The economic impact on the UK of a disruption to GNSS

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LE London Economics

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Table of Contents

Executive Summary

Introduction

Daily life in the UK is underpinned by signals from satellites orbiting in space. People and businesses across the entire economy rely on infrastructure called Global Navigation Satellite Systems (GNSS), often called ‘satellite navigation’, to determine their position, velocity, and time. Many critical sectors depend on GNSS, in many cases without their explicit knowledge. This reliance has developed over decades, based on assumed availability and continuity of GNSS signals.

This reliance comes with its own drawbacks as it slides towards *over*-reliance. Given the substantial use of GNSS in the UK, and the vulnerability of the systems to failure, it is important to understand the impact on the UK to a disruption of GNSS functionality.

This question was first explored by London Economics in a June 2017 report, “*The economic impact to the UK of a disruption of GNSS”,* commissioned by InnovateUK with the UK Space Agency (UKSA) and the Royal Institute of Navigation (RIN). This new report was written in 2021 and improves the accuracy and scale of GNSS benefits and estimated losses for seven priority sectors: Agriculture, Aviation, Emergency Services, Finance, Maritime, Rail, and Road, as well as providing a more general update of all other sectors covered in the previous study.

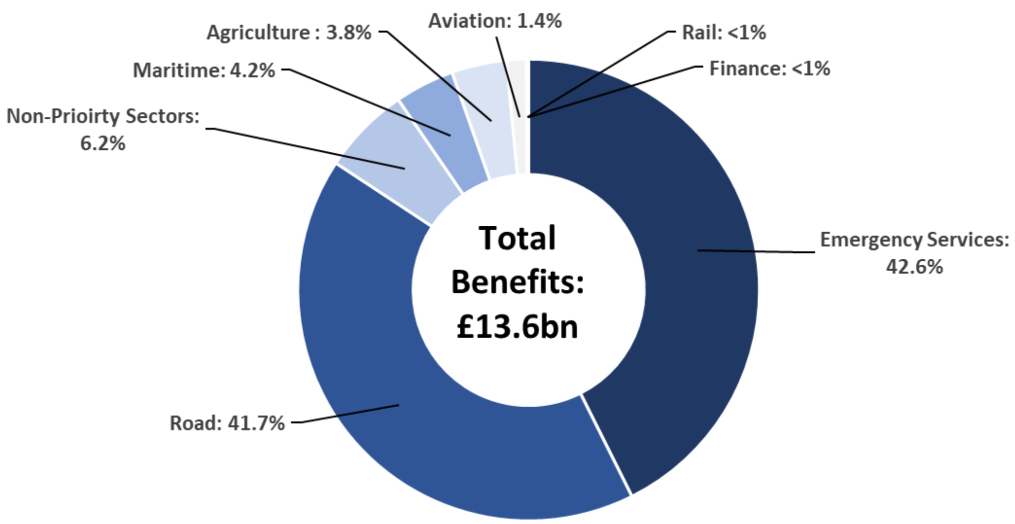
Note that this report was prepared in 2021 to inform policy around PNT resilience. It is now being published in 2023 alongside initial conclusions of a cross government team examining PNT resilience.

Key findings

GNSS: use, benefits, and losses

The economic benefits to the UK from the use of GNSS have been monetised at **£13,622m per annum**. Benefits are estimated against a counterfactual scenario in which GNSS had not been developed or chosen as the primary source of PNT in the applications covered by this study.

Figure 1 Share of economic benefits from GNSS, by sector



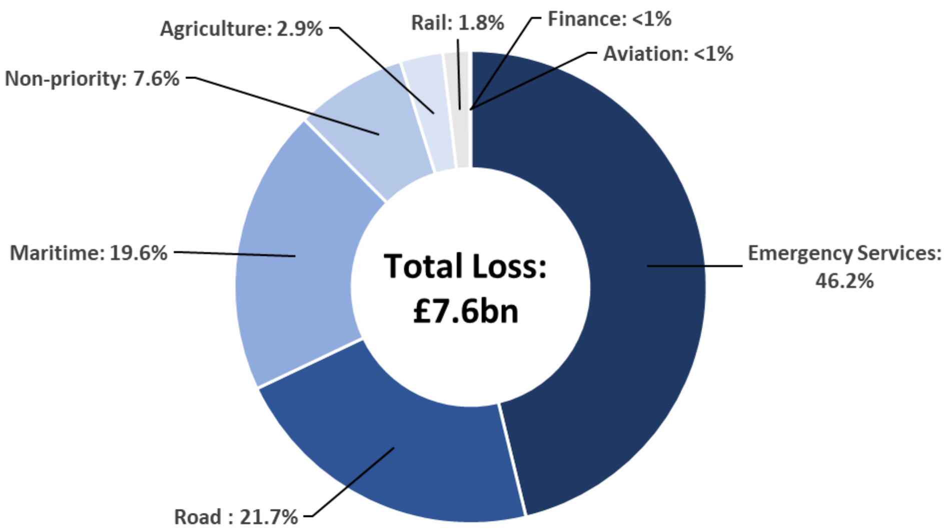
Source: London Economics

Most of the economic benefits are estimated to come from Emergency Services (43%) and Road (42%) (Figure 1). The Emergency Services sector benefits from efficiency gains due to improved navigation and general resource management, which translate into cost savings and improved health outcomes for UK citizens. The road sector benefits from efficiency gains due to GNSS in the form of time and fuel savings, and the associated environmental benefits.

Overall, compared to the 2017 iteration of this report, the total economic benefits have increased by 102%, more than doubling in magnitude. A majority of this change is due to increases in the Emergency Services and Road sectors. In each sector an increase in device penetration (smartphones, satnavs, and insurance telematics devices) explain much of the growth.

The economic loss due to a GNSS outage for 7-days has been estimated at **£7,644m**. Applications in emergency services, maritime, and road together account for 87.6% of the total economic loss.

Figure 2 Share of 7-day economic loss, by sector



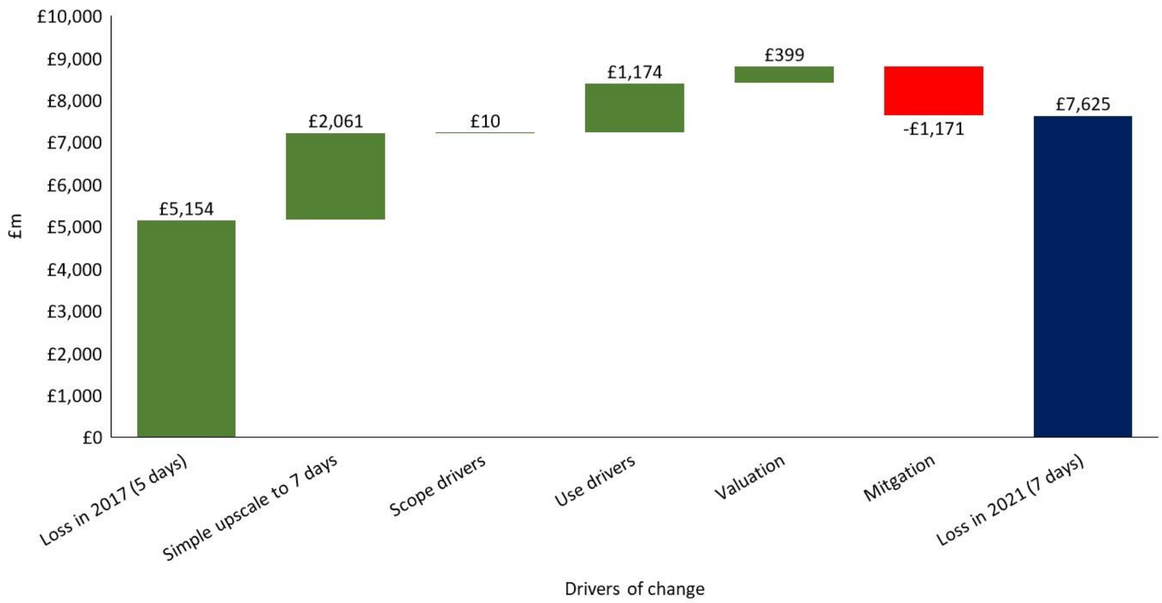
Source: London Economics

A decomposition of the drivers of the difference between the total loss figure of £7,6445m and the £5,153.5m reported in the June 2017 iteration of this report is presented in Figure 3 on the next page.

Applying a simple upscale of 40% (i.e. to reflect the two day increase in the RWCS) allows for some naïve comparison between the 2017 and 2021 loss estimates and increases the economic loss by £2,061.4m. Note that economic losses are considered against a baseline where GNSS is fully functional; mitigating efforts through 'traditional' means (e.g. by using paper maps) will be considered but may be limited owing to the immediacy and brevity of the disruption. These losses may diverge from monetised benefits of an application as they are measured against a different baseline to the marginal improvement considered when monetising benefits.

New applications identified and monetised in this report (scope drivers) increase the economic loss by £10.0m. The change in GNSS penetration and volume of users (use drivers) further increases the economic loss by £1,173.9m. The parameters which are used to monetise impacts have also increased (valuation), increasing the economic loss by £398.6m. Improvement in holdover and resilience since 2017 (mitigation) reduces the economic impact of GNSS loss, decreasing the economic loss by £1,171.1m. All these drivers of change combined bring the figure of £5,153.5m in the 2017 report to the figure of £7,625.3m in the 2021 report.

Figure 3 Drivers behind difference between 2017 and 2021 loss estimates



Note: 'Simple upscale' = a change in the RWCS i.e. 5-days to 7-days, or 40% increase. 'Scope drivers' = new applications identified and applications that were not modelled in the 2017 report but are in the 2021 report. 'Use drivers' = change in GNSS penetration and change in volume of users. 'Valuation' = a change in the parameters used to assess economic impact. 'Mitigation' = change in holdover and resilience.

Source: London Economics

A separate analysis of the impact of a similar UK-wide, instantaneous outage that instead only lasts for 24 hours finds an estimated loss of **£1,424m**. Most of these losses are found in Emergency Services and Road transportation, each of which face severe reductions in efficiency, often with dire consequences.

In the case where holdover capacity exists, users would not notice the outage. We therefore expect either no effect over 24 hours, for those applications with sufficient holdover, or a similar but more short-term outcome as with the 7-day outages considered previously.

Details of the key findings for each sector are provided below.

Agriculture

GNSS plays a key role in modern agricultural practices in the UK, principally through applications related to cultivation, including precision farming and variable rate application (VRA). GNSS is a key driver of increasing yields on UK farms and reductions in the cost of inputs and associated environmental impact.

GNSS users in agriculture generally rely on more sophisticated equipment than many other user groups. GNSS devices for agriculture are more expensive than for other sectors, and track more signals and constellations as standard. Many include EGNOS Open Service and commercial augmentation services such as Real Time Kinematic (RTK) or Precise Point Positioning (PPP) for improved accuracy. The economic losses from a 7-day outage of GNSS in agriculture is due to less efficient cultivation practices, including increases in pass-to-pass overlap and the cost of inputs (seed, pesticide, fuel, fertilizer, etc.). This results in lower yields, which also translate into reduced GVA for the UK food processing industries which rely on agricultural inputs.

Table 1 Agriculture Applications

Application	Economic benefit (annual, £m)	Economic loss (7-day, £m)
Cultivation	524.4 (*+84.4%*)	223.6 (*+43.5%*)
Total	**524.4 (*+84.4%*)**	**223.6 (*+43.5%*)**

Note: *(+%) indicates the variation in economic benefits and loss since the 2017 iteration of this report.*
Source: London Economics analysis

Aviation

GNSS is increasingly being utilised within the aviation sector to optimise routing of flights, but also to improve the efficiency of the agricultural sector. Live and efficient monitoring of crops using drones benefits farmers who can respond in real time to crop and soil needs. Furthermore, in aircraft surveillance, GNSS-dependent systems optimise the distance between aircraft in flight corridors, improving efficiency of the high volumes of air traffic passing through UK airspace and beyond. Manned aircraft have a number of backup technologies that provide robust redundancies in the case of GNSS outages, explaining why a 7-day GNSS outage is associated with negligible levels of economic loss in this application, although some productivity losses are felt across the sector.

Table 2 Aviation applications

Application	Economic benefit (annual, £m)	Economic loss (7-day, £m)
Navigation	5.0 (*+266%*)	0.1 (*+900%*)
Surveillance (communications)	21.2	0.4
Safety	3.1 (*+55%*)	0.5 (*+56%*)
Environmental	0.3	Not assessed
Productivity	158.5	3.0
Total	**187.9 (*+5,509%*)**	**4.0 (*+1,190%*)**

Note: *(+%) indicates the variation in economic benefits and loss since the 2017 iteration of this report.*
Source: London Economics analysis

Emergency Services

Emergency Services utilise GNSS at multiple stages of their operations. Emergency phone calls are located, on-the-ground resources are tracked, and responders are directed using GNSS as a crucial input. A disruption of GNSS service would mean these emergency services, including the Police, Ambulance, Fire Brigade and Coast Guard, would not be able to properly handle demand, emergency-related calls would be longer, congestion would be severe, and navigation systems for service fleets would not function. The cost of this loss of efficiency is measured in the extra staff required to cover the deficit, and in increased response times. Emergency Services' internal communication methods are also supported by GNSS time synchronisation functionality. Finally, there is a growing market for security and surveillance robotics, which are highly dependent on precise location information.

Table 3 Emergency Services Applications

Application	Economic benefit (annual, £m)	Economic loss (7-day, £m)
Public-safety Answer Point (PSAP) caller location	5,433.0 *(+183%)*	1,560.2m (*+207%*)
Automatic vehicle and personnel location	110.4 *(+14%)*	1,968.7 (*+92%*)
Medical delivery and critical supplies	256.0	4.9
Security and surveillance robots	5.7	0.1
Total	**5,805.1 (*+187%*)**	**3,533.9 (*+131%*)**

Note: *(+%) indicates the variation in economic benefits and loss since the 2017 iteration of this report.*
Source: London Economics analysis

Finance

The financial sector requires timestamping of transactions to ensure the prevailing price at the time of the transaction is charged. This is true of both stock exchanges and financial trading centres in banks. The European MiFID II regulation[1] defines accuracies of timing with respect to UTC that are required for an entity to be allowed to continue operating. The equipment used by high-frequency traders has sophisticated oscillators for holdover, ensuring that trade can continue long after an external timing source is lost. Similar equipment is present in stock exchanges, meaning there would be no economic loss experienced during a 7-day GNSS outage.

