU) assets including its overseas territories, at every moment.
Secure Vehicle-to-Vehicle communications	Road, Rail, Air, Maritime	ID Quantique offers a solution based on quantum key distribution to secure satellite and ground-based navigation signals against spoofing and hacking, aims to safeguard vehicular communications against current and future cyber threats, including those posed by quantum computing.
Quantum-Secure logistics Networks	Road, Rail, Air, Maritime	Quantum Base offerings look at protecting the integrity of supply chain communications, from shipment tracking to warehouse management, ensuring the integrity and confidentiality of data transmitted across the supply chain.
Secure Air Traffic Management	Air	Airbus, as part of EuroQCI, is exploring quantum communication for air traffic control systems to ensure secure and reliable information.
Maritime Communication Security	Maritime	The Port of Rotterdam is implementing a quantum security technology project to enhance the security of communications between ships and ports, safeguarding against cyber threats.

Legend

Road Transportation | Rail Transportation | Air Transportation | Maritime Transportation

Table 8: Potentially relevant applications for quantum communications in transport

Part 2

6.0 Socio-Economic Impacts

6.1 Introduction

The maturity of Quantum Technologies varies greatly, with many technologies still in early development stages. Therefore, any attempt to quantify their potential socio-economic impacts is inherently based on a multitude of assumptions (such as the speed of QT development and magnitude of its impact, the state of the economy and transport system, societal developments etc.), with a great number of factors either not understood or known. Even if potential impacts have been quantified in specific research or industry papers, they are yet to be proven at commercial scale.

However, the potential scale of the transformative impact of Quantum Technologies is vast. BCG estimates that Quantum Computing alone unlocks hundreds of commercial use-cases, with global value creation of $450-850 billion by 2035 (net of total end-user revenue growth of $1.8-3.5tn).

The high-level analysis outlined below, triangulating existing sources (commercial plus academic), estimates a **potential net value impact to the UK's transport industry in the range of at least £4-8 billion by 2030-2035**. This indicative range is based on a value creation estimate of ~£7bn, based on selected use-cases, and the explicit assumption that these estimates are only scratching the surface of quantum technologies' full potential for its many transport use-cases.

Illustrative value impact analysis

NB: the below table sets out examples of quantitative value impacts, for specific transport modalities. For example, personalised optimised traffic management through personalised re-routing is relevant for various transport modalities, yet the quantitative impact depicted focuses on a single modality.

NB: the analysis below is an oversimplification. However, we believe it serves as a good indicator of the potential magnitude of various impacts. All examples are based on known, quantified impacts (unless otherwise indicated).

Transport modality *(impact only)*	**Value creation**	**Key assumptions**	**Illustrative impact**
	QC holds the potential to **optimise time-critical traffic management** tasks (e.g. personalised rerouting).	The UK loses £6.9bn annually due to traffic congestion. Fujitsu simulation indicated travel times may be reduced by 40%.	~£2.8bn (2019)
	QC can o**ptimise logistics networks** vs. relative best guesses (current practice).	2% (based on UK GDP) of global net value impact, estimate by BCG.	~£1.2bn (by 2035)
	Quantum Communication systems have the potential to **prevent cyberattacks** from adversary powers.	The estimated impact of a GNSS outage on the UK transport sector is ~£700m per day (excluding impact on F&B sector and emergency services). Adjusted for inflation this amounts to ~£1.4bn by 2035. An illustrative 21-day outage (several weeks to fully restore) at 3% probability (in line with the National Risk Register) amounts to a ~£900m total impact.	~£900m (2035)
	QC can **optimise staff scheduling**, a major computational challenge.	The UK incurs ~£6.2bn of train employment costs annually. Early Hitachi case study suggests potential personnel cost savings up to 15%.	~£900m (2021)
	**QC can optimise global routing for aviation** industry.	2% (based on UK GDP) of global net value impact, estimate by BCG.	~£600m (by 2035)
	**Quantum sensors can prevent accidental strikes** as part of underground work.	~£2.4bn annual UK cost. Assumption of 10% potential effectiveness increase.	~£200m (2021)
	QC could enable **solving complex fluid dynamics** equations in aviation.	2% (based on UK GDP) of global net value impact, estimate by BCG.	~£200m (by 2035)
	Quantum sensors can **prevent erratic construction work** (being carried out in the wrong location).	~£1.5bn annual UK cost. Assumption of 10% potential effectiveness increase.	~£200m (2023)
	QC could **optimise autonomous vehicle** AI algorithm design.	2% (based on UK GDP) of global net value impact, estimate by BCG.	~£100m (by 2035)

Illustrative value impact analysis

Transport modality *(impact only)*	**Value creation**	**Key assumptions**	**Illustrative impact**
	Quantum inertial navigation systems on aircraft could serve as **a reliable back-up to GNSS**.	2% (based on UK GDP) of global TAM, estimate by Citi Group.	~£100m (2024)
	Quantum gravimeters could **reduce exploratory drilling** for energy & mineral exploration.	2% (based on UK GDP) on billions of global savings, estimate by Citi Group.	~£50m (2024)
	**QC-enabled AI/ML techniques** could proportionally benefit UK transport sector.	2% (based on UK GDP) of global net value impact, estimate by BCG. 3% (based on GVA) applied to total.	~£50m (by 2035)
	Quantum sensors potentially offer a **range of extreme precision applications**.	2% (based on UK GDP) of average global TAM estimate of $850m, a 2030 estimate by Citi Group.	~£10m (by 2030)
		Minimum value creation estimate: (by 2030-2035)	**£7bn**
		Additional cost requirement estimate:	**~£1bn**
		Highly illustrative range: (by 2030-2035)	**£4-8bn**

Legend

 Road Transportation
 Rail Transportation
 Air Transportation
 Maritime Transportation

Table 1: Illustrative Value Impact Analysis

Not all socio-economic impacts are quantifiable. We have considered a range of socio-economic impacts that may provide "real value" yet are hard to directly translate into "utility", such as "quality of life". We also note that any analyses exclude opportunity costs, and do not provide policy recommendations as such.

6.2 Costs of Implementing Quantum Technologies

Examples	Caveats
Quantum Computing: up to ~£1bn per FTQC.	Total QC costs may be alleviated if only a single, national FTQC is required, with remaining QPU demand serviced via a hybrid model (QCaaS) with cloud access for specific use-cases.
Quantum Sensing: ~£2bn, based on the equivalent for IoT sensors, although to a significant extent incurred by the private sector.	QS has seen relatively limited investment to date, with ~$80m global private VC investment in 2023.
Quantum Communications: ~$1bn market size estimated by 2034.	Quantitative information tends to be classified.

As the vast majority of Quantum Technologies are still in R&D or experimental stages, accurate estimates of costs and investments required to implement such technologies at scale, are not publicly available. For any implementation of QT into the UK transport infrastructure, additional costs related to staffing, talent training and development, maintenance and servicing will need to be taken into account beyond just hardware and software purchase costs.

Quantum Computing

Quantum computers can currently be accessed via one of two dominant models:

- Purchase of a QPU (Quantum Processing Unit), either standalone or to be integrated into existing high-performance computing systems.
- Accessing a QC through the cloud, also known as Quantum-Computing-as-a-Service (QCaaS).

NISQ-era QPU sales are rare and vary in cost, typically ranging from $10-$50m per QPU. For example, Universal Quantum won a €70m contract to build an ion trap quantum computer at the German Aerospace Centre (DLR) in 2022.

QPUs tend to be accessed via a licensing model, which also includes material annual servicing costs, up to millions per year. For example, the University of Tokyo, the National University of Seoul and the University of Chicago have partnered with IBM to build a hundred thousand qubits QC. This is a $100m project spanning a ten-year period, based on procurement of both the hardware as well as services that are associated with the system's operations.

Once QCs reach fault-tolerant stage, the cost per QPU may increase materially, up to billions per unit sold, similar to prices paid for the most powerful classical supercomputers in recent years. The acquisition of a QPU could allow the government to amortise the cost through different institutions, public or private, due to the usage flexibility rather than paying per project/analysis. QCaaS, where QC is offered via cloud access, is typically priced per hour or per computational unit. QCaaS thereby enables QC adoption for smaller transport companies.

Quantum Sensing

The unit cost of quantum sensors is unknown and will be subject to its further development and market adoption. Similar to the rollout of existing technologies such as GPS, the successful mass adoption of these technologies will likely rely on a reduction in their unit cost to the market, potentially supported by large volumes of government procurement. Industry analysts have speculated an early unit price of $20,000 per sensor based on IoT industry standards, but that figure is difficult to verify until quantum sensors are to be sold at commercial scale.

A high-level cost calculation based on the above estimated unit cost, would show a combined cost of ~£2bn (assumptions shown below);

- **Maritime:** ~85 thousand cargo vessels in UK ports (2021) = £1.3bn
  Cost incurred primarily by private sector companies.
- **Aviation:** ~20 thousand civil, commercial and military aircraft = £0.4bn
  Cost is shared by private aerospace sector and UK defence agencies.
- **Railway:** ~24 thousand active trains on UK rail network (2019) = £0.4bn
  Cost primarily incurred by UK Rail & regional private sector providers.
- **Underground:** ~540 active trains on the TfL network (2023) = £9m
  Cost incurred by TfL.

Quantum Communications

Due to the national security implications of Quantum Communication systems, they have typically been led by governmental agencies, with R&D results and progress generally kept confidential and out of the public domain. However, IDTechEx estimates the global Quantum Communication hardware market to reach $1.2 billion by 2034 (due to the broad applications of Quantum Communications it is challenging to estimate the pro rata share for the UK's transport sector).

6.3 Revenue Growth Opportunities for Private Companies

Examples	Caveats
Quantum Computing: enables advanced materials and vehicle design, optimises dynamic pricing, logistics networks and reducing downtime / improving maintenance.	May be dependent on FTQC rather than NISQ-era QPUs.
Quantum Sensing: improving value-add of products/ services enables private revenue optimisation.	2030 global market size estimates range as wide as $200m-5bn.
Quantum Communications: improving value-add of products/services enables private revenue optimisation.	2030 global market size estimates range as wide as $200m-5bn.

BCG projects that Quantum Computing alone will drive global revenue growth for its end-users (e.g. advanced materials, aerospace fluid dynamics, new battery design) of $1.8-3.5 trillion by 2035. This is based on a bottom-up analysis of many identified industry use-cases, including both monetisation of QC technologies as well as new end applications.

Quantum Technologies carry direct, actionable revenue optimisation opportunities for its users in the UK transport industry. Four areas that harbour significant revenue optimisation potential include:

1. New Vehicle & Material Design

Access to the advanced computing capabilities of QCs could enable industry players to significantly accelerate their R&D efforts, e.g. in advanced material design, vehicle design, fuel optimisation, software and hardware development. This drives increased innovation and customer value, as well as reduced time-to-market, thereby accelerating revenue growth. Early access to QC and QS capabilities will enable private companies to develop products and services which may be better performing, safer, more efficient, accurate, environmentally friendly and reliable (as covered in-depth in following sections), which will increase value-add for end consumers, and thereby revenue optimisation opportunities for companies.

Vehicle manufacturers can leverage QPUs for accelerated research into advanced materials, producing more efficient, reliable and versatile vehicles. Accurate prediction reduces the need for expensive and long lead time physical testing/prototyping which in turn enables a wider exploration of the overall design space in a given time frame. For example:

- **Computational Fluid Dynamics:** through QC-enabled circuits, engine manufacturers can improve engine design modelling to optimise performance and accelerate R&D. For example, in 2023, NVIDIA, Rolls-Royce and Classiq, used QC to design and simulate the world’s largest QC circuit for Computation Fluid Dynamics, measuring 10 million layers deep with 39 qubits. R&D for jet engines is a prime example, as it poses a lengthy engineering challenge with high complexity, cost and computational requirements

- **Predictive aeroacoustic and aerodynamic modelling** enables the development of superior quality products, e.g. reducing noise and lowering fuel consumption. This is one of the areas currently considered by various industry players. For example, BMW Group and Airbus are jointly exploring more efficient ways to solve partial differential equations so that novel product solutions can be identified which meet or exceed the challenging quality and environmental requirements of their customers.

- **Smart coating:** QC enables modelling of smart coating materials, with inhibitors that are embedded to block degradation and thereby inhibit corrosion of vehicles.

- **Quantum Sensors:** Integrating QS into vehicle design could increase the unit price of aircraft sold, and carry additional use cases for autonomous vehicles. For example, incorporating quantum inertial sensors into aircraft would enable navigation that is independent of satellites, increasing their value e.g. for military use-cases. Another example is Hyundai, which partnered with IonQ to explore applications of data from LiDAR sensors in combination with Quantum Computing, with the aim to enhance object detection on 3D data from Autonomous Vehicles.

2. Pricing Model Analytics

Price and revenue management strategies are already applied throughout the transport industry. Airlines, for example, rely on dynamic pricing models - developed using classical computer systems. Their systems price itineraries independently within a network, based only on time before departure and available seats.

These systems have already been implemented throughout organisations: for example, British Airways partnered with Qantas Airways to develop the bespoke British Airways Booking System (BABS), delivering technology to assist airlines with everything from selling their fares through to revenue optimisation and day of operations flight management. Dynamic pricing algorithms have increasingly become a dominant pricing model and continue to be rolled out across transport modalities. For aerospace, BABS case studies have proven to generate sustainable revenue increases in the 5-10% range. Amadeus and Kvantify are currently exploring the use of quantum computing in airline revenue management models, allowing them to optimise pricing offers of their network and maximise, though no quantifiable results have been made public as of yet.

Dynamic pricing models rely on regularly updated data, but currently do not have the capacity to fully consider historical trends and process high volumes of real-time data, given the limitations of classical computers. The computational advantage of QCs offers significant potential to further improve these dynamic pricing model algorithms across established modes such as aviation, as well as introduce them into new transport modalities where such systems have not yet been established at scale. In addition, QCs can be utilised to implement dynamic road pricing, boosting revenues and potentially replace lost fuel duty from an increase in the overall fleet of electric vehicles. In addition, quantum computing enhances optimisation and simulation tasks significantly beyond classical computing's capabilities, primarily through quantum superposition. This allows quantum computers to explore numerous potential solutions at once, making them particularly effective for problems with a wide range of possible outcomes.

While there are no QC case studies in price analytics yet for transport modalities beyond aviation, QC has already been leveraged to achieve advantageous results over classical computing in dynamic pricing algorithms for energy grid management, by LMU University in Munich. The scientists used a hybrid quantum computing approach via D-Wave's Leap Hybrid Cloud (we note the scale of the improvement has not been published).

3. Reduced Downtime

Quantum sensors could potentially introduce efficiencies to infrastructure maintenance via predictive maintenance analytics and optimised maintenance management, offering a tangible opportunity to increase revenues from existing systems by maximising operating time with minimal new investment required, as delays and maintenance represent a significant source of lost revenues in the UK transport industry. Additionally, quantum sensors can facilitate and optimise maintenance in geographically complex environments (hard to reach, underground or hazardous) and avoid delays by preventing damages due to accidents with underground pipes and cables.

Indirectly, a thriving national Quantum industry in the UK could accelerate economic growth and revenue generation. Through continued (public and private) investment into academic Quantum hubs, innovation grants, and start-ups – the UK positions itself as a potential future leader in the sector, paving the way for shared investment, access to local talent and infrastructure, growing demand across the supply chain and thereby a sustainable long-term ecosystem.

See Section 6.4 for a discussion on how QC, QS and quantum-enabled ML can reduce downtime and optimise maintenance, thereby indirectly driving revenue generation and optimisation.

4. Logistics

Logistics are heavily reliant on data computing for optimal operations (i.e. route planning, equipment usage, personnel scheduling, cargo loading, supply chain management) which have direct impact on financial and operational performance (delays, disruptions, shortages, etc.). This requires daily analysis of large datasets from multiple sources. Optimisation can offer not only cost savings but also drive accelerated revenue growth – for example, shipment loads can take up an exponential number of combinations in terms of size and shape, which means cargo companies tend to struggle with maximising capacity. There are a few specific areas where QC may drive accelerated revenue growth:

- **Cargo Load Optimisation:** QC capabilities can optimise cargo placement, increasing payload capacity and thereby revenues. Across the aviation industry, Machine Learning Reply (part of Reply Group) and Airbus are currently testing how QC can enable airlines to maximise cargo loading capabilities; while in 2023, cargo airline Amerijet and Quantum-South completed a Proof-of-Concept (PoC) using QC-enabled load optimisation module that allowed them to increase payload by 30% and volume by 76%.

- **Operations Streamlining:** QC can improve operational efficiency by optimising equipment usage, automating personnel schedules and route optimisation. For example, In 2021, D-Wave partnered with SavantX to optimise operations at the Los Angeles Port. The developed algorithms allowed for significant time savings of over 15% faster truck turn time, 60% increase in deliveries per crane per day, and 60% increase in crane utilisation.

- **Route Planning Optimisation:** QC can also improve operational efficiency through near real-time route optimisation. See next section.

6.4 Cost Saving Opportunities

Examples	Caveats
See illustrative analysis in section 6.1 above.	*Based on large number of assumptions. Highly illustrative.*

Quantum technologies can contribute to significantly more cost-efficient transport systems in the future, primarily via introducing far-reaching optimisation benefits across transport modalities, including both passenger and freight travel.

The enhanced computational capabilities of fault-tolerant Quantum Computers (FTQCs), combined with advanced IoT applications of Quantum Sensors can, among others:

- Improve overall efficiency, route planning, real-time tracking, traffic management and personnel management; and
- Reduce the high-cost burdens faced by the transport industry today due to traffic incidents, system breakdowns or anomalies, high-cost maintenance and inspections.

We are entering a 'hybrid era' where forms of classical, high performance (HPC) and Quantum Computing are expected to co-exist for decades to come. QC capabilities can be accessed over the cloud, via a "Quantum Computing as a Service" model, rather than onboard QCs.

The benefits and potential socio-economic impacts of advances in computing capabilities can be accelerated by the continued development of AI/ML technologies, with (hybrid) quantum computing enabling larger scale algorithm execution that will drive more powerful AI/ML applications. These will impact many use-cases that are relevant to the transport sector, including optimisation problems that could drive cost savings, as outlined below.

Quantum Computing

Early experimental case studies leveraging Quantum Computing (typically hybrid Quantum Annealing systems) show promising results, with the potential of meaningful cost savings across several identified applications. QCs can contribute to more efficient transport systems by solving some of the most complex and challenging issues faced across the value chain today:

- **Personnel Efficiencies:** Classical computers are unable to process large amounts of data and struggle to overcome the 'traveling salesman problem' (exponentially increasing number of options), which leads to suboptimal staff scheduling and personnel management, inflating staff costs for UK transport systems. This creates operational inefficiencies that drive requirements for additional staff members.

    - The complexity of staff scheduling presents a challenge for all transport modalities – with access to (hybrid) QC systems, these challenges could be addressed in real-time. In addition, optimisation could improve productivity across the board.

- **Fuel Optimisation:** In the UK, road transport accounts for more than half of oil demand (mainly petrol and diesel). UK motorists spend ~£40bn p/a on fuel, consuming >45bn litres of fuel. The UK aviation sector spends ~£3.6bn on jet fuel (>11m tons of jet fuel, assuming current prices). QCs could efficiently compute optimal routes for individual vehicles, considering factors such as, fuel costs, modes of transportation, and real-time inventory needs: this enables the calculation of the most fuel-efficient paths, leading to overall improved fuel optimisation across transport networks.

    - For example, IBM and ExxonMobil currently are working to explore the role QC can play in optimising maritime and shipping routes.

    - QCs can offer cost savings for a range of transport modalities e.g. shorter flight routes (with lower fuel consumption) or maritime cargo optimisation (considering a wide array of variables e.g. weather patterns, inventory levels and length of voyages).
        - QC could potentially significantly improve battery performance and reduce charging times, resulting in significant consumer savings and making EVs more attractive, indirectly reducing fuel consumption.

        - Reduced fuel consumption would mean a reduction in income for the UK government, for whom fuel duty is a substantial source of income (e.g. total UK fuel duty of >£26bn p/a).

- **Network Optimisation:** While an optimised route with a handful of delivery stops can be determined relatively quickly by a desktop computer, it would take years for a classical supercomputer to calculate an optimised route with dozens of stops and potentially additional parameters. Last-mile delivery costs are a key driver of costs, and account for 53% of total door-to-freight transportation costs.

    - By supporting global route optimisation and more frequent re-optimisation, recognising capacity constraints of transport assets (e.g. buses), QCs could help significantly reduce freight transportation costs (and boost customer satisfaction). BCG estimates that absolute routing optimisation can unlock $50-100bn in net income for the global logistics sector, and another $20-50bn for the global aerospace sector.

- **Cargo Load Optimisation:** Cargo/freight loads can take up a multitude of combinations in terms of size and shape, driven by weight distribution, space utilisation, freight compatibility and legal requirements. QCs can help optimise cargo loads by leveraging increased computing power to solve complex optimisation problems efficiently. For example, the Quantum software developer SavantX used a hybrid QC from D-Wave to streamline operations at LA-based Pier 300 between 2018-2022, increasing daily crane deliveries from 66 to 97, and trucks spending 58 instead of 66 minutes to await payloads.

- **Traffic Management:** Current, classical systems are not able to process exponentially large data volumes and are therefore limited in their ability to effectively manage traffic congestion. Road congestion caused by road construction, traffic accidents and distance between vehicles, ensures that significant inefficiencies in traffic management persist. In 2019, the UK economy lost £6.9bn because of road congestion, with drivers in London spending as much as 149 hours p/a stuck in traffic.
    - QCs could assist in real-time optimal route calculation, i.e. rapidly compute the shortest paths for millions of vehicles simultaneously. QCs can provide personalised routes, in contrast to conventional navigation services. This minimises detours and traffic congestion, preventing vehicles from converging into the same areas. An example from DENSO describes how QCs can contribute to reduced traffic congestion: *"If a car has three routes and nine combinations, then ten cars could have 60,000 combinations of possible routes; 20 cars could have 3.5 billion combinations and 30 cars as many as 20 trillion combinations. Conventional computers would take an eternity to compute every alternative route to ensure that congestion is eliminated. This is why quantum computing is necessary"*
    - Across traffic management, D-Wave and Volkswagen have partnered to pilot applications of QC annealers, focusing on passenger number prediction and route optimisation. Their initial experiments confirmed that time-critical optimisation tasks, such as continuous redistribution of position data for cars in dense road networks, are applications that could be solved using quantum computing systems.
    - A Fujitsu simulation in 2019 estimated that if vehicles take optimal routes as determined by Digital Annealers based on overall optimisation, travel times for all vehicles will be reduced by 40%. Illustratively, this would equate to a ~£2.8bn annual saving for the UK economy (based on 2019 figures).
    - We note that active replanning requires a heavy computational burden, with time between start and real-world deployment (research, model building, product deployment) estimated at a minimum of 32 months.

Quantum Sensing

Quantum sensors have unique sensing capabilities which could offer material cost savings across all transport modalities, both in lieu or in combination with current IoT infrastructure:

- **Reduction of trackside signal failures:** Current railway and underground systems in the UK rely on trackside signals to control the movement and speed of trains, which are prone to multiple faults (e.g. human error, computer network issues, cybersecurity attacks). According to Network Rail, there were over 19,000 signal failure-driven delays in the UK in 2017, driving high costs related to delays and maintenance

    - Quantum sensors could offer a secondary protection or an alternative to the existing trackside signalling systems, owing to more precise and comprehensive sensing capabilities of Quantum Sensors.