Table 4 Finance applications

Application	Economic benefit (annual, £m)	Economic loss (7-day, £m)
Infrastructure (atomic clocks)	0.3 (*+200%)*	-
Infrastructure (conditioning)	1.4 (*+180%)*	-
Total	**1.7 (*+183%)***	**-**

Note: *(+%) indicates the variation in economic benefits and loss since the 2017 iteration of this report.*
Source: London Economics analysis

Rail

A wide array of core functions in the UK rail network rely on knowledge of train position to manage operations safely and efficiently. GNSS is widely utilised to support positioning, navigation, and timing-dependent applications that create increased safety for passengers and workers, financial and environmental efficiencies for operators, and heightened security for commercial users. A loss of GNSS results in efficiency losses and delays to trains as automatic door systems and other systems fail, resulting in lost leisure and business time for passengers.

[1] European Securities and Markets Authority. (2018). 'MIFID II'. Available at: https://www.esma.europa.eu/policy-rules/mifid-ii-and-mifir [accessed July 2021].

Table 5 Rail applications

Application	Economic benefit (annual, £m)	Economic loss (7-day, £m)
Driver Advisory Systems	2.9 (*-73%*)	0.1 (*-62%*)
Fleet Management	1.7 (*+1,419%*)	0.0
Cargo Monitoring	0.1	0.0
Infrastructure Monitoring	14.8	0.9
Automatic Selective Door Operation	Not assessed	38.7 (*+94%*)
Train Cancellations	Not assessed	100.1 (*+11%*)
Total	**19.5 (*+79%*)**	**139.9 (*+27%*)**

Note: Values of "0.0" represent non-zero quantities that are less than 50,000. *(+%) and **(-%)** indicate the variation in economic benefits and loss since the 2017 iteration of this report.*
Source: London Economics analysis

Maritime

The maritime sector is one of the most GNSS-dependent sectors of the UK economy. Position, Navigation, and Timing (PNT) data are used at all stages of maritime journeys for navigation and safety purposes, from oceanic and coastal navigation to manoeuvres in ports. On the shore, GNSS is used to manage cargo (handling and customs operations) and keep track of vessels.

GNSS is the principal source of PNT for ships and most vessels include several GNSS-integrated systems. These include Automatic Identification Systems (AIS) used to locate ships at sea, radar, and gyrocompasses. Ports and logistics operations heavily rely on GNSS that enables the efficiencies that allow UK retailers and manufacturers to operate with limited warehousing facilities using 'just-in-time' and saving costs. The losses associated with a 7-day outage of GNSS in the maritime sector are quite large as automatic cranes shutdown with no alternative or mitigation. This slows down the loading and unloading of containers, leading to delays, lost trade, and disruption to supply-chains that rely on maritime-enabled logistics.

Table 6 Maritime applications

Application	Economic benefit (annual, £m)	Economic loss (7-day, £m)
Shipping industry	450.9 (*+30%)*	182.8 (*+272%*)
Port operations	*Not monetised*	1,309.2 (*+29%*)
Fishing industry	98.7 (*+27%*)	7.9 (*+104%*)
Preventing fatalities – SAR	18.1 (*+104%*)	0.3 (*+186%*)
Total	**567.8 (*+31%*)**	**1,500.2 (*+41%*)**

Note: *(+%) indicates the variation in economic benefits and loss since the 2017 iteration of this report.*
Source: London Economics analysis

Road

GNSS is used on roads extensively for its positioning and navigation information. Drivers use GNSS for turn-by-turn navigation. Logistics and fleet management companies use it to keep track of the location and use of their vehicles. Insurance companies use it to obtain information on their clients' driving behaviour that would be otherwise difficult. Emergency and breakdown call use it to locate incidents and send help quickly. The reliance on GNSS means a 7-day outage would reduce navigation efficiencies for motorists and fleet operators, slowing traffic and increasing journey times. This effect would be felt by all motorists, whether reliant on GNSS or not.

Table 7 Road applications

Application	Economic benefit (annual, £m)	Economic loss (7-day, £m)
Road navigation	3,956.4 (*+26.1%*)	1,599.4 (*-15.6%*)[2]
Logistics and fleet management	375.5 (*+143.5%*)	60.2 (*+148.8%*)
Insurance telematics	1323.8 (*+8122.4%*)	Not estimated
Emergency and breakdown call	18.6 (*+24.0%*)	0.4
Total	**5,674.3 (*+70.8%*)**	**1,659.9 (*-13.6%*)**

Note: *(+%) and (-%) indicate the variation in economic benefits and loss since the 2017 iteration of this report.*
Source: London Economics analysis

Other sectors

This report primarily focuses on seven priority sectors of the UK economy. There are ten remaining sectors for which economic loss was estimated as a result of a five-day outage of GNSS in the 2017 iteration of this report[3]. Sectors that were deemed to be resilient to a five-day outage, and which were not prioritised for this report, are assumed to be resilient to a seven-day outage and are therefore not analysed in detail.[4]

Table 8 Other sectors

Sector	Economic benefit (annual, £m)	Economic loss (7-day, £m)
Offender Tracking	31.5 (*+2.3%*)	0.6 (*+50.0%*)
Satellite Communications	32.4 (*+2.2%*)	32.2 (*+42.5%*)
Surveying	27.5 (*+97.8%*)	526.5 (*+52.7%*)
Location-Based Services (LBS)	209.8 (*+2.4%*)	1.6 (*+100.0%*)
Energy	4.5 (*+2.3%*)	Not monetised
Fixed line communications	32.8 (*+2.5%*)	-
Cellular telecommunications	5.1 (*+2.0%*)	-
TETRA	4.6 (*+2.3%*)	Unknown
Meteorology	102.0 (*+2.0%*)	2.1 (*+40.0%*)
Health	291.3 (*+17.6%*)	1.0 (*+42.9%*)
Total	**741.5 (*+24.7%)***	**583.0 (*+50.3%)***

Note: *(+%) indicates the variation in economic benefits and loss since the 2017 iteration of this report.*
Source: London Economics analysis

Less-than Worst Case Scenarios

The GNSS Loss estimates that are the focus of this study assume a Reasonable Worst-Case Scenario (RWCS) of 7 days of GNSS outage. Such a scenario is justified by National Security Risk Assessment methods. In reality, more plausible sources of disruptions are likely to be more limited in both scope and duration than this RWCS. This motivates consideration of the economic losses associated with a more likely 'Less than Worst-Case Scenario (LWCS).

[2] Since 2017, a growing number of drivers have shifted towards using smartphones for navigation. This is illustrated by navigation applications such as Apple Carplay and Android Auto. Both have had an increase in market size since 2017. Smartphones are more resilient against GNSS loss than traditional on-board navigation systems, as they can leverage more alternative sources for positioning, for example, using WI-FI hotspots and cell towers. Therefore, there were more navigation devices with stronger holdover and resilience in 2019 than 2017.
[3] London Economics. (2017). 'The economic impact on the UK of a disruption to GNSS'.
[4] In the event that developments in these sectors have rendered them less resilient to a loss of GNSS than was the case in 2017, the results in this report may be viewed as a lower-bound estimate of the economic impact of loss.

To illustrate more likely scenarios of disruption, two case studies of less than worst case scenario events were proposed by LE and agreed by UKSA. These were chosen to demonstrate the potential high impact associated with disruption to economically important areas:

- LWCS 1: jamming event around the Port of Dover;
- LWCS 2: a spoofing event (i.e. provision of fake GNSS-like signals) around the Heathrow area, between Junction 14 and Junction 15 on the M25 (affecting the flight path into Heathrow and the widest part of the M25, so presumably the busiest).

In LWCS 1, it emerges that the port has two main points of vulnerabilities; the road and port entrances. While experienced drivers and employees with local knowledge would not be directly impacted by the jamming of their devices, tourists might respond to the blackout by reducing their speed, triggering traffic jam events. Economic loss would result due to the late arrival of lorries and reduced efficiency due to less available staff. On the seaside, delays may occur as ferries would reduce their speed, having to rely on alternative instruments and line of sight for port approach navigation. Given the intensity of road haulage and passenger traffic at Dover, any delays and cancellation would cause lorries to stack up at the port. Dover handles on average £334m worth of commodities per day and a single 24-hour outage could result in an amount up to this entire value lost to the UK economy as over 850 lorries accumulate in a queue over 10km long and almost 4,000 would-be passengers are stuck at the port until the backlog is cleared.

In LWCS 2, we find that a spoofing event between Junction 14 and Junction 15 on the M25 is highly likely to cause noticeable disruptions to motor vehicle traffic passing these junctions. Shortly afterwards flights operations would be affected. As flight crews and passengers are held up by the traffic, some flights may not take off and some passengers may miss their flights. However, inbound flights are unlikely to be affected as landing procedures at Heathrow do not use GNSS. The total economic cost from this spoofing event is estimated at £1.28m.

Mitigation technologies and strategies

Prior to the wider adoption of GNSS devices, navigation relied on the use of clocks and sextants, or radar systems to determine position at sea, and the use of paper maps on the road. Reverting to these methods could be a solution in the absence of signal but there are multiple reasons to believe this will not be as efficient. There is currently no *universally applicable* alternative to GNSS for the case of positioning and navigation, and many of the traditional means of navigation might not be readily available or useable by users as the capabilities and equipment to use these alternatives have been degraded or lost.

A range of modern options are either currently available or under development, and the development of a resilient PNT infrastructure that employs the appropriate mitigation technology could contribute to reducing the total economic loss during a 7-day outage by almost 50%.

Possible causes of loss of GNSS

Though the focus of this report’s hypothetical Reasonable Worst-Case Scenario is a GNSS outage, there are numerous real-world examples of such outages with varying causes and impacts due to existing GNSS vulnerabilities. Three main categories of threat to GNSS availability and performance exist: receiver vulnerabilities, environmental challenges, and human interaction issues.

Receiver vulnerabilities involve intentional or accidental targeting of GNSS receivers. These incidents are split into three broad categories.

- **Jamming** events entail intentional 'blinding' of receiver antenna with noise. Adaptive notch filters can be incorporated into receivers[5] to mitigate these attacks, and more sophisticated methods are being developed.[6]
- **Spoofing**, the transmission of false GNSS-like signals, attempts to convince GNSS receivers that they are in a different location. Possible countermeasures include encryption mechanisms which restrict access to the GNSS signal itself and authentication of the navigation message.
- **Meaconing** is the term given to 'replay attacks', the rebroadcasting of genuine GNSS signals. The use of multiple receivers to detect and remove the effects of meaconing has been explored.[7]

Environmental challenges include the many technical challenges that the user environment can produce for GNSS devices.

- **Space weather** describes the varying levels of electromagnetic radiation naturally emitted by the sun which impact GNSS signals' passage through the ionosphere and magnetosphere. Advance warning of a major events could inform users of heightened risk of disruption, giving time to seek alternative Position, Navigation, and Timing sources.
- **Space debris** refers to the growing population of orbital debris generated by human space activity. Efforts are underway to track, inform, and assist manoeuvres to avoid collisions.[8]
- **Geographical constraints**, or **multipath**, designate issues related to mountainous terrain or urban environments that obscure satellites from view. Some mitigation is offered by receivers that are designed to be capable of receiving signals from multiple constellations[9].
- **Near-channel radio interference** refers to the unintentional interference of other systems that use the same frequency bands as GNSS, which can degrade GNSS performance. Careful spectrum allocation and frequency management remains essential to minimise risk.

Human interaction issues are the vulnerabilities caused by direct interaction with the GNSS system by users and operators.

- **Ground station anomalies** can occur due to human error in uploads to GNSS satellites, or other improper interaction with the GNSS system. Proper training and careful design of safeguards can mitigate some of these vulnerabilities.
- **Internal inconsistencies** in the system can produce errors that render GNSS unusable. These are generally rooted in design flaws or unanticipated events. Ensuring the firmware of the receiver is up-to-date is the most important user action for mitigation.
- **Infrastructure failure** is an umbrella term that covers the various potential causes of GNSS constellations becoming unavailable for users, such as ceasing of operations due to technological upgrades or space warfare. As dependency on GNSS grows so too does this vulnerability.

[5] Kim et al. (2009). 'Adaptive Two-Stage Extended Kalman Filter for a Fault-Tolerant INS-GPS Loosely Coupled System'. *IEEE.*
[6] Borio, D. (2014). 'A Multi-State Notch Filter for GNSS Jamming Mitigation'. *IEEE.*
[7] Stenberg, N. (2019). 'GNSS spoofing mitigation using multiple receivers'. *Linköping University.*
[8] Oswald, N. (2020). 'Gold from Trash', *Space in Focus*. Available at: shorturl.at/jxEW8 [accessed July 2021].
[9] EUSPA. (2016). 'GNSS User Technology Report'.

Caveats and limitations

The research has been conducted by a team of independent professional economists with specialist knowledge of GNSS technology and markets, using best practice and best judgement. The methodology used and assumptions made are described in a transparent manner, with caveats clearly noted. Nonetheless, the reader should note following caveats and limitations of the study:

- This report portrays information based on codified publicly available information, our own knowledge of downstream GNSS applications, and information gathered through interviews with more than 20 stakeholders in a wide range of domains.
- Though this report does point to potential sources of a disruption (in order to communicate the vulnerability of GNSS, and the real risk of a disruption), the report is **agnostic to the actual source of the considered disruption**.
- The disruption to GNSS is considered as a **standalone event** – pre-existing redundancy systems are assumed to operate as planned.
- This study considers evidence of use, holdover capacity, and resilience that was available during the study period – i.e. from March 2021.
- The latest available data to calculate losses and benefits for this study is the 2020/2021 financial year. However, this study considers benefits and losses calculations based on 2019 economic data. This is because 2020/2021 are abnormal years by any standard because of the disruptions posed by Brexit implementation and the Covid-19 pandemic. It is important to note that despite best efforts, GNSS applications are dynamic and reliance changes over time. The results may therefore have short shelf-life.

1 Introduction

1.1 Understanding GNSS

When faced with an unknown destination, the average UK driver or pedestrian will use a map application on their mobile phone to direct them to their destination. This is possible because modern smartphones access navigation signals from satellites orbiting space. These satellites are part of an infrastructure called Global Navigation Satellite Systems (GNSS). GNSS, more commonly known as 'satellite navigation', is an umbrella term for an infrastructure which allow users with a compatible device (e.g. smart phone or other receiver) to determine their position, velocity and precise local and universal time by processing one or several signals received from satellites in space. With a sufficient number of satellites in view, and with the support of ground infrastructure, this method yields accurate positioning, navigation and timing (PNT) information.

Four GNSS constellations provide these signals:

- **GPS** is the original GNSS (fully operational since 1995) developed, maintained and operated by the U.S. Air Force. Except for a few prototypes, all GNSS receivers use the GPS signal, and because it was the first market entrant, the term GPS has become synonymous for GNSS in common terminology;
- **GLONASS** is Russia's GNSS, managed by the Russian Aerospace Defence Forces. Initially completed in 1995, it has operated at Full Operational Capability since 2011, thanks to restoration following an intervening period of neglect;
- **Galileo**, the European system currently under development, has provided initial services since 2016 and is expected to reach Full Operational Capability in 2020. It is unique in that it is under civilian control of the European Union;
- **BeiDou** is the Chinese GNSS, also under development, set to supersede the COMPASS regional system (operational since 2000) by providing global coverage around 2020. It is managed by the governmental China Satellite Navigation Office.