    - For example, Imperial College researchers are currently exploring Quantum sensing applications for London's underground. The team is developing a new type of hybridised inertial sensor technology with the potential to accurately determine position without the need to send or receive signals. In the future, trains carrying such quantum enhanced navigation systems may be able to register their position on the network accurately and reliably without the need for significant external infrastructure.

- **Optimised Maintenance:** Quantum sensors are novel technologies that provide a broad range of opportunities associated with reducing maintenance costs, across UK transport modalities. There are >190,000 railway earthworks and >6,000km buried assets in the UK railway infrastructure, with an incomplete and immature asset inventory significantly limiting the development of a decision support framework to allow proactive condition assessment.

    - Currently, geophysical sensors are commercially used to detect the location of the ducts and pipes in roads and with limited success on railways, but rarely to detect the asset condition or the condition of the parent asset (earthwork) itself. Thus, geotechnical failures are often reported by train drivers or by walking the asset, at a cost of ~£8M/year.

    - Proactive asset management is constrained;

        - Resulting in longer disruptions to the rail network. There are >314 thousand fully or partly cancelled trains in the UK p/a, of which a large percentage relates directly to train faults.

        - There are >1m potholes in the UK (a £14bn problem in England & Wales alone), one of the leading causes of car breakdowns, and the government is spending £700m p/a on repair.

        - The UK incurs other significant expenditures – e.g. on bridge (>£5.4bn backlog across >70k UK bridges) and railway (~£7.5bn p/a) infrastructure maintenance.

    - Quantum sensors could address these bottlenecks through a number of levers, including:

        - **Condition monitoring:** Quantum sensors can detect and measure changes in temperature, pressure, vibration, and other parameters that indicate potential equipment failures. By monitoring these conditions in real-time, maintenance teams can identify and address issues before they become critical, reducing downtime and repair costs.

- **Structural health monitoring:** Quantum sensors can detect and measure structural changes such as corrosion and cracks e.g. in bridges, tunnels, or railway infrastructure, providing early warning of potential failures and enabling proactive maintenance.

- **Predictive maintenance:** By analysing data from quantum sensors, ML algorithms can predict when maintenance is required, reducing the need for scheduled maintenance and minimising downtime.

- **Improved fault detection:** Quantum sensors such as magnetometers can detect faults in electrical systems before they cause significant damage, reducing repair costs and improving safety. Gravitational quantum sensors can detect buried objects like pipes and cables, which could prevent delays and damage during maintenance work.

- **Quantum LiDAR:** offer a significant advancement in visually detecting gas leaks, particularly methane leaks from oil and natural gas extractions, as well as improving road (bridge) maintenance. This technology provides a substantial improvement upon existing laser-based systems, which rely on complex and expensive mirror arrays. Operating in various conditions, including poor visibility, and capable of continuous, in-situ monitoring, it allows immediate notification of gas escapes and save costs associated with gas leaks.

- **Remote location maintenance:** Quantum sensors could be used in hard-to-reach or hazardous environments in lieu of existing classical sensors, reducing need for unnecessary maintenance – e.g. in combination with robotics haptics systems.

- **Geophysical surveying:** Quantum gravity sensors can accelerate geophysical surveying of underground infrastructure up to 10 times, reducing the time needed for surveys from a month to a few days. Industry initiatives are ongoing, e.g. QT-PRI is a collaboration between RSK, Atkins, Network Rail and the University of Birmingham (UoB) to establish the Quantum gravity sensor market opportunities against assessment of current geophysical technologies. Gravitometers may also offer reliability advantages over legacy Ground Penetrating Radar (GPR) methods, offering additional time and cost savings.

- Accurate Navigation: Precise navigation and highly accurate systems are critical to transport modalities, including aviation and shipping. Many navigation systems today rely on GNSS systems, such as GPS, which uses signals from satellites orbiting the Earth. However, GPS navigation is not always accessible, obstacles like tall buildings can easily block the satellite signals, and they are also susceptible to jamming, imitation, or denial, thereby preventing accurate navigation. It has been estimated that a single day of satellite service denial would incur a cost of £1 billion to the UK – effectively deployed quantum sensors would significantly reduce that cost.

- Quantum sensors could more accurately measure attributes such as frequency, acceleration, rotation rates, electric and magnetic fields, and temperature to improve navigation systems across transportation assets. For example;
  - Quantum accelerometers can provide precise velocity measurements, reducing location errors from meters to centimetres.
  - Quantum Inertial navigation systems can reduce navigation errors by several orders of magnitude, from meters to millimetres.
- **In aerospace**, major industry players such as Airbus are currently exploring the use of quantum sensing technologies to enhance navigation systems.
- **In railway,** the University of Birmingham is working with Network Rail to improve identification methods for the accurate location of moving trains using gravity map matching.
- **In maritime**, Imperial College is working on deploying quantum sensors (accelerometers) based on ultracold atom technology across UK navy ships.

6.5 Potential Time Savings

Examples	Caveats
Quantum Computing: QC carries significant time savings potential through optimisation, e.g. by personnel scheduling, route optimisation, traffic management and dynamic scheduling.	**QC:** may be dependent on FTQC rather than NISQ-era QPUs.
Quantum Sensors: time savings in asset management through optimised maintenance of transport infrastructure, leading to efficiencies in both maintenance and resulting traffic disruption.	

Transport delays and suboptimal efficiency across transport modes are closely linked with significant costs and loss of productivity, negatively impacting the lifestyle of British commuters, exacerbated by material access gaps and regional inequalities. The demand and complexity of the UK transport requirements are only due to increase (as projected in the UK 2050 Transport Vision), creating an urgent need for more efficient transportation systems that are less prone to disruption and delays.

Quantum Technologies can positively contribute to achieving efficiencies and time savings in the UK transport sector, both directly (e.g. via QC enabling optimised routing) and indirectly (e.g. by creating more secure, disruption-free transport systems, and contributing to the development of new public infrastructure and/or novel modalities).
Quantum Computing carries the promise of materialising meaningful time savings for British passengers by wide-ranging optimisation benefits:

Optimisation Area	Overview
Personnel Scheduling	Optimising staff schedules by considering factors like employee skills, location, availability, and preferences, enabling a prediction of staff needs based on historical data and real-time inputs, adjusting schedules accordingly, thereby reducing capacity and/or delay risks.
Route Optimisation	Optimising routes for vehicles (e.g. logistics, railway, buses or cars) in real-time, considering factors like traffic patterns, road conditions, and vehicle capacities. This leads to shorter travel times, reduced fuel consumption, and offers the potential to reduce high wait times for underserved areas in the UK.
Traffic Management	QC could potentially manage traffic effectively by monitoring traffic patterns and adjusting routes dynamically. This helps to minimise congestion, reduce travel times, and increase overall efficiency (offering the potential to reduce congestion in metropolitan areas such as London or Manchester).
Dynamic Scheduling	QC offers additional potential benefits for the logistics sector, through enabling dynamic scheduling (e.g. personnel, supply chain equipment and workflows) by processing real-time data about shipments and cargo. This could enable more accurate predictions and inform decisions in rapidly changing circumstances.
Asset Management	Quantum sensors introduce efficiencies to infrastructure maintenance for all transport modes (e.g. road or rail), reducing the duration of maintenance itself and limiting resulting traffic disruption.

All these optimisation areas produce vast amounts of data, relying on both historical and real-time inputs, which are impossible for classical computers to effectively compute in a timely manner. For example, on the road, all drivers consider the same navigation system to understand congestion and are shown the same ‘alternative’ route, exacerbating the congestion problem and creating a succession of traffic jams. Across different travel modalities, Quantum Technologies have the potential to materialise time savings across the following identified levers:

Logistics

The UK logistics segment offers several opportunities for time savings and increased efficiency. The large volumes of high-variety real-time, internal and external data sources (e.g. traffic, weather, or cargo load variations) are challenging to compute for traditional computer systems. In 2022, it was estimated that ~50% of UK deliveries are delayed.

QC offers the unique computational capabilities to process high data volumes related to the variability of logistics supply chains in real time, and acts as a helpful tool for identifying optimal solutions to complex logistical problems, for example by optimising equipment usage and personnel schedules while ensuring that containers are cleared from the port as quickly as possible, creating time savings across the entire workflow. D-Wave for example, partnered with SavantX to optimise operations at the Los Angeles Port: the developed algorithms allowed for significant time savings, of over 15% faster truck turn time.

Rail & Underground

Rail passengers have been delayed or disrupted on more than half of all train services departing from 15 of UK’s busiest stations in 2022. Disruptions also vary regionally, with some stations such as Coventry or Milton Keynes experiencing delays on more than half of all services. London and Manchester have also been the top two cities in Europe with longest wait times due to insufficient and / or delayed services (with average wait times of 35 minutes and 34 minutes, respectively).

QC could be used to alleviate several structural challenges driving these delays:

Personnel scheduling: Staffing challenges are one of the leading causes of train delays in the UK, and they could be proactively addressed through real-time analysis of high data volumes in real-time offered by QCs.

Route optimisation: QCs may be used to simulate many different alterations to train timetables at once to find the most efficient scenario. In 2024, The Australian company Q-CTRL and UK’s Oxford Quantum Circuits partnered with Network Rail and the Department for Transport to develop a quantum algorithm designed to more efficiently organise train timetables. The computers will be used to simulate many different alterations to train timetables at once to find the most efficient scenario.

Bus

In addition to staffing (as described above), QC could be used to implement dynamic scheduling - leveraging the computational capabilities of QC to calculate the fastest route for buses in near real time to reduce passengers' travel time and enable more efficient use of network resources. The QC assigns each bus to an individual route, ensuring they can navigate around traffic bottlenecks. Early industry case studies include the Government in New South Wales, which has been developing algorithms leveraging QC-annealing systems to optimise bus delays in Sydney through dynamic scheduling. The success rate of the experiment is not yet publicly disclosed, but for reference, the aim was to reduce current average delay rate of 7.5% as of 2021.

Aerospace

Data released by the Civil Aviation Authority (CAA) shows that 37 per cent of flights in and out of UK airports were at least 15 minutes late in 2022. That figure has risen by 17 per cent since 2021 and 2020, and by 25 per cent compared to data recorded in 2019. The overall average plane delay experienced by passengers last year was 22 minutes. This delay is a 60 per cent increase on waits seen in 2019.

Early industry case studies have focused on route optimisation to prevent delays, whereby QCs (potentially in combination with quantum sensors installed across the aircraft) could be used to find the most efficient route based on real-time aircraft positioning, external navigation tower signals and weather data (as well as additional datapoints). For example, Airbus is currently working on route & fuel optimisation initiatives to materialise time savings. At an airport level, additional time bottlenecks related to staffing shortages or aircraft landing plans may also be optimised leveraging the computational power of QCs.

Road

Due to the sheer volume of real-time data from traffic in the UK, classical systems are not able to effectively manage congestion, leading to significant delays. This challenge is only expected to increase in line with growing customer demand. The average UK driver lost 80 hours due to traffic congestion in 2022– up 7 hours from 2021. Drivers in London (156 hours), Bristol (91 hours), and Manchester (84 hours) lost the most time to traffic congestion in the UK.

Quantum Computing can improve traffic management by offering more efficient route planning and optimisation techniques (e.g. analysing datapoints such as traffic flows, weather patterns, and road conditions to generate near-optimal routes for vehicles). There are several industry case studies exploring the potential benefits of QC on the road:

- Volkswagen has partnered with D-Wave to develop QC-supported algorithms for traffic flow optimisation for both private vehicles and buses.

- A study conducted by Fujitsu in 2019 estimated that if vehicles take optimal routes as determined by Digital Annealers based on overall optimisation, travel times for all vehicles will be reduced by 40%.
- A study conducted by Toyota Tsusho Mobility Informatics employing D-Wave's quantum hybrid solver, resulted in greatly improved routes for a relatively small fleet of 18 vehicles. With a quantum assist, those vehicles were able to hit the same number of stops while cutting both their mileage and driving time by nearly 10%.

Even 10% savings would translate to ~8 hours less traffic per driver p.a. on average (but as much as 15 hours in the most congested cities such as London), with 40% savings translating to as much as 32 hours less traffic per driver p.a. (or as much as 60 hours in London).

6.6 Socioeconomic Risks

Examples	Caveats
Quantum Computing: FTQCs involve potential national security risks due to the potential to hack into classical cryptography.	FTQC hacking risks may be effectively mitigated through Quantum Communication systems.
Quantum Sensing: effective quantum sensors may increase the military power of adversary forces.	Still in R&D phase.
Quantum Communications: could provide ultra-secure communication systems, e.g. through QRNG or QKD networks, and/or implementing PQC algorithms.	May have fundamental issues. See chapter 5.

As many Quantum Technologies are still in the early development stages, the full spectrum of risks to the UK's transport systems and British passengers is yet to be fully understood. Systemic risks posed by future commercial scale Quantum Technologies include:

Security Threats – future Quantum Computers may pose a significant threat to current encryption systems, which are the foundation of cybersecurity systems protecting UK transport industry data.

The UK National Risk register has assigned a 'moderate' risk profile to cybersecurity threats in the UK transport system, with a likelihood in the 5-25% range. The reasonable worst-case scenario is based on a cyber-attack against a critical information network or system in the transport sector. This would result in severe disruption to services delivered by operators. A 2017 UK Government report estimated the loss to the UK economy from a GNSS outage to exceed £1bn (~$1.3bn) per day, impacting a broad range of transport modes.

A cybersecurity threat from QCs owned by adversary parties could thus lead to severe disruption of the UK transport system across all modalities. There is also the risk of 'hack now, decrypt later', whereby hacked data may be stored and decrypted once Quantum Computing systems are more readily available and commercially usable.

FTQC, which could pose a cyber threat, is still in development phases however, and there have been no publicly known cases of cyberattacks yet that were made through algorithms developed on NISQ-era Quantum Computers or QC annealing / hybrid systems. Assuming that fault-tolerant computers are not available in the next 5-10 years, 'hack now, decrypt later' attacks carry limited risks for rapidly changing sectors such as transport and national security (unless the compromised historical data still proves useful). Moreover, the implementation of PQC algorithms and QKD networks could provide highly secure communication systems.

Timeline Uncertainty – the timeline for commercial applications at scale is unclear for a majority of Quantum Technologies. For example, the range of industry expert forecasts for FTQCs to become available is as wide as 2-40 years (please refer to Section 1.3).

Cost Overrun Risk – integrating QC systems into existing HPC systems and infrastructure, or QS into UK trackside infrastructure, will be major operational undertakings. Such implementations carry significant execution risk, which may result in cost overruns, exacerbated by limited expert talent pools. Cost overruns tend to be followed by negative PR and reduced societal trust, which could impact future funding.

Opportunity Cost – implementation costs, R&D funding and programs carry significant costs that tend to be borne by UK government agencies, universities as well as the private sector. Opportunity costs should be taken into account for any decision-making policies, considering money and time spent. Developing commercial-scale QT will require significant investments from both public agencies and private sector players (e.g. investment of capital, time and talent resources). In 2023, the UK Government pledged >£2.5bn investment into Quantum Technology R&D over a 10-year period – investments allocated to QT could alternatively be spent on other emerging technologies, infrastructure investments or defined funding goals.

Benefits of Risk Reduction

In addition to the wide-ranging potential benefits described in following sections, QT may also carry indirect risk management benefits to public transport agencies as well as private companies. Improved operational performance related to improved predictive maintenance, increased safety profiles and systemic security will affect asset and system insurability, as well as carry asset management synergies across infrastructure and vehicle lifecycles.

Non-technical Adoption Barriers

In addition to the Practical Challenges outlined in Part 1, there are various social and commercial barriers for QT to overcome and pose a potential risk to QT achieving their full potential (which in turn could limit or eliminate the potential benefits outlined in this report).

Commercial Barriers	Lack of practical applications	• Gap between lab-based innovation and marketable products. • Challenge in proving commercial viability. • Difficulty in identifying superior practical applications. • Need for enhanced quantum hardware development/production to create useful applications. • Limited consumer awareness and demand.
	Major investment with high risks	• Comparison with early-stage AI industry dynamics (high interest but low applicability). • High initial costs with uncertain return timelines. • Capital intensive materials and technologies. • Risk aversion among institutional investors. • Minimal start-up investments in component manufacturing.
	Industry standards and regulation	• Lack of industry-wide standards. • Challenges in ensuring compatibility across platforms. • Need of certification processes for safety and efficacy. • Regulation still evolving, complicating compliance.
	Scepticism	• Unfulfilled promise of surpassing classical computing, resulting in public scepticism ("quantum hype"). • Scepticism around timing of the "quantum revolution", questioning the priority of investing in quantum technologies.

Table 9: Quantum Technologies' Commercial Barriers

Social Barriers	Workforce & education	• Talent gap: shortage of skilled professionals in QT, threatening national competitiveness and sovereignty. • Need for a well-defined education and workforce strategy, including specialised training programs. • Mismatch between formal training and industry needs. • Upskilling programs essential for QT readiness. • Lack of widespread quantum literacy.
	Understanding and general perception	• Complexity and abstract nature of quantum technologies. • Public misconceptions affecting adoption.
	Regulation and policy	• Policymakers' lack of understanding hinders policy development.
	Privacy and security concerns	• Fear of surveillance or misuse of quantum technologies. • Concerns about data protection and encryption strength.

Table 10: Quantum Technologies' Social Barriers

6.7 Regional Development and Inequality

Examples	Caveats
Quantum Computing: QC-enabled traffic and schedule optimisation has the potential to alleviate regional connectivity constraints. QC could accelerate the development of eVTOL aircraft that improve accessibility of rural areas.	QC optimisation potential offers similar benefits to more developed areas, potentially increasing regional inequality despite offering tangible benefits to underdeveloped areas. eVTOL development still faces significant technical barriers.
Quantum Sensing: QS could significantly reduce (underground) construction costs, reducing the investment required for public infrastructure. In addition, they could potentially augment remote network availability through optical communications systems.	QS might improve implementation costs, but political decisions would be required for effective change / investments to be achieved.

Transport is an important facilitator of social inclusion and wellbeing, affecting economic and social outcomes, and therefore inequality. Commute infrastructure is closely related to job and educational opportunities.

- Transport costs are keeping 5 million people (8% of the UK population) below the poverty line. In rural communities, transport is the single largest household expense (excluding mortgage repayments) whilst in urban families, it is the second largest expenditure. For example in Northeast England, 13% of people are likely to suffer from transport poverty, compared to only 3% of people in London.

- Beyond public transport access, there are also significant racial disparities in vehicle access. 58% of black people have a full driving license, compared with 79% of white people; and 33% of black people had no access to a car or van, compared with 16% of white people and 17% of Asian people.

- There has been historical underinvestment in transport infrastructure, especially across several metropolitan areas in northern England. According to the social organisation Centre for Cities, four in ten people in the UK's largest cities (outside London) cannot reach their city centre by public transport in <30 minutes, which exacerbates inefficiencies and loss of productivity across the UK economy. In other large European cities, around seven in 10 people can travel to their city centre in less than 30 minutes.

While regional development and inequality are not direct focus areas in the context of QT development, it is likely to be positively influenced by its resulting efficiencies. QT have the potential to make UK transport modalities more efficient, accessible and safe *(please refer to Sections 6.4, 6.5, 6.7 and 6.8 for further detail)*, providing access to different socioeconomic opportunities. However, if QT are not deployed strategically across the country (e.g. no investment in local quantum networks in underdeveloped regions) then this could potentially exacerbate existing inequalities (e.g. if only London benefits from a QC-optimised transport system due to a centralised investment policy).

The full potential impact of QTs on regional development remains to be seen, however early industry case studies show wide-ranging potential benefits which could accelerate improving access in less developed regions and urban areas:

Public Infrastructure - several UK cities could benefit from a central public transport system and have inferior infrastructure compared to London, or their European peers of similar size.

Leeds is the largest European city without a centralised underground or tram infrastructure – despite previous development efforts, construction of underground infrastructure was deemed too expensive and plans were consequently abandoned. Across Manchester, Leeds, Sheffield, Liverpool and Newcastle there are >4 million people unable to reach their city centres within 30 minutes via public transport. These limitations are preventing them from accessing higher quality employment and education opportunities, resulting in a combined loss of productivity of £16bn every year.

QT could particularly support public transport infrastructure works through:

- **Underground and ground construction:** QS offer several innovative options to modernise and introduce efficiencies into underground development as well as ground-level construction. *See section 6.11*.

- **Network Coverage:** Quantum Sensors have been demonstrated to combine optical light sources with radio frequencies at atomic level (creating so called ‘Quantum Radio’), which could augment network availability and coverage in remote areas.

    - In 2024, BT announced their proof-of-concept Quantum Radio is up to five years away from commercialisation. The proof-of-concept study demonstrated that quantum radio could be integrated into 4G networks in remote areas and estimated the novel communications link can provide “up to 100× more sensitivity than traditional receivers”, establishing “superior ‘edge of cell’ site coverage”, which would be particularly useful in remote areas in the UK.

Novel Transport Modes - in 2020, 9.7 million people were estimated to live in rural areas in England. Advanced air mobility, including electric vertical take-off and landing (eVTOL) aircraft, can help improve transport access for rural communities in the UK by better connecting them and delivering vital supplies and services to currently poorly served areas.

eVTOLs could potentially serve to augment transportation services in underserved areas. However, there are significant challenges in commercial development of eVTOLs, which lack the battery life, payload and range of helicopters in a cost-effective manner. For example, the range of eVTOL aircraft is estimated at 50 miles initially, while the longest-range helicopters can fly as far as 500 miles in a trip. eVTOLs could also have significant potential for use cases in urban mobility, however, current air traffic control systems cannot handle the robust operations of eVTOLs due to lack of computational capabilities of classical computers.

QC computational capabilities offer a unique opportunity for the development of commercially available eVTOL aircraft in the UK: QPUs can aid the design of more efficient batteries and eVTOL vehicle systems, accelerating the solutions to current challenges relating to a commercial roll-out. In addition, QC could help overcome existing challenges relating to air traffic control, which would not be feasible for classical computing systems to effectively manage and control the amount of real-time data. For example, QC company Pasqal partnered with the Quantum Transformation Project (QX-PJ) to use quantum algorithms to optimise routes for low-altitude eVTOL air traffic. QX-PJ is a pilot experiment for developing optimised flight routes and scheduling a fleet of eVTOL vehicles using QC technology.

Shared services - QT could help (i) lower the cost of transport, and (ii) enable development of Mobility as a Service (MaaS), both of which could improve transport accessibility. Cost savings offered by quantum technologies could be partly passed on to passengers, lowering overall cost of transport and financial burden. Mobility as a Service refers to shared use of vehicles, most commonly via a digital platform (smartphone application) that aims to encourage sustainable travel. MaaS offers the potential to lower overall transport costs and increase accessibility, thereby contributing to more equitable and accessible travel. QC has significant potential to help optimise MaaS applications – QCs could be used to analyse large amounts of data, such as usage patterns, weather data and customer preferences, to optimise the availability and pricing of MaaS offerings. For example, in 2021, the Government of New South Wales in Australia partnered with QC company Q-CTRL to enable Mobility as a Service (MaaS) and dynamic scheduling for a multimodal network in Sydney.