In addition to these global constellations, there are regional systems (BeiDou-1, QZSS, NAVIC) and regional Satellite-Based Augmentation Systems (SBAS), such as EGNOS (Europe), WAAS (North America), GAGAN (India) and MSAS (Japan) that provide improved accuracy and supplementary information on the reliability of the GNSS signal.[10] These augmentation systems allow GNSS to support safety critical applications such as aviation.[11]

All four GNSS and Regional Navigation Satellite System (RNSS) constellations are either in the process of modernisation or reaching full operational capability within the next decade. The increasing availability of more satellites and frequencies promise enhanced accuracy, availability, robustness and interoperability between GNSS constellations – improving the overall performance of PNT services.

1.2 Motivation for the study

GNSS capabilities have become critical to the UK. The free-to-access and global availability of the open signals have driven a growing number of applications for consumers, public sector users, and

[10] EUSPA. (2015). 'GNSS Market Report Issue 4'
[11] European Space Agency. (2013). 'What is EGNOS?'. Available at http://m.esa.int/Our_Activities/Navigation/EGNOS/What_is_EGNOS [accessed July 2021].

commercial users. In fact, many critical sectors – such as road transport, aviation, communications, emergency services, and agriculture – depend on GNSS to some extent, in many cases without their explicit knowledge. This reliance that has developed over decades, based on assumed availability and continuity of GNSS signals.

The simultaneous widespread use and vulnerability of GNSS to interference creates the potential for catastrophic impact. In the UK "*GNSS has become integral to our daily lives*"[12], and in the U.S., *"GPS has been called 'a single point of failure' for much of the U.S. economy and critical infrastructure,"*[13], highlighting the serious fallout that may result from an outage of GNSS signals. Closer to home, the week-long mass outage of all Galileo services other than Search and Rescue in July 2019[14,15] was described by Chronos Technology as being *"one of the most significant service-affecting issues for GPS timing users"*[16].

Furthermore, The Royal Academy of Engineering found that *"non-GNSS based back-ups are often absent, inadequately exercised or inadequately maintained"* and identifying *"an increasing number of applications where PNT signals from GNSS are used with little, or no, non-GNSS based back-ups available."*[17]

Thus, given the substantial use of GNSS in the UK, and the vulnerability of the systems to failure, it is important to understand the UK's exposure to a disruption of GNSS functionality.

This question was first explored by London Economics in 2017. This report detailed these use and benefits of GNSS across 13 Critical National Infrastructures (CNI) and the economic losses expected from a 5-day outage of GNSS. Given the rapidly evolving technological landscape and shifting trends in the use of GNSS-dependent systems, an updated assessment of the role of GNSS and the UK's resilience to its loss is urgently required.

This report was updated in 2021 to inform policy-making and is being published in 2023 alongside initial recommendations from a cross-government PNT team within the Department for Science, Innovation and Technology.

1.3 Research objectives

To fulfil this requirement, the UK Space Agency has commissioned London Economics to refresh the June 2017 report "*The economic impact to the UK of a disruption of GNSS*".

The objective is to improve the accuracy and scale of GNSS benefits and estimated losses for seven priority sectors: Agriculture, Aviation, Emergency Services, Finance, Maritime, Rail, and Road, as well as a more general update of all other sectors covered in the previous study.

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[12] Government Office for Science. (2018). 'Satellite-derived time and position: Blackett review'.
[13] Bartlett, S. et al. (2015). 'Innovation: Enhanced Loran'. Available at: http://gpsworld.com/innovation-enhanced-loran/ [accessed July 2021].
[14] Wired. (2019). 'Europe's Weeklong Satellite Outage Is Over'. Available at: https://www.wired.com/story/galileo-satellite-outage-gps/ [accessed July 2021].
[15] EUSPA. (2019). 'Galileo Initial Services have now been restored'. Available at: https://www.euspa.europa.eu/newsroom/news/galileo-initial-services-have-now-been-restored [accessed July 2021].
[16] Curry, C. (2016). 'The impact of the GPS UTC anomaly event of 26 January 2016 on the Global Timing Community'. *Chronos Technology.*
[17] The Royal Academy of Engineering (2011). 'Global Navigation Space Systems: Reliance and Vulnerabilities'. Available at: http://www.raeng.org.uk/gnss [accessed July 2021].

In addition, this updated study considers the benefits and economic impacts associated with disruption to GNSS over a longer 7-day period, a 'Reasonable Worst Case Scenario' (RWCS) that is longer than the 5-days assumed for the 2017 study. This new scenario was defined by the Cabinet Office PNT Working Group. This change is relevant because it extends the period over which economic benefits are estimated, and the period over which holdover and resilience need to be assessed.

A further scenario for losses over a shorter 24-hour period is also estimated.

More specifically, there are four objectives:

1) Identify changes in the seven priority economic sectors and industries supported by GNSS in the UK, including identification of new applications, changes in penetration and use of GNSS in each sector;
2) Quantify the economic benefit that GNSS technology and services bring to the UK within seven priority sectors;
3) Estimate the economic impact to the UK (government and private sector) of a disruption to GNSS functionality for two scenarios: a seven day outage and a 24 hour outage, considering changes in the quality and prevalence of holdover capacity and alternative mitigation strategies; and
4) Analyse the economic impact to the UK of a degradation to GNSS functionality of limited duration in two geographically constrained areas (two Less-than Worst Case Scenarios).

1.4 Report structure

This report presents the findings of the study, and is structured as follows:

- **Chapter 2** presents an assessment of known **vulnerabilities and mitigations** of GNSS;
- **Chapter 3** outlines the scope, definition and **analytical framework** used to frame the research, including the 'impact logic model';
- **Chapter 4** reports on the **current usage, benefits, and losses resulting from an outage of GNSS in the UK** across seven priority sectors: Agriculture, Aviation, Emergency Services, Finance, Maritime, Rail, and Road, and a further ten Critical National Infrastructure sectors;
- **Chapter 5** presents an analysis of impact of two **'Less-than Worse Case Scenario' GNSS disruption incidents**, considering the economic impact of a disruption event on a sub-national scale;
- **Chapter 6** presents an overview of **alternative mitigation technologies** that could increase robustness to GNSS outages;
- **Chapter 7** closes with a **conclusion** summarising each of the questions answered by this report, and suggests future work in this and related fields.

The annex presents additional supporting material.

1.5 Caveats and limitations

The research has been conducted by a team of independent professional economists with specialist knowledge of GNSS technology and markets, using best practice and best judgement to calculate the most robust and fair estimates of GNSS benefits and loss. The methodology used and assumptions made are described in this report in a transparent manner, with caveats noted as required. Nonetheless, the reader should bear in mind the following high-level limitations and caveats of this study throughout:

- This **report** portrays information based on codified publicly available information, our own knowledge of downstream GNSS applications, and information gathered through interviews with more than 20 stakeholders in a wide range of domains. Information gathered from stakeholder interviews is presented at face-value, trusting the contact. This may potentially add an **optimism bias** reflecting complacency and/or reticence to acknowledge a vulnerability.
- Though this report does point to potential sources of a disruption (in order to communicate the vulnerability of GNSS, and the real risk of a disruption), the report is **agnostic to the actual source of the considered disruption**. However, it should be noted that the overall impact of an outage of GNSS is not necessarily independent of the source of the disruption: e.g. a severe natural space weather event causing a loss of GNSS may also cause an outage of other (satellite) services (communications, broadcasting, meteorological, earth observation) and power supply.
- The disruption to GNSS is considered as a **standalone event** – pre-existing redundancy systems are assumed to operate as planned.
- This study is motivated by a desire to consider new knowledge about and changes in the use of GNSS, holdover capacity, and resilience of different sectors. For this reason, this study considers evidence of use, holdover capacity, and resilience that was available during the study period – i.e. from March 2021.
- The latest available data to calculate losses and benefits for this study is the 2020/2021 financial year. However, this study considers benefits and losses calculations based on 2019 economic data. This is because 2020/2021 are abnormal years by any standard because of the disruptions posed by Brexit implementation and the Covid-19 pandemic. It is presumed that the pre-pandemic economy is a more relevant indicator of the economy going forwards in the long-run, and so pre-pandemic data from 2019 is used in this report's analysis. It is important to note that despite best efforts, GNSS applications are dynamic and reliance changes over time. The results may therefore have short shelf-life.

2 Possible causes and likelihood of loss of GNSS

Though this report is agnostic as to the source of the seven-day disruption to GNSS, this chapter considers the possible causes of such an outage. As this chapter will show, there have been a number of GNSS outages with varying causes and impact, and a number of vulnerabilities remain.

The chapter begins with an evaluation of existing GNSS vulnerabilities and possible solutions and continues on to consider two case studies. It concludes with a discussion of the likelihoods of the various GNSS-disrupting events covered in the chapter.

2.1 GNSS vulnerabilities

The GNSS signals that users on earth receive have travelled tens of thousands of kilometres through the atmosphere and magnetosphere, and as a result have an extremely low signal strength. This means receivers are susceptible to a number of deliberate and unintentional sources of interference that impact their performance. Two methods of deliberate interference are considered in Section 2.2's case studies.

This section considers a set of GNSS vulnerabilities, and ways to reduce the risk of these. Three main categories of threat to GNSS availability and performance exist: receiver vulnerabilities, environmental challenges, and human interaction issues.

2.1.1 Receiver vulnerabilities

This category of threats includes direct targeting of GNSS receivers, whether intentionally or accidentally. The case studies presented in Section 2.2 cover two types of these – jamming and spoofing. This section also considers a third type, meaconing.

Jamming is the name given to intentional disruption of GNSS signals. These interferences aim to 'blind' the receivers antenna with noise, rendering them incapable of discerning GNSS signals and hence unable to operate. Note that specific instances of jamming can in theory be unintentional, as seen in the first case study – the driver reportedly *accidentally* jammed signals at the airport. To mitigate the impact of GNSS jammers, adaptive notch filters can be incorporated into receivers.[18] These filters are based on the same principles as methods to remove Continuous Wave Interference, and as such are only effective when the jamming signals are continuous. More sophisticated methods are being developed which can better handle 'fast frequency variations' in jamming signals.[19]

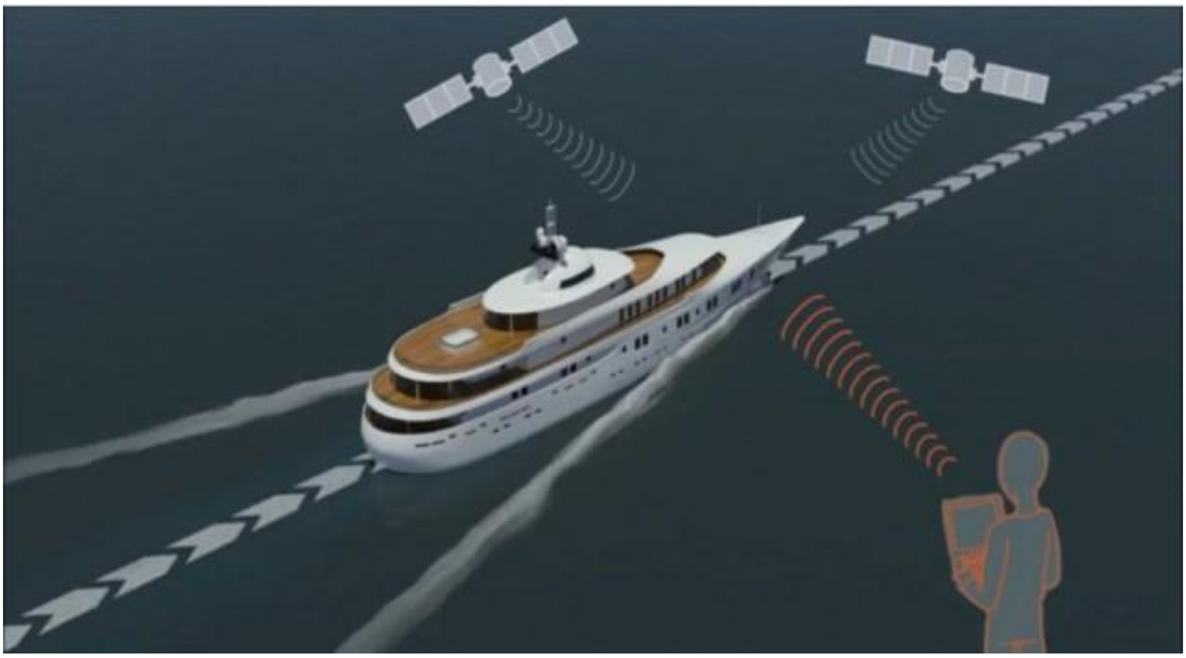
Spoofing involves the transmission of false GNSS-like signals in an attempt to convince GNSS receivers that they are in a different location. These are generally considered to be more dangerous than jamming attacks, as they can go entirely undetected. A 2013 University of Texas experiment[20] showed it was entirely possible to lead even top-of-the-line superyachts onto significantly different trajectories without their crew or navigation devices ever realising. One possible countermeasure is found in encryption mechanisms which restrict access to the GNSS signal itself. Such measures are complex and expensive which makes them impractical for most end-user applications, but they see

[18] Kim et al. (2009). 'Adaptive Two-Stage Extended Kalman Filter for a Fault-Tolerant INS-GPS Loosely Coupled System'. *IEEE.*
[19] Borio, D. (2014). 'A Multi-State Notch Filter for GNSS Jamming Mitigation'. *IEEE.*
[20] Ars Technica (2013). 'Professor fools $80m superyacht's GPS receiver on the high seas'. Available at: https://arstechnica.com/information-technology/2013/07/professor-spoofs-80m-superyachts-gps-receiver-on-the-high-seas/ [accessed June 2021].

some use in GPS military signal communications.[21] Furthermore, Galileo's open service-navigation message authentication (OSNMA) service, will enable authentication of navigation data and hence detection of spoofing.[22]

According to professional 'white hat spoofers', it is so complex to spoof signals from multiple constellations and across multiple frequencies that the preferred approach is to jam all genuine GNSS signals and spoof only the GPS Coarse Acquisition (C/A) signal.

Figure 4 Visual representation of spoofing (of a yacht) in action



Source: Todd Humphreys, from 'Spoofing on the High Seas', available at the 'UT Radionavigation Lab' YouTube channel

Meaconing is the term given to 'replay attacks', the rebroadcasting of genuine GNSS signals. As these come from directions other than satellites themselves, but are in fact 'real' GNSS signals that originate from a satellite, they function much like spoofing but are harder to detect as the GNSS signal is almost identical to the genuine article other than a slight delay. Users would measure the same position as the antenna used to capture the rebroadcast signal, which does not necessarily have to be static. This is troublesome when combined with the fact that simply retransmitting genuine signals is technically simpler than sophisticated spoofing attacks, which must credibly mimic GNSS signals. The use of multiple receivers to detect and remove the effects of meaconing has been explored.[23]

2.1.2 Environmental challenges

Despite mankind's rapid technological advances in the space domain, much remains out of direct control. This section describes the types of technical challenges that the user environment can produce for GNSS devices, as well as potential sources of mitigation.

[21] Zidan et al. (2017). 'GNSS vulnerabilities and existing solutions: a review of the literature'. *IEEE.*

[22] Septentrio. (2021). 'OSNMA: the latest in GNSS anti-spoofing security'. Available at: https://www.septentrio.com/en/learn-more/insights/osnma-latest-gnss-anti-spoofing-security [accessed July 2021].

[23] Stenberg, N. (2019). 'GNSS spoofing mitigation using multiple receivers'. *Linköping University.*

Space weather and ionospheric disruption describe varying levels of electromagnetic radiation naturally emitted by the sun. These impact GNSS signals via the disturbances they cause in Earth's ionosphere, a layer of atmosphere 80-600km above the ground. The Space Weather Preparedness Strategy[24] notes that there is no clear pattern to when these events occur. Historical events such as the Carrington event of 1859 would have disabled all satellites on the impacted side of Earth if it happened today. As GNSS satellites orbit Earth approximately twice per day, the duration of a space weather event determines what proportion of satellites is affected. As the President of the Resilient Navigation and Timing Foundation noted in 2021, major solar storms represent a game of Russian roulette and *"… we don't have a choice over whether or not we play."*[25] If such a major space weather event occurs, it cannot be avoided. The International Space Environment Service (ISES) is a collaborative of space weather service-providers across all continents.[26] Advance warning of a major space weather event could inform users of heightened risk of ionospheric disruption, giving little more than 12 hours[27] for users to seek alternative Position, Navigation, and Timing sources.

Space debris refers to the growing population of orbital debris generated by human space activity. Whilst satellites have the capability to avoid larger, trackable objects, smaller high velocity fragments occurring in orbit are almost impossible to detect or avoid. The number of such objects in orbit is growing rapidly – the latest estimates from the European Space Agency identify over 125 million objects in Earth orbit.[28] A catastrophe-level event in future years is not inconceivable unless debris mitigation activities are successful. If one satellite is severely damaged by a high energy collision, then the resulting debris field could lead to a chain reaction of collisions with other spacecraft that occupy similar orbits. This could lead to GNSS outages if such an event were to occur within the orbital plane of a GNSS constellation. Fortunately, the majority of existing debris is not in the region of space that GNSS satellites are generally placed (Medium-Earth Orbit), but the implications of a collision means the risk should continue to be monitored to allow satellites to steer clear of any incoming piece of debris. To this end, Space Surveillance and Tracking (SST) and Space Situational Awareness (SSA) providers are building capacity to track, inform, and assist manoeuvres to avoid satellite collisions.[29] That Galileo performed its first collision avoidance manoeuvre in March 2021 demonstrates that the risk of space debris is real – even for GNSS satellites in Medium-Earth Orbit.[30] Efforts to reach an international agreement on debris mitigation efforts are underway, though they come with challenges and hence such agreements provide no easy solution.[31]

Geographical constraints, often referred to specifically as **multipath** in urban settings, designate issues stemming from challenging terrain and environmental or urban obstructions. GNSS receivers require at least four satellites in view to estimate a position. This becomes challenging in non-flat locations, including both mountainous terrain and urban environments with tall buildings. Further complications can arise in urban settings as buildings reflect signals off glass or metal surfaces, resulting in GNSS signals reaching receivers from multiple paths (hence 'multipath') rather than from a direct line of sight. Some mitigation is offered by receivers that are designed to be capable of

[24] Department for Business, Innovation, and Skills. (2015). 'Space Weather Preparedness Strategy'.
[25] Goward, D. (March 2021). Presentation at Royal Institute of Navigation's PNT Webinar series.
[26] International Space Environment Service. (2021). Available at: www.spaceweather.org [accessed June 2021].
[27] Department for Business, Innovation, and Skills. (2015). 'Space Weather Preparedness Strategy'.
[28] European Space Agency (2021). 'Space debris by the numbers'. Available at: https://www.esa.int/Safety_Security/Space_Debris/Space_debris_by_the_numbers [accessed July 2021].
[29] Oswald, N. (2020). 'Gold from Trash', *Space in Focus*. Available at: https://londoneconomics.co.uk/wp-content/uploads/2020/12/Space-In-Focus-Gold-from-Trash-FINAL.pdf [accessed July 2021].
[30] EUSST (2021). 'EU SST supports Galileo: first collision avoidance manoeuvre for a Galileo spacecraft'. Available at: https://www.eusst.eu/newsroom/eu-sst-supports-galileo-collision-avoidance-manoeuvre/ [accessed July 2021]
[31] Dennerley, J. A. (2018). 'State liability for space object collisions: the proper interpretation of 'fault' for the purposes of international space law'. *The European Journal of International Law*.

receiving signals from multiple constellations[32], which have demonstrated greater performance capabilities in multipath environments, as they are more likely to obtain an accurate position fix using only line-of-sight signals rather than a less accurate fix relying on signals reflected off buildings.

Near-channel radio interference refers to the unintentional interference of other systems using electromagnetic signals in the same frequency band as GNSS applications. This risk is not insignificant – the high occupancy of the spectrum around the GNSS frequency bands creates significant risk that other signals will interfere and degrade operation. In 2011, a satellite communications services company called LightSquared filed for access to radio-spectrum at the low end of the GNSS L1 band. The request was denied because technical analysis found a great risk of disruption of L1 and therefore degradation of the performance of all GPS receivers. In addition, in-band interference is a growing concern as the multitude of GNSS satellites broadcasting on the same frequency makes it increasingly difficult for receivers to reject noise and noisy multipath signals. Careful spectrum allocation by the International Telecommunications Union has thus far minimised this vulnerability's impact, though careful monitoring remains essential to maintain this state of affairs.

2.1.3 Human interaction issues

Finally, we turn to vulnerabilities introduced into the system due to direct human interaction with GNSS. Some mitigations exist in the form of improved training and system design, while others have no easy solution.

Ground station anomalies of many different types can occur due to human error in uploads to GNSS satellites, or other improper interaction with the core components of the GNSS system. Proper training and careful design of safeguards to prevent improper interaction with GNSS can mitigate some of these vulnerabilities. Ground station anomalies may arise for a variety of different reasons ranging from malicious activity through power failures to human error. Three disruption events linked with the ground segment have affected individual GNSS constellations in the last decade: 1st April 2014, GLONASS ephemerides (data on the position of orbiting objects, including future positions) were corrupted, resulting in satellites broadcasting an incorrect location to users and receivers therefore computed erroneous positions on the ground. In late January 2016, a discontinued GPS satellite propagated incorrect time to other GPS satellites, resulting in users observing inaccurate time from their devices. In July 2019, a service incident occurred in the Galileo ground infrastructure, taking the system offline for six days.

Internal inconsistencies in the system can produce errors that render GNSS unusable. These are generally rooted in design flaws or unanticipated events. The way that leap seconds are accounted for and handled by various satellites, ground stations, and receivers is a classic culprit that generates these inconsistencies. Along similar lines, Y2K-style bugs can mean that some elements of GNSS need to periodically reset their date – a 'week number reset' of this type occurred in April 2019 for GPS.[33] Being aware in advance of these issues and proactively managing them is essential to avoid unexpected damage, though of course some issues may go unnoticed until they occur or will be ignored by users despite being informed in advance.[34] In general, ensuring the firmware of the receiver is up-to-date is the most important user action for mitigation, as manufacturers tend to identify the problems and issue patches ahead of time

[32] EUSPA. (2016). 'GNSS User Technology Report'.
[33] GPS.gov website. (2021). 'GPS Week Number Rollover'. Available at: https://www.gps.gov/support/user/rollover/ [accessed July 2021].
[34] Neuman, W. (2019). 'The Bug That Crashed New York's Wireless Network', *The New York Times.*

Infrastructure failure is an umbrella term that covers the various potential causes of GNSS constellations becoming unavailable for users. One such cause of this, could be due to a ceasing of operations due to financial constraints or upgrades to entirely different technological systems. More aggressive causes could be found in cyber-attacks on the GNSS digital infrastructure or in physical attacks on satellites. Space warfare is a growing area of interest and concern for militaries around the globe, and as dependency grows on GNSS its relative vulnerability is likely to grow too.[35]

While each of these human interaction causes could affect all constellations, it is most likely that each would occur to only one constellation at a time. If a GNSS receiver can use at least three constellations in the position solution, it is possible to ensure that the affected constellation can be removed to allow uninterrupted function. Otherwise, international cooperation is required to mitigate these vulnerabilities, though details of such cooperation lie outside the scope of this report.

2.2 Loss of GNSS case studies

With many of the potential causes of loss of GNSS covered in Section 2.1, one simple way to gain insight into the causes and likelihood of a loss of GNSS is to understand the history of such outages. We consider two localised outages, one caused by jamming at an airport and one caused by spoofing at a port.

First, in April of 2017 an individual forgot to turn off a GPS jamming device in their vehicle when parking at Nantes Atlantique airport.[36] Such devices are illegal for members of the public in France, as in many other countries, though some motorists still use them to prevent their vehicle being tracked by employers or anyone else. The individual's device caused such severe disruption to aircraft tracking systems that several flights had their landing or departures delayed. The disruption only ceased once the jamming device was physically located and disabled by law enforcement officers. The knock-on effect on airport logistics likely lasted far longer than the event itself, with the tightly scheduled flow of both aircraft as well as their passengers and cargos disrupted. We see here how the vulnerability of GPS to jamming devices means that even localised, small-scale, and ultimately accidental disruptions can have significant economic impacts.

Our second case study takes us to the other side of the world. In Shanghai, a number of ships reported that their locations were being reported incorrectly. The Center for Advanced Defense Studies, an American non-profit, investigated and found patently false circular patterns hundreds of metres in-land.[37] Ships rely on GNSS-based automatic identification system (AIS) transponders which broadcast (and receive broadcasts of) ship positions and velocities to keep crowded shipping lanes safe. Usually, if ships lose navigation signals they can fall back on other methods such as radar, physical maps, and even visual navigation. If their GNSS signal is spoofed, however, the ship and any other ships tracking it will believe it is in a completely different position. The risks of such a misalignment between beliefs and reality are potent: the European Maritime Safety Agency found in 2019 that 44% of all marine accidents were due to navigation issues that subsequently led to 'contacts, grounding/stranding, and collision'.[38] The implied potential for economic damage due to

[35] Goulding, T. (2021). 'Star Wars and Space Clubs', *Space in Focus*. Available at: https://londoneconomics.co.uk/wp-content/uploads/2021/04/Space-in-Focus-Star-Wars-and-Space-Clubs.pdf [accessed July 2021].

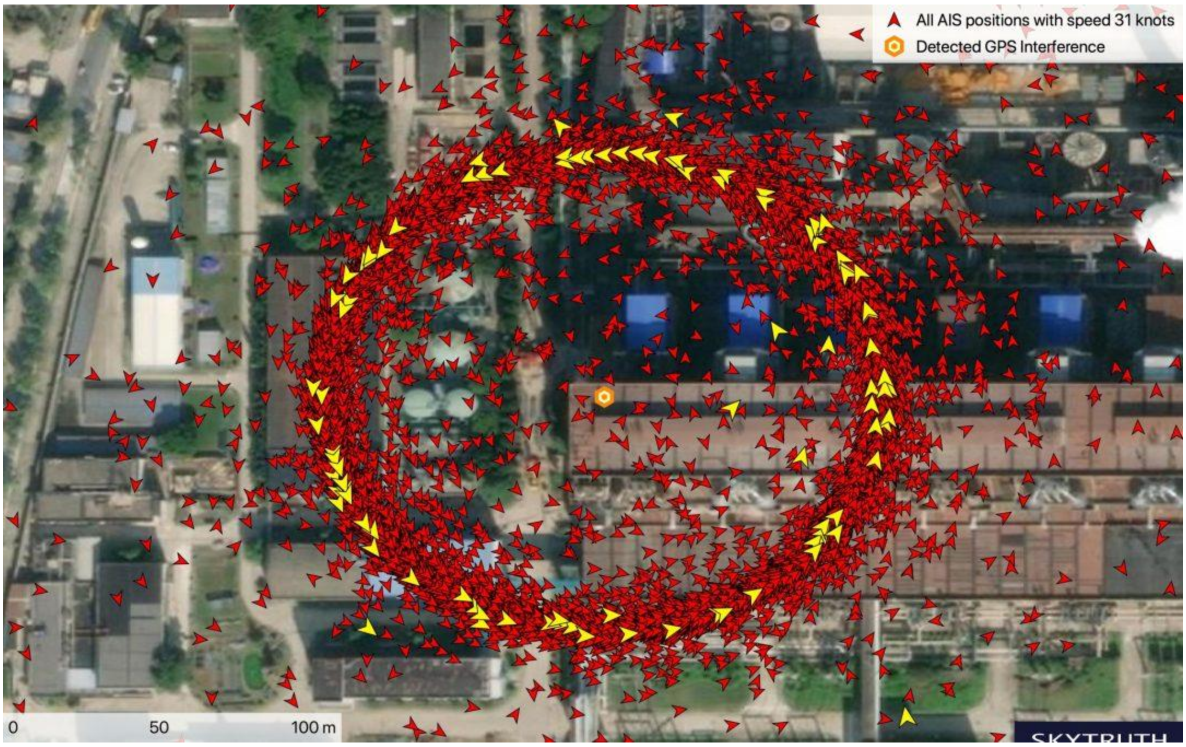
[36] Connexion France. (2017). ''Forgotten' GPS jammer costs motorist €2,000'. Available at: https://www.connexionfrance.com/French-news/Forgotten-GPS-jammer-costs-motorist-2-000#:~:text=A%20La%20Rochelle%20man%20has,correctionnel%20de%20Nantes%20was%20told [accessed June 2021].

[37] The Warzone. (2019). 'New type of GPS spoofing attack in China creates "crop circles" of false location data'. Available at: https://www.thedrive.com/the-war-zone/31092/new-type-of-gps-spoofing-attack-in-china-creates-crop-circles-of-false-location-data#:~:text=Unlike%20previous%20examples%20of%20spoofing,positions%20that%20forms%20odd%20ring%2D [accessed June 2021].

[38] European Maritime Safety Agency. (2020). 'Annual Overview of Marine Casualties and Incidents 2020'.

spoofing cases such as is seen in Shanghai is therefore significant. State sponsored spoofing attacks of this sophistication obviously create a threat that such methods could ultimately be deployed elsewhere. The alternatives, that this is either a deliberate spoofing attempt by a rogue non-state actor or a technical glitch that nobody understands, are not particularly palatable either.