6.8 Passenger Safety Impact

Examples	Caveats
Quantum Computing: Advanced compute capability from QCs enables real-time decision-making, potentially optimising traffic across transport modes. The superior data processing capabilities from QPUs also enable advanced manufacturing, potentially contributing to safer vehicles in the future.	Still in R&D phase.
Quantum Sensing: improved hazard detection via QLiDAR; optimised monitoring & maintenance of critical transport infrastructure; improved safety by way of reduced reliance on GNSS systems through development of GNSS-independent navigation.	Still in R&D phase with unclear implementation complexity & cost.
Quantum Communications: may provide ultra-secure communication systems, e.g. through QRNG or QKD networks, and/or implementing PQC algorithms.	May have fundamental issues. See chapter 5.

The computational advantage of QCs, combined with advanced measurement by Quantum Sensors, can significantly contribute to improving the everyday travel experience for British passengers across all travel modalities. Quantum Communications offers critical safety benefits at a national security level *(please refer to chapter 5 and the next section for further details)*.

Quantum Computing

QC has far-reaching applications across transport modalities, with positive implications for passenger safety;

- QC enables the optimisation of existing transport systems, for examples across scheduling, traffic management, predictive maintenance, and personnel management. QPUs potentially enable superior processing of the terabytes of data that are produced daily, for example on engine performance, fuel utilisation, passenger and traffic data. Classical computers do not have the capability to leverage this data to generate real-time, deterministic insights.

- QC may enable the design of more secure transport modes, through powerful computational applications across the respective value chains. These include superior vehicle design (through aerodynamic modelling), incorporation of advanced materials (e.g. preventing corrosion), more efficient batteries, or improved safety mechanisms (e.g. crack detection in aerospace).

Early industry case studies have identified three specific areas where QCs may offer the most benefits to passenger safety:

Improved Disaster Response

Enhanced computing power through QC capabilities will allow for real-time planning of emergency disaster response in a more holistic way (i.e. ability to process more data and input variables vis-a-vis classical computers, thereby improving planning capabilities, speed of response, and optimising overall resource allocation). This could optimise communication systems, evacuation routes during natural disasters, and more efficient allocation of resources during humanitarian crises.

For example, collaborative efforts between Terra Quantum and Honda Research Institute Europe have shown promising results in optimising evacuation routes during emergencies using hybrid quantum computing methods. This technology can efficiently predict dynamic escape routes, minimise evacuation times, and make decisions based on local information, requiring less than 1% of map information.

Performance of Autonomous Vehicles

Autonomous vehicles (self-driving cars or autonomous drones) rely on real-time data analysis, processing information about their local environment or traffic to ensure safe and reliable performance. In the US, autonomous vehicles (AVs) are involved in more crashes than traditional cars: 9.1 crashes per million miles travelled, compared to 4.1 for conventional cars. Quantum Computing has numerous potential applications in improving the safety profile of AVs:

- **High-Speed Calculations:** QCs can process data much faster than classical computers, enabling the exploration of larger design spaces and accelerating the AV's decision-making.
- **Optimal Route Planning:** Quantum algorithms can analyse large datasets to determine the best routes for autonomous vehicles, accounting for factors such as traffic patterns and road conditions.
- **Training Neural Networks:** QC can train neural networks for AVs more effectively and efficiently compared to classical computers, thanks to its ability to process vast quantities of data in shorter periods. According to Arrow Electronics, in an autonomous vehicle AI model training application, a quantum computer would be able to process 10,000 years of training data in 200 seconds, allowing for infinitely more opportunities for AV model trainers.
- **Material Design and Manufacturing:** Quantum simulations can help optimise vehicle design and manufacturing processes, resulting in lighter, safer, and more fuel-efficient vehicles.

- **Traffic Management:** Quantum computing can assist in reducing traffic congestion by analysing sensor data and optimising traffic flow.

Quantum Machine Learning

ML has a broad range of applications through which it can improve passenger safety, although it requires vast computational capacity to achieve its full potential, which QC capabilities could support (allowing for more scaled and powerful calculations in contrast to classical computers). Notable Quantum-enabled ML applications include **border control** (improving efficacy of automated border control facial recognition procedures that scan passengers and cargo) and **predictive maintenance** (increase system reliability, e.g. predicting with high accuracy when specific railcar components need to be replaced, reducing downtime and improving fleet utilisation, ultimately leading to higher passenger safety and satisfaction).

Quantum Sensing

Quantum Sensing technologies can improve accuracy of safety mechanisms across transport modalities, and reduce the transport system's reliance on Global Navigation Satellite Systems (GNSS). Despite GNSS' dominant position, it is not failsafe and due to a "line of sight" requirement and risk of spoofing or jamming remains vulnerable to weather conditions. In addition, GPS (the widely used American satellite system) is not always available due to independency requirements of critical safety systems, and does not work underground – for example in tunnels for the London underground system, or in the Channel Tunnel. Innovation in QS effectively supports existing IoT systems used across all transport modalities ("hybrid sensing") and significantly enhances their capabilities and accuracy – driving an overall safer transportation system.

There are four major areas for Quantum Sensors to augment or improve legacy systems:

Improved accuracy and functionality

The precision and sensitivity of quantum sensors make them ideal for detecting subtle changes in motion, gravitational fields, electric fields, and magnetic fields, which are crucial for safe navigation in complex environments. Legacy sensor systems are unable to measure atomic properties. As a result, they may be suboptimal solutions for measuring metrics such as gravity or magnetic fields. As quantum sensors measure activity in the physical world using atomic properties, they allow for more precise insights in real-time.

- **Road** - For AVs, Quantum sensors could accelerate the AV's response to other vehicles or obstacles on the road, reducing accident risk, and enabling them to "see" around corners. These sensors, leveraging QT, can enhance the performance of AVs by providing improved object detection, navigation around obstacles, and real-time data processing. The incorporation of quantum sensors in AVs is being explored by companies like Hyundai and IonQ, aiming to utilise QC for interpreting sensor data from LiDAR systems and enhancing object detection tasks on 3D data gathered by AV sensors. In addition, QS could potentially enhance GNSS independent navigation systems.

- **Railway** - In 2021, Germany's Deutsche Bahn partnered with Cambridge Quantum to explore how Quantum Sensors and QC can optimise rail traffic and accident response.
- **Maritime** – QS could enhance GNSS independent navigation systems for MASS (Marine Autonomous Surface Ships).
- **Aerospace** – QS could be used to augment crack detection systems, enabling faster crack detection, or enhance other aircraft systems (e.g. via quantum clocks). In addition, QS could potentially enhance GNSS independent navigation systems.

Reduced reliance on GNSS

As GNSS cannot be solely relied upon for safety critical positioning on rail networks, there is a need for more accurate and reliable positioning systems, particularly on the London Underground or the Channel Tunnel, where GPS cannot operate. It is estimated that over £360 billion (about 17%) of the UK's non-financial business GDP per year is dependent on satellites and that the negative financial impact of the UK losing access to global navigation systems could be as high as £5.2 billion for a five day disruption.

Through the ability to detect electric and magnetic fields with high sensitivity to receive signals, quantum sensors could provide accurate location information in environments where GPS signals are not available (e.g. underground, or in denied locations), improving safety and navigation. For example, Imperial College is exploring implementing quantum sensors in lieu of signalling systems to improve safety and reliability in the London Underground (and reduce existing reliance on GNSS where GNSS is denied).

Enhanced Visibility

Despite significant innovation in cameras and imaging systems in recent decades, modern (classical) technology still suffers from suboptimal safety for passengers with many accidents taking place across transport modalities. Traditional cameras typically rely on 2D imaging, without geometrical knowledge and detailing. On the other hand, Quantum imaging systems offer 3D vision capabilities, which can operate based on detection of the smallest amount of light – just a single photon – enabling enhanced accuracy and navigation, regardless of the time of day or weather conditions.

Quantum LiDAR example: Quantum LiDAR enhances the capabilities of AVs by providing precise and detailed 3D mapping of the surroundings. It utilises the principles of quantum mechanics to improve object detection, reaction time, and navigation. With quantum LiDAR, self-driving cars can detect and recognise objects with higher accuracy, enabling them to respond quickly and effectively to potential hazards. This advanced technology offers enhanced range and resolution, allowing autonomous vehicles to perceive their environment with greater clarity and detail.

Meteorology

Low light conditions and adverse weather increase the likelihood of accidents. In 2019, an average of 4 deaths and serious injuries per day (1,292 in total per year) were partly caused by slippery roads, due to the weather.

Use cases for Quantum Technologies have been identified in atmospheric data - satellites equipped with quantum sensors (such as gravity gradiometers) could potentially measure atmospheric data at enhanced depth and breadth compared to technologies today (e.g. vital metrics such as temperature, humidity, or pressure), allowing for a more informed study of the environment and weather. This data could be leveraged to inform transport planning (e.g. limiting risk for aircraft during adverse weather conditions), or early detection of extreme weather conditions or natural disasters, allowing for better emergency planning response.

Asset Management

The potential role of Quantum Sensors such as gravimetry, magnetometers or QLiDAR in infrastructure maintenance carries further potential passenger safety benefits by improving the risk profile of roads and railways.

6.9 Public Security and Trust

Examples	Caveats
Future FTQC capabilities operated by adversary powers could have a significantly disruptive effect on UK transport sectors. However, quantum encryption methods (QKD/ QRNG) and PQC could potentially provide ultra-secure communication systems, beyond the capabilities of any classical computers.	PQC may likely become the standard for adoption in the medium term, e.g. cloud providers / hyperscalers (e.g. Google, Microsoft) and Big Tech companies (e.g. Apple) have already implemented "quantum-safe" solutions, protecting their end-users.
QC optimisation could provide significant efficiency, time and cost savings – that could contribute to enhanced public trust in the UK transport system. See sections 6.4, 6.5 and 6.7.	Research questions remain around the security of QKD, which should be investigated further before large-scale deployment.

Transport is one of thirteen critical national infrastructure sectors in the UK, deemed pivotal for the functioning of the country. As the UK transport system continues to undergo digitisation, from IoT connectivity to automated data collection, the industry becomes increasingly vulnerable to adversary attacks. The attack could result in an immediate outage to services and systems, with potential for this outage lasting several hours and requiring multiple days for services to return to normal. The disruption to critical services and systems could result in economic and reputational damage, as well as present an increased threat to passenger safety of the affected operators within or connected to the UK.

Cybersecurity poses an increasingly large threat for transport systems and organisations, with the global transport sector having experienced a 186% year-on-year increase in weekly ransomware attacks since June 2020. There are many examples of cyber incidents impacting transport operators both in and outside the UK:

- **Aviation:** In August 2023, a cyber-attack to UK's air traffic control resulted in cancellation of 1,500 flights in a single day.

- **Railway:** In 2023, a Russian hacker groups succesfully compromised UK rail ticketing services. In 2021, Northern Rail shut down its new self-service ticket machines following a suspected ransomware cyber-attack.

- **Bus:** In September 2022, one of TfL's largest contractors (Go-Ahead), suffered a cyber-attack that has affected software used to schedule bus drivers and services.

- **Shipping:** A 2022 DDoS attack on the Port of London Authority saw the public trust entity, responsible for overseeing commercial operations on 95 miles of the Thames, knocked offline.

Consequently, Quantum Encryption and Post-Quantum Cryptography are increasingly becoming a priority of international Quantum strategies. QT have the potential to improve the public trust and overall security of the UK transport industry in two distinct ways;

1. National Security - a lack of innovation in QT as well as inertia to adopt PQC solutions, poses significant risks to the continuity and reliability of British transport systems. QC capabilities owned by adversary parties might be able to bypass even the most secure cybersecurity defences that are in place today / as were developed by classical computers, and in turn risk major disruption to transport networks, maintenance, or even emergency services in the UK.

Innovations in Quantum Communications and Quantum Computing are effectively a 'double edged sword' from the perspective of British transport systems:

- Risk: Most systems today rely on advanced encryption standards (AES) or transmission layer security (TLS), which are secure versus NISQ-era QC systems, however are vulnerable to fault tolerant QCs that we may encounter in the future. A real risk today is called "hack now, decrypt later", whereby data that was hacked today (in the NISQ-era) can be accessed and used in the future for malicious purposes. Innovation in resilient communication systems is crucial to ensure the continuity of digitally managed transport systems in the "post quantum" security era (with fault tolerant QC capabilities), limiting risks from the advanced infiltration QC capabilities of adversary (government) agents. See chapter 5 for details.

- Opportunity: QT can leverage the laws of quantum physics to protect data, making encrypted data potentially impossible to access for traditional (super)computers. The successful implementation of Quantum-based communication systems such as QKD and QRNG is expected to ensure a much more reliable transport system, with limited risk of cyberattacks or disruption. See chapter 5.

    - QRNG: Quantum Random Number Generators generate randomness by measuring quantum processes (by nature random and non-deterministic). There are multiple benefits to this approach over the traditional methods, including typically faster performance, higher reliability (via greater, or true randomness) and the ability to verify the origin of unpredictability, which is key in assuring encryption security.

    - We note that various quantum communication systems are still under development or their effectiveness is debated, e.g. given the persistence of security risks relating to human error in QKD systems (human interaction cannot be entirely deleted from the process) and lack of proper authentication mechanisms. QKD systems may not be immune to Man-in-the-Middle (MITM) attacks, with adversaries able to potentially compromise the QKD system's security. Similarly, PQC algorithms may not be able to protect against all future fault-tolerant QCs.

2. Public Trust - As discussed in previous sections 6.4 – QC holds the potential to meaningfully address issues around efficiency, reliability, and cost savings that could be passed on to the passenger.

The UK transport system faces delays and reliability challenges across transport modalities, which are proportionally reflected in the public trust and perception. In December 2018, the Williams Rail Review commissioned the Department for Transport's Rail Analysis team and BritainThinks to carry out research to explore perceptions of trust in the railway, specifically to examine the decline of the public's trust in railway services;

- The review found the public trust in railway services to be 'very low'; the major driver for limited trust was the public's 'strong feeling that UK's railways are unreliable'. Most of the survey's participants had extensive first-hand experience with delays and cancellations.

- The secondary factor was related to lack of pricing transparency and high overall cost. Furthermore, the negative feelings around unreliability were heightened by lack of clear communication and information around what has gone wrong, alternative travel arrangements, and compensation and/or refunds.

- Commuter concerns are particularly acute in larger cities (and public trust varies regionally, with less developed and relatively underinvested areas more affected) – carrying additional implications around transport equality and regional disparities in the UK.

6.10 Lifestyle

Examples	Caveats
Quantum Computing: QC-enabled optimisation benefits have the potential to make transport modalities more efficient, environmentally friendly, safe and reliable – impacting both mental and physical health. This is especially relevant for public transport systems, and vulnerable population groups (e.g. elderly and low-income households). **Quantum Sensing:** improved reliability and accuracy through navigation systems independent of GNSS.	Impacts are primarily indirect, and therefore hard to quantify, nor are they a key objective at early stage of QT development.

QT can contribute to more efficient, safe and reliable transport systems in the future (please refer to Sections 6.4, 6.5, 6.7 and 6.8 for further detail) – which should improve the end-user transport experience, and have significant “quality of life” benefits. The National Centre for Social Research (NatCen) identified that transport systems affect the wellbeing of its passengers mainly through (i) physical health, and (ii) mental health. Their study highlighted three primary mechanisms that link transport with health and wellbeing:

- **Transport and access:** Transport plays a key role in improving access to health services, particularly for vulnerable groups like older people.
- **Mode of transport:** Mode of transport affects physical and mental health, via mechanisms including physical activity and commuting time.
- **Wider effects of transport and infrastructure:** Transport can facilitate social interactions and promote social inclusion.

QT also have the potential to support and accelerate development of new transport modalities such as autonomous vehicles or drones which could transform the travel practices of UK passengers (please refer to Sections 6.2 and 6.3 for further detail). All of these potential applications can positively contribute to improving the public’s mental and physical health:

Physical Health

The major impact of QT on physical health of passengers in the UK relates to (i) reduced pollution (section 6.12), (ii) more efficient and reliable emergency services (sections 6.4, 6.7). There is a bi-directional relationship between physical health and transport: the mode and frequency of transport used can impact the health status of individuals. Conversely, an individual’s health can impact their mode choice and their frequency of transport use; those with mobility issues are more likely to experience negative transport impacts, as more active modes may not be suitable.

In addition, the transport industry is a major contributor to air pollution in the UK (which has widespread impact on health of the UK population) - the annual mortality of human-made air pollution in the UK is roughly equivalent to between 28,000 and 36,000 deaths every year.

Mental Health

Quality of transport provision affects stress and wellbeing as it affects the quality of the travelling experience. Public transport interventions can positively impact mental health in two ways: 1. alleviating traffic and 2. reducing commuting times. For example, buses are instrumental for vulnerable passenger groups, in particular the elderly or passengers facing mobility issues. Quantum Technologies have the potential to materially reduce time spent commuting *(please refer to Section 6.5)* and improve feeling of security and public trust across the passenger community in the UK *(please refer to Sections 6.8 and 6.9)*.

6.11 Infrastructure Design

Examples	Caveats
Quantum Computing: QC-enabled optimisation offers a multitude of potential efficiency, time and cost savings. For example, D-Wave's hybrid / annealing QC demonstrated a 10% productivity increase for a Japanese construction company, through optimal excavation route planning.	May be dependent on FTQC rather than NISQ-era QPUs.
Quantum Sensing: Quantum sensors have the potential to improve the design of transport infrastructure, detecting issues before digging / excavation works commence; with special use cases in areas prone to subsidence (earth movement). The impact could be in the hundreds of millions of pounds.	According to Citi, quantum sensors are likely the first QT to see mass commercialisation, as their advantages over conventional sensors have already been proven. However, there are many different quantum sensing technologies, each of which have a unique roadmap and a plethora of use-cases.

Over the past two decades, UK transport budgets have continued to increase, with a £96bn integrated rail plan for upgrades in the Midlands and the North, £27.4bn announced for the second Roads Investment Strategy, and £5.7bn set aside to transform local transport in eight city regions. Over 85% of public sector investment in infrastructure since 2000 has been spent on transport sectors.

The need for capital investment for ongoing modernisation efforts will consume more government funding in the future – McKinsey estimates a £100 billion funding gap until 2030, to carry out the necessary investment to strengthen UK rail and road infrastructure. Air transport infrastructure is largely privately funded. Combined with a decline in land-based travel demand and profitability, and heavy reliance on public funding, the UK government must find ways to maximise its revenues capabilities from its existing infrastructure and network to generate long-term value and reduce the funding gap.

Quantum Technologies have the potential to support the ongoing investment initiatives in several ways. To date, experimental use-cases of QT in infrastructure build-out have focused on two major areas:

Quantum Sensing applications in underground construction and maintenance

A significant proportion of the UK's transport infrastructure is buried underground, including around 4 million kilometres of pipes, electricity and telecoms cables, and sewers. Current sensing technologies have several systemic shortfalls which could be effectively addressed via Quantum Sensors. Underground construction is one such example, which has been successfully proven to benefit from gravimetry quantum sensors in early case studies.

Unknown underground conditions present the largest single risk in infrastructure projects and cause significant delays and cost overruns, potentially costing up to half a percent of the UK's GDP. Existing technologies such as GPR (Ground Penetrating Radar) rely on transmitting an electromagnetic wave through the ground, which is then reflected off a buried pipe or cable, with the reflected signal received at the ground surface. However, the ground, especially wet clay, can make it difficult to see through anything deeper than a few centimetres. It is estimated that a hole is dug every seven seconds to access these pipes and cables for repairs, upgrades and installations. This busy and usually unseen environment suffers from an estimated 60,000 accidental strikes per year, leading to injury, project delays, and disruption to traffic and local economies. The total direct and indirect costs of these accidental strikes are estimated to be £2.4 billion a year.

Quantum sensors offer many potentially breakthrough options to modernise underground development, detecting issues before the start of construction works. The UK National Quantum Technology Hub in Sensors and Timing aims to bring a range of quantum sensor devices out of the laboratory and into the real-world.

One notable area for quantum sensing is gravimetry sensors, which measure gravitational fields with superior sensitivity to existing systems, providing unique insights for construction projects. The technology allows sensors to penetrate much deeper below ground than existing remote sensing tools, and potentially speeds up gravity measurements from several minutes to just a few seconds. According to Citi, quantum gravimeters could be particularly useful for examining previously developed land (which may have hidden infrastructure beneath them), locating underground tunnels and large utilities close to the surface, or identifying early signs of erosion that might lead to sinkholes.

Quantum sensing in the area of gravimetry is currently actively explored by the Gravity Pioneer project, a collaboration between the University of Birmingham, environmental, engineering and sustainability solutions provider RSK, the Defence Science and Technology Laboratory (part of the UK Ministry of Defence) and technology company Teledyne e2v. The project managed to create a gravimetry sensor capable of finding a tunnel buried outdoors in real-world conditions, one metre below the ground surface. The breakthrough will allow future gravity surveys to be cheaper, more reliable and delivered 10 times faster, reducing the time needed for surveys from a month to a few days.

Another notable Quantum Sensing technology are Quantum Magnetometers, which could be used to monitor and maintain metallic structures either below ground or encased in concrete (e.g. maintenance of bridge joints).

Quantum Sensors may also prove useful in areas at higher risk of subsidence (sinking of the ground due to underground material movements). In the UK, this is a particularly high risk in urban areas, such as London. In 2021, the British Geological Survey (BGS) launched maps that assessed the risk of climate related subsidence to homes and properties in the next 50 years. This research found that as many as 57 per cent of properties in London will be affected by 2070. This will render the use cases for Quantum Sensors especially relevant for future infrastructure development and maintenance for areas affected by subsidence.

Quantum Computing optimisation benefits

The computational advantages offered by Quantum Computers have broad use cases in infrastructure design and construction, as well as the development of advanced materials *(as described in sections 6.4 and 6.5 - which could also be relevant to materialising efficiencies in the construction of transport infrastructure)*. Key QC-enabled optimisation areas that are explored by construction industry players include:

- **Quantum Simulation:** analysing high data volumes to support optimal design of buildings and infrastructure. In early 2020, Shimizu Corporation teamed up with Japanese QC pioneer Groovenauts to explore how their technology could optimise the excavation component of the construction process. Leveraging D-Wave's Quantum-annealing system, the team increased construction project productivity by 10% through finding optimal excavation route planning.

- **Supply Chain optimisation:** *see sections 6.4 and 6.5.*

- **Predictive Maintenance:** *see section 6.4.*

- **Energy Systems:** *see section 6.12.*

- **Trackside Digital Twins:** In addition, the computational benefits of Quantum Computing have significant use cases in simulation of digital twins. Quantum-enabled digital twins (informed by quantum sensors) of railway tracks may answer existing bottlenecks around track realignment. Due to earth movement and weather changes, railway tracks are subject to constant movements, which poses risks to railway operations and increases maintenance burdens.