Figure 5 **Incorrect ship location reporting in Shanghai, China**



Source: Resilient Navigation and Timing Foundation. (2019). 'China Spoofing GPS to Circles at Multiple Sites to Hide Iran Oil?'

2.3 Could we lose GNSS?

To answer this question, it is important to clarify what is meant by losing GNSS. The following definition applies:

A user has lost GNSS if they are unable to estimate Position, Navigation[39], or Time (PNT) based on signals from satellites in space.

To understand the likelihood of losing GNSS, it is useful to classify users into different categories based on the capabilities of the devices, they use.

2.3.1 Single-constellation device users

Single-constellation devices are GPS-only.[40] Users of these devices do not demand other GNSS constellations for one of three reasons: i) cost and power restrictions mean only the very cheapest option is viable (e.g. IoT devices without a power source); ii) regulation is limited to GPS-only devices (e.g. aviation and maritime transport); and iii) long procurement and life-in-service timescales

[39] Technically, users do not compute an estimate navigation. Instead, they compute an estimate of velocity and heading, which is used alongside position as inputs into navigation systems.

[40] Other single-constellation devices are available, but for testing or redundancy purposes only (i.e. as independent sources of space-based PNT).

coupled with a need for safety certification demonstrated by a long service history favour older specifications that typically pre-date other constellations than GPS (e.g. CNI timing users such as finance, telecoms, power).

The likelihood of a GNSS outage is greater for single-constellation users because the Human Interaction Issues in 2.1.3 would all result in these users losing access to PNT from satellites.

2.3.2 Dual-constellation users

Dual-constellation devices use GPS and one additional constellation. The most prevalent second constellation is GLONASS owing to its earlier declaration of full operational capability than Galileo and BeiDou. Such devices can be considered legacy devices that are likely to be replaced as they reach end-of-life. Technically, GPS and Galileo are so easy to include in parallel that future dual-constellation receivers are likely to take this specification. The impact of loss of one of the two constellations in the specification depends on decisions related to implementation and prioritisation. This is exemplified by GLONASS' erroneous ephemerides on 1st April 2014, which provided a real-world experiment. At the time, only Asia had meaningful coverage of at least one GNSS beyond GPS and GLONASS, and the incorporation of BeiDou meant that receivers in coverage were able to identify that GPS and BeiDou provided similar positions and GLONASS did not, so they could filter GLONASS out of the solution. In Europe, on the other hand, where only GPS and GLONASS were available, receivers were not able to select which constellation was correct and behaved in different ways as a result. Some oscillated between the two positions while others computed the average position between the two constellations. Neither of those solutions provided the user with relevant information.[41]

Dual-constellation users would be affected by degradation of performance of one of the constellations, but would continue to operate if one constellation was lost in a clean break. The accuracy of the observed position at user level would likely reduce, and the availability in challenging environments could also be affected, but the user would continue of be able to derive PNT from satellites in space.[42]

2.3.3 Triple and quad-constellation users

Mass-market and high-precision GNSS users rely on three or four constellations. These users would not observe marked impacts of degradation or loss of a single constellation as the remaining signals would be sufficient for continuity of operations.

These users would therefore only be affected by events that affected all GNSS simultaneously. Jamming, spoofing, and meaconing devices are capable of attacking all GNSS at the same time, so there is limited benefit from multi-constellation in this dimension. A White Hat hacker has confirmed that the easiest way to spoof GNSS is to jam all signals and then spoof only GPS C/A. A clever device could therefore, probably, detect spoofing by raising an alarm if only GPS C/A was observed.

[41] Diggelen, F. (2014). 'How GLONASS Failed for 11 Hours and Multi-GNSS Survived'. Available at: https://web.stanford.edu/group/scpnt/pnt/PNT14/2014_Presentation_Files/7.van_Diggelen-GLONASS-multi_GNSS.pdf [accessed July 2018]

[42] However, the validity of this statement still depends on the exact implementation of constellations in the receiver. Anecdotal evidence suggests that, at least some receivers, implement dual-constellation capabilities (GPS and GLONASS) in such a way that jamming GPS could render the device inoperable.

2.3.4 All users

Disruption caused by a space weather event is capable of causing complete and instantaneous loss of GNSS signals for a meaningful period of time. A space weather event of the magnitude required to disable all GNSS satellites has only been recorded once *on Earth*, namely the Carrington Event in 1859, yet it remains the only realistic source of outage that does not involve intentional disabling of all satellites or ground stations.

However, the paucity of such events on Earth does not imply the risk is negligible. For a space weather event to disable all GNSS satellites, two conditions need to be met. Firstly, a coronal mass ejection (CME) of sufficient magnitude is required. CMEs occur regularly as part of the 11-year solar cycle, and vary significantly in magnitude. Secondly, the CME needs to be directed at Earth.

Recent research has found that *great solar storms* have occurred six times on Earth in the last 150 years.[43] This implies a probability of 4% per year of a great solar storm. The probability of a Carrington class storm is found to be 0.7% per year.[44]

For context, at solar maxima, 3 CMEs are produced per day at varying levels of intensity. This drops to 1 per day at solar minima.[45]

[43] This research excludes the Carrington Event itself as it occurred before the measurement stations providing the data for the analyses were established.
[44] Chapman, S. C., R. B. Horne, N. W. Watkins (2020). *Using the aa Index Over the Last 14 Solar Cycles to Characterise Extreme Geomagnetic Activity*. Geophysical Research Letters. Available at: https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2019GL086524
[45] Fox, N. (no date). *Coronal Mass Ejections*. NASA. Available at: https://pwg.gsfc.nasa.gov/istp/nicky/cme-chase.html [accessed 30/7/2021]

3 Analytical Framework

This chapter sets out the framework used to structure the analysis to provide answers to the research questions. To this end, this framework covers the scope, definitions, counterfactual, and an 'impact logic model', culminating in a high-level list of inputs required for successful implementation of the methodology.

3.1 Scope

The scope of the research and analysis presented in this report is limited by the following:

- The disruption event considered in Chapter 4 is a single instance of a 7-day disruption to all GNSS (GPS, GLONASS, Galileo, and BeiDou) following which all services are restored to full capacity (a second 24-hour disruption is also assessed later);
- The disruption events considered in Chapter 5 are a single instance of a time-limited disruption to the same extent as in Chapter 4, though the geographical extent in each case is limited to the Port of Dover and a specified area of the M25 Motorway;
- The analysis is agnostic to the cause of the disruption event;
- The disruption occurs in 2019, with economic activity and technology usage characterised by then-current usage/reliance – the effects of Brexit and Covid-19, and responses to both induced an uncountable number of changes that make models of more recent years unrepresentative of 'business-as-normal' times, and for which reliable national statistics data are not yet available at the required level of granularity;
- The disruption period is a 'typical' week in the year, and no seasonal effects are considered;
- Iridium's alternative STL PNT service is confirmed to depend on GNSS and therefore not a genuine alternative;
- Military and defence applications are excluded from scope, but civil law enforcement, emergency response, and judicial applications (e.g. offender tracking) are in scope;
- Benefits are monetised whenever possible, though non-monetiseable benefits are considered where appropriate;
- Economic losses are considered against a baseline where GNSS is fully functional; mitigating efforts through 'traditional' means (e.g. by using paper maps) will be considered but may be limited owing to the immediacy and brevity of the disruption. These losses may diverge from monetised benefits of an application as they are measured against a different baseline to the marginal improvement considered when monetising benefits.

3.2 Definitions

GNSS signals The information (carrier identification, ranging code, navigation data, timestamp, etc.) transmitted by a satellite of any global navigation satellite system (GPS, GLONASS, Galileo, BeiDou-2), or the EGNOS regional system.

Disruption event An unforeseen situation of the complete loss of GNSS signals and all associated functionality, howsoever caused, for a period of up to 7-days.

Critical National Infrastructures (CNIs) The UK's Critical Infrastructure is defined by the Government as: "Those critical elements of infrastructure (namely assets, facilities, systems, networks or processes and the essential workers that operate and facilitate them), the loss or compromise of which could result in major detrimental impact on the availability, delivery or integrity of essential services, leading to severe economic or social consequences or to loss of life."[46]

There are 13 UK CNIs: Chemicals; Civil Nuclear; Communications; Defence; Emergency Services; Energy; Finance; Food; Government; Health; Space; Transport; and Water. CNIs typically employ specialists with a clear understanding of technical need and implementation of GNSS.

Uses of GNSS Universe of applications of GNSS used by any type of user.

Role of GNSS The functional role of GNSS within a system, including consideration of the resilience (e.g. redundancy) systems and strategies. This is important, as even if as it separates 'equipage' from 'usage' – if GNSS is used in a redundancy role, a disruption to GNSS may not have any impact if the primary system remains fully functional.

User An economic agent (individual or organisation) that is benefitting from GNSS-supported functionality in the current business-as-usual counterfactual scenario. Such use may be direct or indirect, defined as follows:

- **Direct use:** An individual (e.g. a private citizen using GNSS positioning on a Smartphone map application) or organisation (e.g. energy network distributor using GNSS for synchronisation) that employs GNSS as a direct input to its operations, an application being used, and/or a product or service provided.
- **Indirect use:** An individual or organisation that uses a product or service of a direct user (e.g. electric railway company using electricity from an energy network distributor).

Note that any individual or organisation may be simultaneously a direct and/or an indirect user.

Disruption A loss of GNSS service, howsoever caused, for a period of up to 7-days.

3.3 Counterfactual

This report considers two separate counterfactuals. One covers the estimates of benefits of GNSS whilst the other applies to estimates of loss.

The counterfactual applicable to benefits of GNSS can be considered as the best *possible* alternative to GNSS. This is different from the counterfactual in the estimate of economic loss from a disruption to GNSS, which is assessed against the best *available* alternative. The implication is that impact of loss can outweigh the benefits by large factors. This is because the best *available* alternative falls short of the best *possible* alternative, which may require investment and installation time.

3.4 Impact logic model

GNSS delivers value to the UK economy and society via a value chain. To better understand the potential impact of a GNSS outage, it is informative to first identify and map the logical relationship

[46] Cabinet Office. (2018) 'Public Summary of Sector Security and Resilience Plans'. Available at: https://www.gov.uk/government/publications/sector-security-and-resilience-plans-2018-summary [accessed July 2021].

between inputs, processes, outputs, and impacts of GNSS signals. This is done in two steps, which is reflected in the structure of Chapter 4:

- Identification of the current usage and benefits of GNSS in the UK; and
- Identification of the impacts of a disruption to GNSS.

The first step is to identify and map the pattern and extent of GNSS use across all types of user in the UK, and to understand the benefits that users enjoy – as it is these benefits that are at risk to disruption.

Taking this further, the next step is to track the economic impact 'domino effect' that would be experienced in the instance of a disruption event to GNSS signal availability.

It is noteworthy that a brief disruption event is capable of producing negative economic impacts in excess of the pro rata benefits of GNSS over the same period. While the counterfactual considered for the benefits of each application is the next-best alternative that is technically feasible, the impact of a loss of GNSS is measured for a world unprepared for such an event. As such, rather than assessing the benefits lost and further economic damage caused due to a regression to the next-best alternatives, we estimate the effects of an unanticipated switch to the best **readily available** alternatives. These most readily available alternatives are by no means the same as the next-best technically feasible alternatives.

3.5 Inputs required for successful implementation

To successfully implement this framework, the following information has been gathered and/or generated:

- Complete identification of users;
- Complete identification of applications and uses;
- For every use case:
  - Clear understanding of the full range of user benefits and socio-economic impacts;
  - Monetisation of user benefits and socio-economic impacts;
  - Clear understanding of the role of GNSS within a system, including resilience (e.g. hold-over performance, etc.);
  - Clear understanding of the effect (potentially progressive) of a disruption to GNSS signals;
  - Appropriate parameters to inform estimation of the economic impact of a disruption to GNSS signals.

4 GNSS in the UK: uses, benefits, potential losses

The following sections identify the uses and value of economic benefits of GNSS across the UK economy across seven priority sectors: Agriculture, Aviation, Emergency Services, Finance, Maritime, Rail, and Road. An update to the other updated Critical National Infrastructure sectors is included at the end of this chapter. In addition, each section considers the economic impact on the UK economy of a temporary loss of GNSS for two scenarios: a 7-day outage and a 24-hour outage. The benefit generated in each sector is estimated on an annual basis, while the impact of a loss of GNSS is modelled for a seven-day national outage as per the methodology outlined in Chapter 3.

Each section follows a common structure, with an outline of the scope of the sector followed by a more detailed consideration of the applications, the economic benefits of GNSS, and the economic losses from its disappearance. They each conclude with an evaluation of the drivers of change since the previous iteration[47] of this report. This chapter concludes with a consideration of a shorter, 24-hour GNSS outage period.

4.1 Agriculture

GNSS plays a key role in modern agricultural practices in the UK, principally through applications related to cultivation, including precision farming and variable rate application (VRA). GNSS is a key driver of increasing yields on UK farms and reductions in the cost of inputs and associated environmental impact. GNSS underpins a trend towards technologically advanced farming operations and the automation of many farming practices. The adoption of cutting-edge GNSS technology is highest among large-scale cultivators, with second-hand equipment trickling down to smaller and often family-owned farms over time.

GNSS users in agriculture generally rely on more sophisticated equipment than many other user groups. GNSS devices for agriculture are more expensive than for other sectors, and track more signals and constellations as standard. Many include EGNOS and commercial augmentation services such as Real Time Kinematic (RTK) or Precise Point Positioning (PPP) for improved accuracy.

The use case monetised in this section includes activities related to cultivation. Additional applications can be found in the emerging field of precision livestock farming/tracking, asset monitoring, hunting, and silviculture. It is assumed that soil sampling, biomass monitoring, and harvest monitoring are accounted for under the umbrella of precision farming and VRA more broadly within cultivation. Agriculture/Food relevant applications not covered above (due to primary coverage in other sections/other updated sectors) include:

- Inspections/Land Parcel Boundaries (Cadastral Surveying)
- Drones/Aircraft for agriculture
- Just-in-time logistics
- Geo-traceability

The applications that are considered in this section are shown below in Table 9. The annual economic value they generate and the estimated economic losses due to a seven-day loss of GNSS are summarised for each.

[47] London Economics. (2017). 'The economic impact on the UK of a disruption to GNSS'.

Table 9 Agriculture Applications

Application	Economic benefit (annual, £m)	Economic loss (7-day, £m)
Cultivation	524.4 (*+84.4%*)	223.6 (*+43.5%*)
Total	**524.4 (*+84.4%*)**	**223.6 (*+43.5%*)**

Note: *(+%) indicates the variation in economic benefits and loss since the 2017 iteration of this report.*
Source: London Economics analysis

4.1.1 Cultivation

Fundamentally, GNSS is used for two purposes within cultivation. The first purpose is to navigate the tractor, either through a **tractor guidance** system where the driver is constantly told whether to steer left or right or by using an **automatic steering** system that autonomously steers the tractor. Using GNSS for tractor navigation increases the efficiency of farm operations as it is possible to reduce pass-to-pass overlap[48]. This means that the working of the field (e.g. ploughing, sowing, fertilising, etc.) can be completed faster and using fewer inputs. The monetised benefits estimate the value of saved inputs (labour, fuel, and other products), and associated environmental benefits.