6.12 Carbon Emission Reductions

Examples	Caveats
QT have significant potential to decarbonise transport models. Notable examples include; • QPUs could enable advanced EV and battery design, making EVs more scalable and affordable – reducing carbon emissions. • QC-enabled optimisation of road and air traffic – reducing aviation and in-traffic emissions. • QC-enabled research into alternative materials for the construction of transport infrastructure; e.g. finding an alternative to clinker, with cement being a material contributor to global emissions. • QC-enabled research into more efficient, scalable and affordable solar cells and green hydrogen.	QCs are likely to have significantly higher energy demands than classical computers. The additional energy requirements may be outweighed by the scale of optimisation problems that they are able to solve – although this is as of yet uncertain, and much will depend on the ability to develop and manufacture FTQCs at scale. Growing transport demand may offset achieved efficiencies, which may only be realised at scale from 2035 onwards. The QT impact on the UK's net-zero targets for 2050 is as of yet uncertain.

QT hold significant potential to address sustainability and environmental challenges, enabling the UK transport industry to accelerate its existing decarbonisation initiatives and achieve the UK's Net-Zero commitments. Some of the known use cases of QC require large-scale fault-tolerant devices, and may not be achievable at scale before fault-tolerant computing becomes a commercial reality.

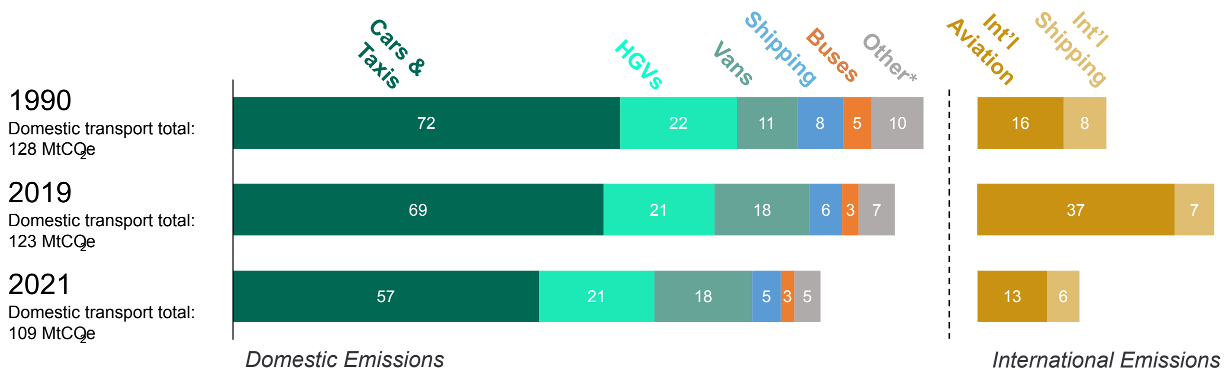
The UK has committed to net-zero carbon emissions by 2050. Transport is currently the largest emitting sector of the UK economy, responsible for >25% of total UK greenhouse gas emissions, the largest contributor to the country's national environmental footprint. Despite extensive ongoing decarbonisation initiatives, the UK 2050 Transport Vision predicts that demand for transport is projected to increase materially, posing a serious challenge to the UK's plan to reduce carbon-intensive activities by 2050. Demand can be reduced, but there is an equally important role for zero emission technology and a modal shift away from more polluting transport modes – all of which can potentially be supported by Quantum Technologies.

Transport Environmental Footprint – Status Quo

Owing to ongoing governmental initiatives and a shift to more environmentally friendly vehicle designs, the UK total transport emissions dropped by 15% overall from 1990 to 2021. Domestic transport emissions dropped by 15%, while emissions from international aviation and shipping dropped by 17%. As per the latest government carbon emission tracking data, the UK registered the following environmental footprint in 2021:

- Transport is the largest emitting sector of greenhouse gas (GHG) emissions, producing 26% of the UK's total emissions in 2021 (427 MtCO2e).
- Domestic transport was responsible for emitting 109 MtCO2e (million tonnes of carbon dioxide equivalent) in the UK.

Figure 1: Greenhouse gas emissions by transport mode, 1990, 2019, and 2021 (ENV0201)



*Comprises, in 2021: Rail, 1.6; Domestic Aviation, 0.7; Motorcycles and mopeds, 0.5; other transport, 1.7; other road transport, 0.6

QC has major potential applications across the transport and energy industries which can answer several existing bottlenecks to a net-zero transition:

Road Applications

Over half the UK's transport emissions (52%) come from passenger vehicles, and road traffic combined accounts for over 90% of national emissions (including logistics, shipping, vans, and buses).

- The UK government has highlighted a transition to Electric Vehicles (EVs) as a key opportunity to effectively decarbonise the industry, but to date uptake has been limited, with zero-emissions EVs accounting for <3% of all cars on British roads as of Q3 2023. Slow uptake has been driven by several manufacturing challenges to achieve cost-effective EV alternatives, and many leading automotive manufacturers are currently exploring QC applications to optimise vehicle and battery design, advanced materials, and more generally – accelerate scalability.

- The Logistics segment is also inefficient from an emissions perspective, with Heavy Goods vehicles used in logistics producing >5x the amount of emissions compared to passenger vehicles.
- Traffic Optimisation offers an additional lever for localised decarbonisation, with in-traffic emissions being on average 40% higher compared to driving emissions.

QT could support decarbonisation of road transport (including passenger automotive and logistics) through the following levers:

1. Transition to EVs

EVs offer one method of reducing emissions. In May 2019, the Committee for Climate Change (CCC) suggested that all new vehicles should be electrically propelled by 2035, if not sooner, to achieve the net zero target.

The market for EVs is immature yet growing. Most cars on the road in the UK are fuelled by petrol and diesel. At the end of September 2022, 2.5% of all licensed road vehicles in the UK were plug-in vehicles.

The shift to EVs will require more batteries to be manufactured. However, batteries currently represent the costlier and most challenging part of an EV to manufacture in terms of supply chain & process. According to a 2020 study by Oliver Wyman for the Financial Times, batteries alone make up almost 40% of the total production cost of a battery electric vehicle (BEV), which means their costs are higher: it still costs about 45% more to produce a BEV than an equivalent combustion-driven car.

Improving battery chemistry may result in optimal energy density and increase the amount of power a fully charged battery can hold. This would allow for increased range and greater flexibility as to where batteries are placed within the vehicle. QCs (in contrast to classical computers) have proven the potential to simulate the chemistry of batteries in ways that cannot currently be achieved. QCs would enable the production of higher density, longer lasting and critically cheaper batteries at commercial scale. Researchers have not found a way to simulate large complex molecules using conventional computers, as the problem grows exponentially with the size or complexity of the molecules being simulated. (e.g. if simulating a molecule with 10 atoms takes a minute, a molecule with 11 takes two minutes, one with 12 atoms takes four minutes and so on). This exponential scaling quickly renders a traditional computer useless: simulating a molecule with just 70 atoms would take longer than the lifetime of the universe (13 billion years).

Car manufacturers globally including Daimler, Toyota and Hyundai are turning to QC as an accelerator for battery research. In 2022, IonQ partnered with Hyundai on their initiative to develop new variational quantum eigensolver (VQE) algorithms to study lithium compounds and their chemical reactions involved in battery chemistry, a key element of Hyundai's Strategy 2025 vision to transition their organisation into a smart mobility solution provider, including the sale of 560,000 EVs per year and a lineup of twelve or more battery electric vehicle models by the middle of the decade.

In the UK, a battery electric car is estimated to have greenhouse gas emissions which are 66 per cent lower than a petrol car and 60 per cent lower than a diesel, when recharged using electricity from the national grid. When 50% of passenger cars will be EVs, QC contribution to battery chemistry could help reduce car emissions by up to 30%, or ~30 MtCO2e (million tonnes of carbon dioxide equivalent), as car transport is responsible for emitting 101 MtCO2e in the UK (2021).

2. Traffic Optimisation

The average UK driver spends 61 hours per year in traffic congestion (approx. 10% of total hours spent in a car). It is estimated that vehicles in traffic jams can emit up to 40% more pollutants compared to when they are moving smoothly, which would bring total vehicle pollution related to traffic jams to ~13% of total car-related emissions. In 2021, cars and road vehicles produced 101 MtCO2e - traffic emissions thus account for ~15MtCO2e.

QC can improve traffic by offering more efficient route planning and optimisation techniques (e.g. analysing datapoints such as traffic flows, weather patterns, and road conditions to generate near-optimal routes for vehicles). A study conducted by Toyota Tsusho Mobility Informatics employing D-Wave's quantum hybrid solver, allowed to greatly improve routing for a relatively small fleet of 18 vehicles. With a "quantum assist", those vehicles were able to hit the same number of stops while cutting both their mileage and driving time by nearly 10%. Please refer to section 6.5 for more details.

Beyond road applications, improved efficiency of railway achieved via QC algorithms may promote increased usage of environmentally friendly modes such as rail. As part of the Quantum Catalyst Fund, DfT and Network Rail have awarded a QT company Q-CTRL a grant with the purpose of exploring optimisation potential of the UK rail network.

3. Logistics Optimisation

In 2021, cars made up 75% of the road vehicle miles travelled within the UK, but produced 57% of transport emissions, while Heavy Goods Vehicles (HGVs) made up a much smaller proportion of the vehicle miles (6%) and their emissions were disproportionately greater (21%). This is mainly because smaller vehicles are more fuel efficient, and HGVs typically travel longer distances with greater loads.

Reducing emissions from the UK logistics sector is key to achieving net-zero targets, but decarbonising the segment is a complex exercise which will rely on improving the vehicles themselves, batteries, fuel, as well as streamlining operations by optimising routes and cargo load, to name a few.

- **Cargo Load optimisation:** QCs can aid in optimising cargo load management in real-time (see section 6.5).

- **Battery Innovation:** as described above, higher energy density batteries for use in heavy- goods electric vehicles could substantially bring forward their economic use.

- **Route Optimisation:** real-time data analysis via QCaaS can offer additional emissions benefits from shorter routes (with lower fuel consumption). For example, a Japanese development company, Mitsubishi Estate, performed a successful case study utilising quantum annealing to improve truck routing for waste collection. As a result, CO2 emissions were reduced by approximately 57%, and the number of vehicles reduced by approximately 59%.

Energy Applications

A transition to green energy sources is key to achieving the UK's net-zero goals, and QC has the potential to solve several structural challenges in green fuel development as well as more efficient grid operations, which will be necessary as a backbone of the net-zero economy in 2050. To date, experimental cases leveraging QC-annealing systems have shown benefits in energy grid management, as well as promising early momentum in solving the most pressing development challenges faced in solar energy and green hydrogen production:

1. UK Grid

Enabling the transition to EVs across both passenger transport and logistics will require significant infrastructure changes to the UK grid. According to the National Grid, it is expected that electricity demand would increase by 10% if the entire country switched to EVs overnight and started charging. They believe that a subpar public charging network will inhibit the uptake of EVs due to range anxiety. ~52% of drivers worry about driving any distance in an EV, and so National Grid is working on a network of 50 ultra-fast chargers at motorway services.

Dynamic Price Incentivisation is a strategy that enables consumers to actively participate in managing electricity demand, where the impact of QT is already being explored by academia. It aims to alleviate strain on the grid during high demand and promote a more balanced and efficient use of electricity resources. As the algorithms leverage large volumes of real-time data volumes, which classical computing is unable to effectively process, QPUs could enhance DSR (Demand Side Response) mechanisms across the grid. For example, researchers at LMU University in Munich have successfully achieved superior results to incumbent classical computing systems in incentivising optimised customer energy usage behaviour via dynamic pricing, leveraging a hybrid quantum computing approach using D-Wave's Leap Hybrid Cloud (though the scale of the improvement has not been published).