The second purpose is for **Variable Rate Application (VRA)**, which requires more detailed field information. VRA requires accurate steering of the tractor and is therefore used in conjunction with an automatic steering device. Software packages on offer from leading equipment manufacturers (and other sources) integrate agronomy and remote sensing data on the health of the field[49] to determine which sections require more or less fertiliser (or pesticides, and so on) than the average. This information is stored by the equipment, and the spray is adjusted according to needs. Benefits of this technology are primarily in the form of yield increases or reduce input costs because pesticides can be applied to infested plants, crops that are too small can receive a fertiliser boost, and crops that are so large they are at risk of falling over can be prescribed a reduced amount of fertiliser.

Economic benefit

The annual economic value generated by GNSS in cultivation is estimated at **£524.4m.**

These benefits are associated with improvements to cultivation practices through precision farming methods and VRA. The benefits are monetised firstly though reduced agricultural inputs required such as labour, seed, fertiliser, pesticide, and fuel. Additionally, utility benefits are calculated through reductions in fuel, fertiliser, and pesticide externalities. These negative externalities include environmental degradation, harms to human health, and the social cost of carbon. Finally, benefits accrue due to increased crop yields, a product of reduced soil compression through narrower pass-to-pass overlap by GNSS-enabled tractors, and highly targeted quantities of water, fertiliser, and pesticide for optimal growth of crops.

Economic loss

The economic impact of loss of GNSS in cultivation is estimated at **£223.6m.**

[48] Pass-to-pass overlap refers to the gap between successive lengths travelled down a field by a tractor or combine. Narrower pass to pass overlap implies more efficient use of the total plot of farmland.
[49] Both types of data maybe themselves gathered using GNSS.

Benefits of GNSS for an average seven-day period have been estimated at £10.1m, which would all be lost. However, benefits have been estimated against a baseline in which farmers achieve the best possible results absent GNSS, i.e. a pass-to-pass overlap of 30cm which has been reduced to 4cm by GNSS. It is reasonable to assume that a farmer who has relied on GNSS for a decade would be unable to achieve the same pass-to-pass overlap as the baseline, and therefore that further detriment would materialise during a GNSS outage. No recent and widespread experiments have been conducted on the degradation of traditional skills (including for farmers). However, unsurprising anecdotal evidence from the expert consultation process suggested newly trained farmers and those operating on older, non-GNSS enabled equipment, struggle to produce output in line with those specifically trained and practiced in traditional methods. Therefore, further detriment is estimated based on an assumption that pass-to-pass overlap for a current farmer would be double what a traditional farmer could achieve. The detriment is therefore twice as high as the benefit estimated, £20.2m

Assuming 15% yield increase from GNSS, the detriment suffered from its loss would be a reduction of domestically-produced cereal of 13%.[50,51] In 2019, the value of cereals produced in the UK was £3.7bn.[52] The loss in yield would reduce self-sufficiency of the UK in terms of cereal production, and supplies would be needed from elsewhere. A seven-day outage of GNSS could affect the yield of the crop season by 13%, so assuming three seasons, the loss is estimated at £158.9m.

Further losses of £44.5m in lost GVA over the seven-day period can be expected in the food processing industries that rely on UK and imported agricultural inputs. This is because the 13% reduction in agricultural productivity will reduce the total domestic inputs available to the sector – by £83.7m[53] over the seven-day period – and therefore the total economic value added.

Expert consultations also highlighted the importance of GNSS during harvest season. Yield data collected by combine harvesters during harvest offers a critical input into the VRA calculations for the next planting season. By assessing the relative yields of a given plot of soil, a farmer can identify which areas can support more seed and fertiliser during the next planting cycle. In the absence of GNSS, this precise data would be lost.

Additionally, consultees offered scenarios highlighting the potentially catastrophic effect of a delay in harvesting. Certain crops are highly sensitive to the moisture conditions under which they are harvested. Changes in moisture content can increase the risk of crop spoiling or of damage to the harvesting equipment. The combination of a delay in harvesting due to a GNSS outage and a change in weather patterns could produce such a scenario. However, disaggregating this risk by crop type, weather risk, and the unique response of a given farmer in the case of a GNSS outage at the time of harvest is beyond the scope of this report. Larger cultivators, whose harvest operations are more likely to be dependent on GNSS for successful and timely execution, are most at risk during an outage.

[50] Low end of the 9%-35% range reported in: Ingenia Online. (2015). 'Precision farming'. Available at: http://www.ingenia.org.uk/Ingenia/Articles/972 [accessed July 2021]. Approximate figure has been corroborated in consultations with sector experts.

[51] 13% is the inverse of 15%. Ex: (1+0.15) x (1-0.13) ≈ 1

[52] UK Department for Environment, Food and Rural Affairs. (2019). 'Agriculture in the United Kingdom 2019'. Available at: https://www.gov.uk/government/statistics/agriculture-in-the-united-kingdom-2019 [accessed July 2021].

[53] Office for National Statistics. 'Input-output supply and use tables'. Available at: https://www.ons.gov.uk/economy/nationalaccounts/supplyandusetables/datasets/inputoutputsupplyandusetables

Drivers of change

In the previous iteration of this report, the estimates of economic benefit **£284.4m** and loss **£155.8m** differ from the updated estimates presented in this report of **£524.4m** (benefit) and **£223.6m** (loss).

The benefits value has most significantly been impacted by two key updates. The first is organic growth in the uptake of VRA technology, which has increased by 60% since the 2017 report. The second is an increase in the scientifically accepted value of the Social Cost of Carbon (SCC) to £304 per tonne. From these two factors, 75% of the change in benefits are derived from increased VRA uptake, and 25% are from reductions in externalities from reduced fuel, fertiliser, and pesticide use.

The estimated value of economic impact of loss of GNSS has been impacted by four changes, in addition to the extended 7-day outage window. Like benefits, the loss figures have been impacted by organic growth in VRA technology. Further, they have been impacted by increases in the value of cereals produced in the UK over successive years. Another component are updates to UK input-output tables for intermediate goods, which feeds into the impact on food processing industries which rely on domestic inputs. And finally, a modest proportion (£10.1m) is due to increased assumed value of the SCC.

4.1.2 Other Agriculture applications

Other applications of GNSS technology in agriculture include precision livestock farming and tracking, silviculture, hunting, and asset monitoring/tracking. Expert consultation suggested many of these are fledgeling technologies and have not yet achieved adoption widespread enough to merit monetisation in this report. In the case of precision livestock farming/tracking, the high cost of GNSS enabled collars remains prohibitively expensive. Further the wide roaming area of UK livestock have made approaches relying on centralised base stations with lower cost collars impractical. Testing of these technologies remains ongoing as proponents hope such technologies will provide advantages such as earlier identification of disease amongst a herd, or oestrus[54] in breeding animals.

Similarly, for silviculture, benefits have not been monetised, but given a fairly limited market with users of forestry software solutions estimated at 1,195 subscriptions in Europe in 2019[55], the benefits to the UK (and therefore losses incurred from outage) are expected to be of limited magnitude.

With respect to hunting, namely GNSS equipped collars for hunting dogs, consultees suggested both limited penetration and questioned the value added by such technologies over current practices. The benefits have therefore not been monetised.

Asset monitoring refers to the embedding of GNSS tracking units on farm plant and machinery. These units are typically integrated in new models of equipment such as tractors and quad bikes but may also be purchased as after-market stand-alone components. The units are leveraged in the case of theft to aid with asset recovery. Forthcoming applications of this technology may enable geofencing of farms, which would disable equipment when removed from property. However, while this may prevent farm equipment from being driven off site, it would not mechanically disable thefts which occur using a secondary vehicle such as a lorry or van to transport the stolen equipment off site. Consultations with expert stakeholders indicated that the current deterrence effect of asset

[54] A recurring period of sexual receptivity and fertility in many female mammals; heat.
[55] EUSPA. (2019). 'GNSS Market Report Issue 6'.

tracking units is limited as these are generally easily dismantled or disabled by thieves. Furthermore, limitations on available data, both in terms of the penetration of these GNSS tracking units across farm assets in the UK and reliable longitudinal indicators of their theft deterrence value, have prevented them from being monetised in this report.

4.2 Aviation

GNSS is increasingly being utilised within the aviation sector to optimise routing of flights, but also to improve the efficiency of take-off and landing operations at airports. Indeed, Space Based Augmentation Systems (SBAS) are now installed at a number of airports across the UK to improve efficiency and support passenger safety. Air traffic management systems routinely utilise GNSS signals for aircraft as an important input in monitoring the high volumes of air traffic passing through UK airspace and beyond.

4.2.1 Scope of sector

GNSS supports five applications in manned aviation and this number is largely unchanged since the 2017 iteration of this report. The key difference with this updated analysis is the inclusion of unmanned aviation applications, the number of which looks set to increase rapidly over the coming years. For the purposes of this assessment however, noting that the full potential of Unmanned Air Vehicle (UAV) operation has yet to be fully realised, the aviation sector only covers applications relating to agricultural services as these are deemed to be the most mature and quantifiable at this stage of development of the industry.

Of note since the previous iteration of this study are the specific ramifications for the aviation sector of the withdrawal of the UK from the European Union. From 25 June 2021 UK users will not be able to use the EGNOS Safety of Life (SoL) service and the EGNOS Working Agreements (EWAs) will no longer be recognised by the EU. A direct implication of the loss of EGNOS for UK users is that LPV (Localizer Performance with Vertical guidance) approaches at UK airports will no longer be possible. Instead, users must rely solely upon ILS (Instrument Landing System) approaches, which is a lower precision approach method. The result of this is that acceptable margins of error for landing approaches during poor weather conditions are likely to be much lower, and as such delays, diversions, and cancellations of flights to and from UK airports are expected to increase from mid-2021. In terms of the level of impact caused by the loss of EGNOS, the UK has 125 licensed aerodromes and 69 have at least one instrument approach, with 81 runways in total having an ILS approach option available. Only 45 runways use LPVs and 20 of these feature ILS, meaning around 25 will be forced to rely upon non-precision approach methods[56].

The applications that are considered in this section are shown below in Table 10. The annual economic value they generate and the estimated economic losses due to a one-week loss of GNSS are summarised for each.

[56] Lougheed, R. (2021). 'UK: No more LPV approaches after June'. Available at: https://ops.group/blog/uk-no-more-lpv-approaches-after-june/?print=pdf [accessed July 2021].

Table 10 Aviation applications

Application	Economic benefit (annual, £m)	Economic loss (7-day, £m)
Navigation	5.0 (*+266%*)	0.1 (*+900%*)
Surveillance (communications)	21.2	0.4
Safety	3.1 (*+55%*)	0.5 (*+56%*)
Environmental	0.3	Not assessed
Productivity	158.5	3.0
Total	**187.9 (*+5509%*)**	**4.0 (*+1190%*)**

Note: *(+%) indicates the variation in economic benefits and loss since the 2017 iteration of this report.*
Source: London Economics analysis

4.2.2 Navigation

This application corresponds to all take-off and landing operations at UK airports, plus routing of flights between domestic, international, and transcontinental destinations, and air traffic management operations. As mentioned above, many UK airports make use of high precision EGNOS signals for LPV landing approaches. This technology is particularly useful for landing aircraft during inclement weather conditions such as fog or heavy rain/snow where visibility is poor, and pilots may struggle to navigate via visual information. High precision orientation techniques enabled by GNSS allow planes to touchdown in optimal positions on the runway which can be highly beneficial when surface conditions are compromised by pools of water or ice.

Economic benefit

The total benefits arising from Navigation applications involving UK airports and flights amount to **£0.5m**. This stems from the reduction of delays, diversions, and cancellations of UK flights owing to the availability of GNSS enabled navigational aids and landing operations.

Two of the monetised benefits in aviation are driven by shorter delays resulting from the ability to land in more hostile weather conditions thanks to GNSS.

By examining annual statistics produced by aviation safety body Eurocontrol concerning flight movements across European airspace, the percentage of flights that are either delayed, diverted, or cancelled, the duration of these disruptions, and the associated costs, it is feasible to estimate the aggregate benefit to airlines conducting operation originating or arriving in the UK. It is important however to only consider disruption due to inclement weather conditions, as disruption relating to issues such as mechanical failure, staffing issues, or drone incursions would not be in scope to be mitigated via GNSS.

Economic loss

The value of economic loss during an outage total some **£0.1m**.

Benefits of GNSS estimated for SBAS enabled landing procedures would all be lost for the duration of the outage as these are all additional to existing alternative systems (i.e. ILS approaches). SBAS systems are particularly useful when attempting to land during poor weather conditions as this ensures a high level of accuracy with detecting the correct runway approach for landing aircraft. The level of impact would then be dependent upon the weather conditions at the time, but we have estimated a worst-case impact in the value stated above.

Out of all planes either **delayed, diverted,** or **cancelled**, it is assumed that 75% are delayed, 20% are diverted, and 5% are cancelled. The loss calculation for each is broadly similar and is based upon annual flight disruption data and impact estimates provided by Eurocontrol.

Taking the delay calculation as an example, it is assumed that 25% of the delay minutes per flight can be improved by using GNSS and assumed that GNSS will reduce delay by 48.5%, with the rest of weather delays deemed too severe. Eurocontrol provides various costs of delays in addition, as well as information relating to the total number of flight movements originating/arriving across different classes of aviation. This results in an estimated number of delayed flight movements in commercial aviation, and the corresponding saving for airlines.

The calculation for diversions is similar but applies the ratio of diverted to delayed movements as it is assumed that there is correlation between delay and diversion. The analogous calculation for cancellations instead applies the ratio of cancelled to delayed movements.

Multiplying by the share of all runways with a published landing procedure ensures that only movements to relevant airports contribute to the benefit calculation. The only step remaining is to multiply the monetised cost savings by the share of aircraft that are GNSS enabled so as to ensure only the relevant flights contribute to the loss calculation and apportion for the period of the outage.

It is possible that disruption to terrestrial transportation systems may impact the availability of flight crew travelling to airports, however this is difficult to quantify and is not included within the loss calculation. Some aircraft systems may also react in an unpredictable manner, as seen by the grounding of several Boeing aircraft during the 2019 GPS rollover event.[57] Also, it should be noted that the calculation assumes poor weather conditions during the seven-day outage; should the visibility and/or runway surface conditions be nominal during the period of disruption then it is conceivable that the loss amount would be lower.

Manned aircraft typically feature systems with multiple levels of redundancy, and no additional impact is expected beyond those outlined above.

Drivers of change

In the previous iteration of this report, the estimates of economic benefit (**£1.35m**) and loss (<**£0.1m**) differ from the updated estimates presented in this report of **£4.95m** (benefit) and **£0.1m** (loss).

The benefits value has most significantly been impacted by two key updates. Firstly, the percentage of the number of flights delayed was increased based upon updated inputs from the Eurocontrol CODA Digest 2019. The Eurocontrol CODA 2018 was utilised to update the average arrival time delay per flight, which was increased from 2018 onwards.

4.2.3 Surveillance (communications)

The regions of airspace surrounding the UK such as the North Atlantic and the North Sea are amongst the busiest oceanic or sea airspaces in the world, and GNSS enabled Automatic Dependent Surveillance – Broadcast (ADS-B) offers significant potential for fuel efficiency improvements and hence reductions in CO_2 emissions. Space-based ADS-B reduces lateral and longitudinal separation,

[57] Davis, D. A. (2019). 'GNSS Rollover hamstrings New York city wireless network'. Available at: https://insidegnss.com/gps-rollover-hamstrings-new-york-city-wireless-network-and-a-handful-of-other-systems/ [accessed July 2021].

increases access to preferred altitudes, and allows fuel-saving speed changes for the majority of aircraft. Essentially by providing high fidelity positioning information to controllers managing densely populated airspace, the total number of aircraft occupying a region of airspace can be increased. This is because the minimum separation distance between aircraft can be lowered due to the confidence in positioning information versus other solutions such as radar. ADS-B can also span large regions without the constraints a radar-based system would involve in terms of limitations of range from a fixed location.

Economic benefit

The total economic benefit from Surveillance (Communications) application amounts to **£21.2m**.

The benefit is calculated by multiplying the number of flight movements across the UK by the average benefit per ADS-B monitored flight. Data from Aireon suggests a fuel saving of 30-40 kg of fuel per transatlantic flight[58], based upon improvements to routing of aircraft. The model uses the value of cancellation of a continental flight, where an intercontinental flight is substantially more costly to cancel and a regional flight less so. Converting the aggregated fuel saved based upon market jet fuel costs results in the estimated total economic benefit presented above.

Economic loss

The value of economic loss during an outage total some **£0.41m**.

During an outage pilots would still be able to navigate between destinations, but the unavailability of ADS-B would remove the efficiency savings enabled by this capability. Specifically, this would relate to the minimum safe separation distance between flights, as lower fidelity solutions such as radar would increase the level of uncertainty in positioning information. Therefore, the minimum separation distance would need to be increased during a GNSS outage to ensure safe flight operations. This means that fewer aircraft would be permitted to occupy the same region of airspace simultaneously, resulting in an increase to flight delays and less efficient routing of flights. Managing air traffic beyond the reach of radar would be more problematic, as since ADS-B was certified and assured as approved means of providing traffic in the North Sea in 2018 no alternative systems have emerged. This would in turn mean that voice control would be the only practical solution. However, it is important to note that increasing flight separation will not materially impact on the scheduling at airports. Aircraft would continue to arrive at the expected rate, but it would cost them more fuel to get there.

Drivers of change

Space-based ADS-B from Aireon had not been rolled out in 2017 and so this application was not monetised in the previous iteration of this report. Therefore, the estimates of economic benefit (**£21.2m**) and loss (**£0.4m**) are entirely additional to the aviation sector's total. This is a clear example of a sector increasing its overall use of GNSS and generating additional benefits as a result.

4.2.4 Safety

Search and Rescue operations rely on activation of positioning beacons installed onboard aircraft to locate survivors of air crashes. Although tracking of aircraft has improved via techniques such as ADS-B, incidents such as the loss of Air France AF447 from Rio de Janeiro to Paris in 2009 and

[58] Marais, K. (2016). 'Environmental Benefits of Space-based ADS-B'. *School of Aeronautics and Astronautics, Purdue University*.

Malaysian Airlines MH370's disappearance in 2014 illustrate that automated systems that relay the location of aircraft to rescuers without the need for human action are potentially of great benefit. GNSS can also be used to avoid Controlled Flight Into Terrain (CFIT) scenarios, although within the airspace of the UK the occurrence of such scenarios is likely to be limited.

Economic benefit

The COSPAS-SARSAT initiative monitors the use and triggering of Emergency Locator Transmitters (ELTs) that are mounted on the tail of aircraft and activate on impact. In 2018 (the last year data is available), the number of beacon activations reported within the UK Mission Control Centres (UKMCC) Service Area or involving UK registered beacons overseas was five. Across 2018, the total number of people rescued from ELT related SAR events assisted by COSPAS-SARSAT data was nine. The benefits of saving those individuals therefore are approximately £15.3m using the average value of preventing a fatality, and with the GNSS contribution to the value assumed to be 20% this would be equivalent to a total GNSS benefit of **£3.1m**.

Economic loss

COSPAS-SARSAT's primary source of position is doppler-based. However, GNSS has been incorporated in an increasing proportion of beacons as it offers faster and more accurate positioning than the doppler-based method. In the event of a loss of GNSS, people in distress would therefore be located, but the lower accuracy will result in increased search times and potential impacts on the health of the distressed. As such the magnitude of loss from a GNSS outage is assumed to be the pro-rata value of the benefit calculation, amounting to **£0.5m**.

Drivers of change

The increase in both benefits (from **£2.0m** to **£3.1m**) and losses (from **£0.3m** to **£0.5m**) is driven by a higher number of GNSS enabled population of search and rescue beacons, with increasing numbers of devices being manufactured globally. This resulted in a greater number of people being rescued versus the time period for the previous study, hence a slight increase in both the economic benefits and losses estimated.

4.2.5 Productivity

Implementation of GNSS-enabled UAVs can demonstrate appreciable benefits across a range of applications. With the UK government's Airspace Modernisation Strategy aiming to facilitate integrated airspace across the UK, it seems likely that we will see adoption of unmanned and possibly autonomous systems being utilised to enable productivity benefits across a number of sectors.

Economic benefit

The total benefits from GNSS are estimated at **£158.5m** per annum.

Whilst many of these applications are still in development or at an early stage of implementation (e.g. drone-based delivery services, autonomous shuttles etc.) one area in which tangible benefits can be identified is within the agricultural sector. The vast majority of benefits are associated with crop and soil monitoring using UAVs with GNSS enabled precision navigation systems. The benefits are monetised through examining the improved yield for GNSS drone monitored fields for different types of crops, and by the amount nitrogen from fertiliser saved per hectare. Extrapolating this saving across the total area of arable land across the UK provides the aggregate saving. Using market values for fertiliser and crop prices allows the economic value of benefits enabled by GNSS to be calculated.

Economic loss

Manned aircraft typically feature systems with multiple levels of redundancy, while unmanned systems on the other hand would likely lack such capabilities owing to vehicle mass and size constraints. Drone-based crop monitoring would be the most severely impacted operation however, as the lack of precision navigational capabilities would prevent the precise application of fertiliser and pesticides at the optimal times. The total losses attributed to such inefficiencies in productivity amount to **£3.0m**.

Industry stakeholders have confirmed the increasing reliance of drone-based aerial monitoring in agriculture, as part of a combination of monitoring techniques such as earth observation satellites or synthetic aperture radar (SAR) imaging. Whilst the growing adoption of technological solutions may have reduced the knowledge of traditional techniques within the industry, for a longer-term outage it is feasible that alternative solutions such as plane or helicopter-based monitoring could act as a substitute for drone platforms. A seven-day outage is not deemed long enough to induce a move to these more expensive methods.

Drivers of change

This application was not modelled in the previous iteration of this report, and so the estimates of economic benefit (**£158.5m**) and loss (**£3.0m**) are entirely additional to the aviation sector's total.

4.3 Emergency Services

Emergency Services utilise GNSS at multiple stages of their operations. Emergency phone calls are located, on-the-ground resources are tracked, and responders are directed using GNSS as a crucial input. A disruption of GNSS service would mean these emergency services, including the Police, Ambulance, Fire Brigade and Coast Guard, would not be able to properly handle demand, emergency-related calls would be longer, congestion would be severe, and navigation systems would not function. Emergency Services' internal communication methods are also supported by GNSS time synchronisation functionality. Finally, the growing market for security and surveillance robotics, which are highly dependent on precise location information, are included in this section.

A number of emerging applications that utilise GNSS to some extent are not monetised due to low current penetration in the UK, though their use is anticipated to grow over the next 10 years. These include the use of drones to provide support in covert or dangerous operations, the interception of autonomous vehicles, tracking of emergency responders within buildings, Augmented Reality being used in professional training, border policing that utilises geofencing to document illegal crossings, and the use of GNSS-based positioning to efficiently follow grid-search patters during Search and Rescue missions at sea and on land.

The applications that are monetised in this section are shown below in Table 9. The annual economic value they generate and the estimated economic losses due to a one-week loss of GNSS are summarised for each.

Table 11 Emergency Services Applications

Application	Economic benefit (annual, £m)	Economic loss (7-day, £m)
Public-safety Answer Point (PSAP) caller location	5,433.0 *(+183%)*	1,560.2m (*+207%*)
Automatic vehicle and personnel location	110.4 *(+14%)*	1,968.7 (*+92%*)
Medical delivery and critical supplies	256.0	4.9
Security and surveillance robots	5.7	0.1
Total	**5,805.1 (*+187%*)**	**3,533.9 (*+131%*)**

Note: *(+%) indicates the variation in economic benefits and loss since the 2017 iteration of this report.*
Source: London Economics analysis

4.3.1 Public-safety Answer Point caller location

Emergency services immediately benefit from GNSS at the point of contact with the public. Calls received from many smartphones automatically transmit caller location to emergency response centres (also called Public-Safety Answer Points or PSAPs). Mobile phones achieve this using Advanced Mobile Location, which has been available on Android devices since 2016 and Apple devices January 2018.[59] The devices use GNSS as an input into their multi-sensor derived location to deliver accuracies in the tens of metres rather than thousands from network-based location from mobile network operators.[60] Emergency Services dispatch centres therefore have highly accurate location information that is automatically delivered for calls made from mobile phones – often the hardest calls to locate as landlines are tied to specific addresses and are hence easy to communicate over the telephone.

Economic benefit

The annual economic value generated by GNSS in PSAP caller location is estimated at **£5,433.0m**.

These benefits accrue due to reduced call and search times: call handlers only have to confirm locations rather than discussing them with callers, and emergency services responders such as police or ambulance drivers are provided with an exact destination. Data on the numbers of calls fielded by emergency services and the distribution of response times are inputs into a model of time saved due to the automatic location information from smartphones. Following the London Ambulance Service's approach[61] the value of the resulting improved response time is monetised using a Swedish study[62], which found the economic cost of an additional minute for emergency responders was €1,300 (~£880) in 2004. The majority of this value comes from the economic value of a citizen's life[63], which is itself dependent on GDP per capita. By adjusting the 2004 figure according to GDP per capita growth between 2004 and 2019[64] we arrive at an updated value per minute of approximately £990.

[59] Apple. (2018). 'Apple previews iOS 11.3'. Available at: https://www.apple.com/newsroom/2018/01/apple-previews-ios-11-3/ [accessed July 2021].
[60] European Commission. (2017). 'Pilot project on the design implementation and execution of the transfer of GNSS data during an E112 call to the PSAP'.
[61] Detailed in a May 2014 presentation that is not in the public domain.
[62] Jaldell, H. (2004). 'The Importance of the Time Factor in Fire and Rescue Service Operations in Sweden'.
[63] Jaldell, H. (2019). 'Saving lives: How Important is the Time Factor Using Fire and Rescue Services – A statistical analysis!'. Available at: https://www.msb.se/siteassets/dokument/amnesomraden/skydd-mot-olyckor-och-farliga-amnen/brandskydd/evidence-based-fire-safety_oct219/ws-henrik-jaldell-presentation-time-factor-karlstad-msb-10-oct-2019.pdf [accessed July 2021].
[64] World Bank. (2021). 'GDP per capita growth (annual %) – United Kingdom'.

Economic loss

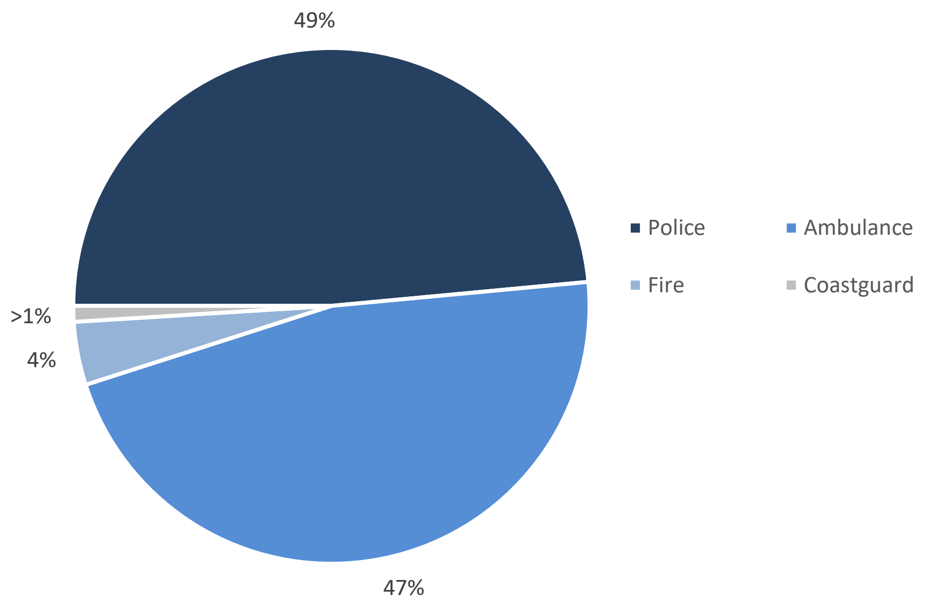
The economic impact of loss of GNSS in PSAP caller location is estimated at **£1,560.5m**.

A loss of GNSS would result in smartphones reverting to less accurate network-based Cell-ID location, meaning all benefits estimated for PSAP caller location in the 7-day period (£104.2m) would be lost.

Due to the short outage period and lack of prior warning, it is reasonable to assume that no mitigatory increase in call-handling capacity in PSAPs could be achieved during the GNSS outage. Combining this with the significant pressure on PSAPs in normal times, a likely increase in emergency calls across the UK as a result of the outage, and the requirement for operators to spend more time with each caller to ascertain their location, it is likely that a proportion of callers would fail to reach an operator at all.

In 2019 PSAPs handled around 33.1 million emergency calls.[65] Loss of efficiency in PSAPs is proxied by an assumption that 3% of the call volume in normal times would fail to reach operators, resulting in approximately 19,000 emergency calls going unanswered during the outage period. The UK Department for Transport estimates the value of preventing an accident is between £2,142 and £2,005,664 depending on severity. Using the weighted average value for all severities,[66] the value of the unanswered calls is estimated at £1,456m.