2. Fuel Innovation

Developing new, "green" sources of energy and optimising manufacturing at scale using Quantum Computers is key to achieving UK's national decarbonisation targets, in the transport sector and more broadly. Two of the leading 'technologies of tomorrow' offer significant advantages to increasing share of green energy in the UK:

- **Solar cells:** Innovation in solar cells could have wide-reaching implications for the transport industry by augmenting vehicle power needs (e.g. solar panels on buses and trains could help power vehicles), extending battery life (e.g. power auxiliary systems like AC and navigation), and reducing reliance on fossil fuels (e.g. generate electricity while protecting vehicles from weather). Today's solar cells rely on crystalline silicon and have an efficiency in the order of 20%. Solar cells based on perovskite crystal structures, which have a theoretical efficiency of up to 40%, could be a better alternative – but they haven't been produced at scale due to chemical stability challenges. In their current state, photovoltaics cannot generate the sufficient amount of energy needed to fully power electric vehicles, however further development may enable private and public transport vehicles that are fully solar-panelled.

- **Green Hydrogen:** Green hydrogen could make the transportation industry greener by decarbonising shipping, aviation, and trucking. It is widely considered to be a viable replacement for fossil fuels in many parts of the economy, but due to limitations in manufacturing and storage, it is currently too expensive to be a viable alternative - before the 2022 gas price spikes, green hydrogen was about 60% more expensive than natural gas. It can also enable more efficient energy storage, as compressed hydrogen tanks can store energy for long periods of time and weigh less than lithium-ion batteries.

The computational advantages offered by QC can act as a significant aid in fuel innovation, accelerating decarbonisation in (and beyond) the UK transport industry:

- **Solar Cells:** QC could aid scaling challenges by enabling precise simulation of chemical structures, thereby identifying higher efficiency, higher durability, and nontoxic solutions. If theoretical efficiency increases can be reached, the cost of solar cells could be decreased by as much as 60%. In 2023, Oak Ridge National laboratory explored QC applications in developing more efficient solar cell panels, leveraging the Quantinuum H1-1 quantum computer for molecular simulation, although results have not been publicly quantified.

- **Green Hydrogen:** QC could help model the energy state of pulse electrolysis to optimise catalyst usage, which would increase efficiency. QC could also model the chemical composition of catalysts and membranes to ensure the most efficient interactions, increasing efficiency and reducing cost of hydrogen by up to 35%. In 2023, Multiverse Computing used a digital twin and quantum optimisation to boost the efficiency of green hydrogen production – boosting production efficiency by 5%.

3. Advanced Materials

Construction activity accounts for ~50m tonnes of CO_2 emissions, over half of which is linked to construction product and materials production. Materials such as steel and cement account for around 15% of global carbon emissions. The construction sector generates ~60% of waste produced in the UK. Reducing and ultimately eliminating these emissions, through minimising materials requirements, particularly those of carbon-intensive materials, maximising the energy and heat efficiency of built assets and improving levels of reuse and recycling is critical to the delivery of the 2050 target.

QC can aid in discovery and accelerate manufacturing of more environmentally friendly materials. Several industry players such as Mitsubishi Heavy Industries are currently exploring QC applications in finding an alternative to clinker as a key step in cement's decarbonisation journey (the International Energy Agency states the main ingredient in cement, known as clinker, is the main reason why the industry's CO2 emissions have been rising in recent years.)

Aviation Applications

Aviation is widely recognised as both one of the most carbon-intensive forms of transport and one of the most difficult to decarbonise. This means that aviation could well be the largest contributor to UK greenhouse gas emissions by 2050, particularly if demand continues to grow. Quantum Computing as well as Quantum Sensors are currently explored by industry leaders, with several potential use cases identified.

In July 2021, the UK government published its Transport Decarbonisation Plan, accompanied by its Jet Zero Strategy consultation. The Transport Decarbonisation Plan consolidates a number of pre-existing policies, which QT can support in the following ways:

- **Sustainable aviation fuels and materials:** QC can accelerate the development and deployment of sustainable aviation fuels and other materials. For example, Boeing partnered with IBM to leverage QC systems in material development and study corrosion, a multibillion-dollar problem for the aerospace industry. The team developed two techniques to simulate a key step in the corrosion process known as water reduction.

- **Improve efficiency:** QC can expedite complex simulations and calculations for aircraft design, leading to faster development of aerodynamic profiles, structural optimisations, flight mechanics simulations, and fuel optimisation.

- **Enhanced navigation:** QT, such as quantum sensing for precise navigation, can enhance aircraft accuracy in positioning, contributing to safer flights and optimised air traffic management.

6.13 Job Creation

Examples	Caveats
A wide range of new jobs could be created, e.g. quantum software engineers, algorithm developers and network administrators.	The extent of job opportunity creation, will largely depend on the extent and pace to which QT-related R&D will be progressed to production on a commercial scale.

New Job Creation

Skilled job creation related to new openings for quantum technology experts (software engineers, developers, network administrators, etc.). Quantum-enabled transport systems will drive the requirement for new jobs and professions. In addition, major infrastructure construction projects, e.g. for QKD and Quantum Sensor networks, will create new job opportunities for both skilled and unskilled workers.

According to McKinsey, there is only one qualified quantum candidate for every three quantum job openings, indicating a significant talent gap in the field. By 2025, it is estimated that less than 50% of quantum jobs will be filled, highlighting the urgent need for skilled workers in this area. In alignment with this shortage, the UK government is making significant investments in quantum technology education to develop a skilled workforce and drive innovation in this cutting-edge field and prepare the UK workforce for technological talent requirements in the future - e.g. via Quantum hubs, doctoral training centres and fellowships, or other R&D initiatives across British academia.

New skilled and unskilled positions creation in relation to infrastructure build-out (e.g. related to roll-out of Quantum Sensor networks for railway infrastructure).

Additional QT Impact on AI / Robotics Development

According to the UK Department for Education, 10-30% of jobs in the UK could be automated with AI (including transport value chains).

Deloitte estimates that robotics and automation can additionally impact up to 11 million jobs in the UK. QC is expected to play a significant role in enabling and scaling AI / ML algorithms as well as robotics, due to its computational capacity that is well-suited for processing high data volumes (several industry players are currently exploring the synergies between AI and QT – for example, Zapata is developing AI algorithms on quantum-annealing systems for the logistics industry).

7.0 Appendix

Types of Quantum Computers

Quantum computing hardware is still under development, so there is no clear standard for building a quantum computer. So far, qubits can be created through various physical systems with advantages, challenges, and physical mechanisms for representing different states and their superposition. Table below shows some of the most common qubit modalities, their main strengths, and weaknesses following the study conducted by Ezratty on "Understanding Quantum Technologies."

Modality	Strengths	Weaknesses
Neutral Atoms	• Ability to trap and control large arrays of atoms • Good coherence times	• Requires precise laser control • Individual atom addressing is challenging
Photonic	• No extreme conditions needed (like cryogenic temperatures) • Very suitable for quantum communications • Longer coherence times	• Error correction is hard • Single-photon generation is difficult
Semiconductor	• Potentially compatible with existing semiconductor manufacturing technologies • Potentially easy to scale	• Widely variable coherence times • Low temperature and sophisticated techniques required
Superconducting	• Relatively straightforward to scale using existing semiconductor fabrication techniques • Fast gate operations	• Short coherence times • Requires cryogenic temperatures
Topological	• Theoretically, they are highly resistant to local noise and decoherence	• Still largely theoretical • Particular materials and conditions to create and maintain the topological states
Trapped Ions	• Long coherence times • High gate fidelity	• Hard to scale • Low operational speed

Table 11: Strengths and weaknesses of qubit modalities

Types of quantum sensors

Table below presents a non-exhaustive list of the most common types of quantum sensors:

Category	Sensor Type	Main Characteristics	Strengths	Weaknesses
General Sensing	Atomic Interferometers	• Excel in measuring tiny variations in gravitational. fields or accelerations • Use examples: geophysics and navigation.	• Highly sensitive. • High precision for time and space-related quantities.	• Vulnerable to environmental disturbances (noise).
General Sensing	Nitrogen-Vacancy (NV) Centre Sensors	• Utilise defects in diamonds to sense magnetic fields and temperature. • Use examples: nanoscale thermometry and magnetic field mapping.	• Operates at room temperature. • Robust.	• Limited resolution and sensitivity for weak fields.
General Sensing	Quantum Accelerometers	• Measure acceleration with precision. • Use examples: submarines, spacecraft, undergrounds.	• Operate without GPS. • Ideal for inertial navigation.	• Environmental sensitivity. • Requires advanced technology for operation.
General Sensing	Quantum Gravimeters	• Measure minute variations in gravitational force. • Use examples: mineral exploration and geological activity monitoring	• Highly sensitive to gravitational changes.	• Sensitive to environmental noise. • Complex operation.
General Sensing	Quantum Magnetometers	• Unparalleled sensitivity to magnetic fields. • Use examples: archaeological surveys and space exploration.	• Highly sensitive to magnetic field measurement. • Versatile applications.	• High cost. • Need for precise calibration to achieve optimal performance.
Quantum Imaging	Photonic Quantum Sensors	• Utilise light properties for secure communications and measurements. • Use examples: precision metrology.	• High sensitivity. • High precision for optical properties and light fields.	• Challenges in deployment and integration.
Quantum Imaging	Quantum LiDAR	• Uses entangled photons for ranging and imaging. • Use examples: potentially enhance autonomous vehicles obstacle detection.	• High resolution. • Works in challenging conditions (e.g., through foliage).	• Currently experimental- • High complexity,
Quantum Imaging	Quantum Radar	• Employs quantum entanglement for detection. • Use examples: improved navigational aid in complex environments.	• Potential stealth detection. • Reduced signal interception.	• Technical challenges. • Still largely theoretical.
Timing	Atomic Clocks	• Use atomic oscillations for ensuring precise time keeping. • Use examples: GPS satellites for precise timing and accurate location.	• Extremely accurate and stable	• Complex and expensive to build and maintain

Table 12: Types of quantum sensors (Multiple sources: 1, 2, 3)

Types of Quantum Communications systems

Table below presents a non-exhaustive list of the most common technologies, protocols, methods, and algorithms related to quantum communications.

	Name	Detail	Strengths	Weaknesses
Hardware	**Quantum Repeaters**	Devices that extend the range of quantum communication by enabling entanglement distribution over long distances.	Overcome decoherence and signal loss, crucial for establishing long-distance quantum networks.	Technologically complex and resource-intensive; still in experimental stages.
	Photon Detectors	Devices capable of detecting single photons, essential for quantum communication and computing.	High sensitivity allows for detection of quantum states, enabling quantum cryptography.	Limited by noise and efficiency; challenges in detecting without disturbing quantum states.
	Quantum transmitters & receivers	Devices for generating and receiving quantum bits (qubits) in quantum communication systems.	Enable the transmission of quantum information over distances.	Sensitive to environmental factors; maintaining fidelity of quantum states is challenging.
	Quantum Dots & Trapped Ions	Systems used for storing and manipulating qubits, with quantum dots using semiconductor particles and trapped ions using charged atoms.	High level of control over quantum states; potential for scalable quantum computing and communication.	Quantum dots face issues with coherence time; trapped ions require complex setups.
Protocols	**Quantum Key Distribution (QKD)**	Cryptographic protocol using quantum mechanics to securely distribute encryption keys.	Provides theoretical security based on the laws of quantum physics.	Requires direct line of sight or fibre connection; distance limitations.
	Quantum Secure Direct Communica-tion (QSDC)	Enables direct transmission of information in a secure manner without the need for a pre-shared key.	Direct and potentially more secure than QKD in specific scenarios.	Still largely theoretical and faces similar practical challenges as QKD, including distance limitations.
	Entanglement Based Protocols	Use quantum entanglement for tasks like secure communication and teleportation.	Allow for secure communication and state transfer with no risk of interception.	Generating and maintaining entanglement over long distances is difficult.
Methods		Method using a QRNG device to generate truly random numbers based on quantum phenomena.	Offers a higher level of randomness and security for cryptographic applications.	Implementation cost and complexity; ensuring the randomness is truly quantum and not influenced by classical factors.

Table 13: A non-exhaustive list of the most common technologies, protocols, methods, and algorithms related to quantum communications.