Figure 6 Share of 2019 UK Emergency Calls by service



Note: Total calls equal to approximately 33.1 million.

Source: Rossshire Journal (2019). It's 999 Day. Available at: https://www.ross-shirejournal.co.uk/news/confusion-continues-over-when-to-ring-999-survey-reveals-182732/ [accessed July 2021].

[65] Rossshire Journal (2019). 'It's 999 Day'. Available at: https://www.ross-shirejournal.co.uk/news/confusion-continues-over-when-to-ring-999-survey-reveals-182732/ [accessed July 2021].

[66] Department for Transport Statistics. (2015). 'Average value of prevention per reported casualty and per reported road accident [RAS60001]'.

Drivers of change

In the previous iteration of this report, the estimates of economic benefit (**£1,921.0m**) and loss (**£508.0m**) differ from the updated estimates presented in this report of **£5,433.0m** (benefit) and **£1,560.5** (loss).

The benefits value has most significantly been impacted by a strong increase in the penetration of smartphones with Advanced Mobile Location capability. There is also an update to the value per minute for emergency responders due to growth in UK GDP per capita.

The estimated value of economic impact of loss of GNSS has also been impacted by the change in smartphone device penetration, as well as an increase in the number of emergency calls made in a typical week.

4.3.2 Automatic vehicle and personnel location

Each branch of the modern Emergency Services interact with the public and their surroundings through operatives and vehicles that are often scattered across their service area. Police officers spend time patrolling on foot or in their vehicles, and ambulance crews often position themselves so as to be able to reach reported incidents as fast as possible. Knowing exact locations (and trajectories) allows efficient management of the resources at the Emergency Service's disposal, and GNSS underpins this capability. All UK Emergency Services vehicles are usually fitted with GNSS devices that allow centralised dispatch centres to have an understanding of where each one is.

Economic benefit

The annual economic value generated by GNSS in automatic vehicle and personnel location is estimated at **£110.4m**.

A portion of the benefits of automatic monitoring comes from the cost savings related to improved operational efficiency in the emergency services, estimated at £104.4m. By giving dispatchers oversight of their entire fleet's real-time locations, GNSS-enabled monitoring allows them to reduce downtime and prevent inefficient return trips to central base locations before heading out once more. Due to the technological impact of GNSS, the Command and Control system for emergency services requires very few staff members to monitor the location, destination, and status of all vehicles. This constitutes a substantial improvement in efficiency over historical methods which entailed physical maps and radio reports from on-the-ground emergency responders.

Further benefits materialise in the form of reduced maintenance costs, as accurate vehicle use information allows operators to service vehicles in a timely and efficient manner, preventing serious issues and costly breakdowns before they occur. Vehicles in the emergence services' fleet will be required to operate across a range of intensities, including periods of high speed on motorways and periods of many starts and stops in urban areas. Accurate knowledge of vehicle use therefore enables better maintenance programmes, generating an estimated £6.0m in benefits.

Economic loss

The economic impact of loss of GNSS in automatic vehicle and personnel location is estimated at **£1,968.7m**.

The majority of the impact comes from increased response times across the emergency services. The UK Fire and Rescue Services[67], Ambulance Service[68], and Police Service[69] field a combined 17.8 million calls per year – over 340,000 in an average week. As GNSS-enhanced fleet management becomes impossible during the outage period, it is assumed that it takes responders longer to reach incidents due to less optimal positioning and allocation to incidents by control centres. For the police and fire services it is assumed that response times increase by 2 minutes, while the ambulance service's response time is assumed to increase by 4 minutes – 50% of their targeted response time. The economic value per minute of delayed response for each service is sourced from the Swedish study[70] referenced in Section 0, giving an estimated value of £1,737m of loss over the outage period.

The operational efficiencies created by GNSS in Command and Control centres would be lost for the duration of the outage period as emergency services would be forced to revert to higher-manpower methods that rely on radio calls and marks on physical maps. There are over 200 control centres in the UK and an assumed 6 extra staff would be required 24-hours-a-day 7-days-a-week at each centre to handle the extra administrative burden in the absence of GNSS. If these people could be recruited and trained quickly and were paid a 20% premium to the minimum wage, an additional cost of £2.0m would be imposed on Emergency Services. The value created due to timely maintenance work because of accurate vehicle tracking would also be lost for the duration of the outage, as accurate and automatic vehicle usage statistics would be unavailable. This loss of value is estimated at £0.1m.

Drivers of change

In the previous iteration of this report, the estimates of economic benefit (**£96.5m**) and loss (**£1,023.5m**) differ from the updated estimates presented in this report of **£110.4m** (benefit) and **£1,968.7m** (loss).

The benefits value has most significantly been impacted by an increase in the volume of calls that emergency services must respond to, while a small portion of the change was induced by an increase in the total emergency services fleet size that requires maintenance spending. Reliance on GNSS remains unchanged in our model since 2017, a conservative assumption that has been validated by interviewed stakeholders.

The estimated value of economic impact of loss of GNSS has been impacted by the same changes, with the increase in call volume again explaining the majority of the change. Furthermore, an update to the value per minute for emergency responders drives a substantial portion of the change.

4.3.3 Medical delivery and critical supplies

The movement of medical and otherwise critical supplies across the UK is completed, in part, by the Emergency Services themselves. By their very nature, it is crucial that the supplies of this type are delivered in a timely manner. Delays have severe health implications, and logistical hold-ups can therefore cost lives. With much of the navigation devices, logistical monitoring, and hence distributional efficiencies in the current system enabled by GNSS, the UK's medical and critical supplies delivery depends on GNSS to function at the required level.

[67] UK Home Office. (2021). 'Fire statistics data tables'.
[68] National Health Service. (2020). 'Ambulance Quality Indicators Data 2019-20'; StatsWales. (2020). 'Ambulance Quality Indicators by area and month'; Department of Health. (2019). 'Northern Ireland Hospital Statistics: Emergency Care 2018/19'.
[69] College of Policing. (2015). 'College of Policing analysis: Estimating demand on the police service'.
[70] Jaldell, H. (2004). 'The Importance of the Time Factor in Fire and Rescue Service Operations in Sweden'.

Economic benefit

The annual economic value generated by GNSS in medical delivery and critical supplies is estimated at **£256.0m**.

Benefits are created by the use of GNSS in this high-value logistics domain as it improves health outcomes, on average, for the 8.6 million incidents that the emergency services respond to each year. Ambulance Service data on incidents they responded to in 2019, including the severity of injuries encountered, is a vital input into a model of the economic damage suffered in incidents where they are called. Different severities of injury are monetised using Department for Transport estimates that take into account lost output, medical and ambulance costs, and human costs.[71] The value of GNSS' role in effective interventions is then estimated as being a very small portion of the benefit of moving incidents to a less severe rating – a 'serious' injury incident with an economic cost of £191,463 down to a 'slight' injury incident with a cost of £14,760, for example.

Economic loss

The economic impact of loss of GNSS in medical delivery and critical supplies is estimated at **£4.9m**.

A GNSS outage would result in the loss of all economic benefits associated with improved logistics in medical delivery and critical supplies. The estimated loss figure is therefore the 7-day pro rata benefits amount.

Drivers of change

This application was not modelled in the previous iteration of this report, and so the estimates of economic benefit (**£256.0m**) and loss (**£4.9m**) are entirely additional to the Emergency Services sector's total.

4.3.4 Security and surveillance robots

As the technical capabilities of remotely controlled or entirely automatic machines improve, so does their usefulness to Emergency Services and adjacent services. A basic requirement for many robotics applications is the ability to move through the physical environment, which requires precise positioning. GNSS can, in conjunction with RTK technology, provide a positioning solution precise enough for robots to operate at centimetre-level accuracies. This in turn makes them safe and effective in a number of security and surveillance applications.

Economic benefit

The annual economic value generated by GNSS in security and surveillance robots is estimated at **£5.7m**.

The business case for security and surveillance robots generally relies on the saved cost of human security workers, and so the benefits are considered to be the reduced cost that robots generate. Of course, robots are not currently capable of completing many tasks within the remit of security and surveillance, and so it is assumed that only 5% of manpower can be replaced with robotics. Furthermore, even where it is possible, it is assumed that only 5% of potential users decide in favour

[71] Department for Transport Statistics. (2015). 'Average value of prevention per reported casualty and per reported road accident [RAS60001]'.

of using them due to unfamiliarity or security concerns. Finally, robots are not free, and in particular come with a significant initial cost and ongoing running costs – it is estimated that over the course of a year they can save 50% of the cost on equivalent amounts of manpower. With almost 200,000 employed as security guards and in related occupations in the UK[72] and an industry average salary just under £24,000[73], security and surveillance robots' value generated is estimated as equivalent to replacing 237 full time security workers.

Economic loss

The economic impact of loss of GNSS in security and surveillance robots is estimated at **£0.1m**.

Security and surveillance robots typically require constant GNSS-provided location information to ensure safe operation. This means that a GNSS outage would immediately result in a loss of benefits for the 7-day period considered – the value reported is the 7-day pro rata share of annual benefits.

Drivers of change

This application was not modelled in the previous iteration of this report, and so the estimates of economic benefit (**£5.7m**) and loss (**£0.1m**) are entirely additional to the Emergency Services sector's total.

4.4 Finance

The financial sector requires timestamping of transactions to ensure the prevailing price at the time of the transaction is charged. This is true of both stock exchanges and financial trading centres in banks. The European MiFID II regulation[74] defines accuracies of timing with respect to UTC that are required for an entity to be allowed to continue operating. High street banks are required to be able to timestamp activities with an accuracy of at least 1 millisecond with respect to UTC, while high-frequency traders (HFTs) need accuracy of 100 microseconds. In high-frequency trade, the accuracy with which a transaction can be timestamped has significant impact on the amount of money a trader can earn from a transaction. Therefore, while the legal requirement may be 100 microseconds, competitive pressures may lead a HFT to pursue timestamping as precise as 100 nanoseconds. Thus, the equipment used by high-frequency traders has sophisticated oscillators for holdover, ensuring that trade can continue long after an external timing source is lost. Similar equipment is present in stock exchanges.

ATMs do not receive timing information from GNSS, but certain payment services, such as Apple pay, rely on GNSS as an input in a risk assessment that ultimately decides whether a transaction is approved by card issuing companies. However, this geo-fencing technology for fraud prevention has not been monetised in this report as its function is assumed to be adequately met by redundant location technologies in the event of a loss of GNSS.

[72] Office for National Statistics. (2020). 'Annual Population Survey – Employment by occupation'.
[73] Office for National Statistics. (2020). 'Annual Survey of Hours and Earnings (ASHE)'.
[74] European Securities and Markets Authority. (2018). 'MIFID II'. Available at: https://www.esma.europa.eu/policy-rules/mifid-ii-and-mifir [accessed July 2021].

Table 12 Finance applications

Application	Economic benefit (annual, £m)	Economic loss (7-day, £m)
Infrastructure (atomic clocks)	0.3 *(+200%)*	-
Infrastructure (conditioning)	1.4 *(+180%)*	-
Total	**1.7 *(+183%)***	**-**

Note: *(+%) indicates the variation in economic benefits and loss since the 2017 iteration of this report.*
Source: London Economics analysis

4.4.1 Infrastructure (atomic clocks)

The relevance of GNSS in this system is due to its use as the external source for timing and synchronisation of financial applications for decades. It also has the added advantage of being a global resource, ensuring that all trade undertaken by different sites across the globe are traceable to the same reference time.

The benefits of GNSS in the financial sector reflect savings on alternative timing infrastructure. This includes reduced spending on atomic clocks and the capital costs of their conditioning. Most clocks employed for holdover capacity in the financial sector are rubidium atomic clocks, with some firms opting for higher-end caesium atomic clocks.

Economic benefit

The annual economic value generated by GNSS in infrastructure (atomic clocks) is estimated at **£0.3m**.

These benefits encapsulate savings in infrastructure costs on atomic clocks of **£0.3m** (assuming prices are comparable, the savings derive from the longer lifetime of a GNSS device versus an atomic clock).

Economic loss

The economic impact of loss of GNSS in atomic clock infrastructure is estimated at **£0.**

Consultations have suggested robust holdover capability within financial institutions. The implications of loss of GNSS have been 'tested' on a small scale using a jamming detector at the London Stock Exchange, which identified more than 1,000 events of at least 30 seconds in the year to March 2016. The longest such event was 42 minutes.[75] This proves the London Stock Exchange has holdover capability that is sufficient for that length of disruption. Given the concentration of banks nearby and the paucity of public news concerning any disruptions to trade, it can be inferred that banks have similar holdover capacity.

Related research has indicated holdover capacity via atomic clocks sufficient to provide up to 30 days of holdover capability before falling to comply with current synchronisation requirements of 100 microseconds for HFT transactions.[76] Expert consultations confirmed that rubidium or caesium clocks would provide a maximum holdover capability for 30-45 days without GNSS. Thus, the

[75] Curry, C. (2016). 'eLoran – The Future of Resilient PNT' (Conference presentation at ITSF, 1-3 November 2016)
[76] National Institute of Standards and Technology. (2019). 'Economic Benefits of the Global Positioning System (GPS)'. Available at: https://www.rti.org/sites/default/files/gps_finalreport.pdf [accessed July 2021].

difference between a 5-day and 7-day GNSS outage period is insignificant in terms of the limits of holdover capability.

However, expert consultees suggested that certain critical infrastructure in the finance sector may use GPS-only receivers, leaving these systems at elevated risk for outage compared to systems able to draw on additional GNSS signals (such as those from GLONASS, BeiDou, Galileo). Expert consultations suggested that 30-40% of GNSS receivers currently operating within UK financial institutions are GPS-only. Consultees suggested a reticence to update these receivers to multi-constellation configurations given their sufficient performance over the last 20 years. For institutions that have chosen to update, GPS + Galileo configurations are common, while GLONASS and BeiDou configurations have been avoided, with those involved in these decisions citing security concerns.

Heterogeneity of holdover capability remains a key area of investigation for GNSS loss within the finance sector. Financial institutions remain reluctant to go on the record regarding their current holdover capacity. However, expert consultation with industry suppliers suggested 90% of institutions have at least rubidium atomic clock-level holdover capacity. The level of holdover coverage is assumed to be even greater when considered in terms of total assets, as consultees suggested all large and name-brand institutions meet at least this standard. Those opting for lower specification holdover devices are typically relatively small traders, and thus a failure of their holdover capability is assumed to have minimal economic impact.

Drivers of change

In the previous iteration of this report, the estimate of economic benefit was **£0.1m** while the updated estimate presented in this report is **£0.3**. Losses were not assessed in either case.

The benefits value has most significantly been impacted by changes in volumes/activity of stock exchanges and bank applications between 2017 and 2019.

4.4.2 Infrastructure (conditioning)

The benefits of GNSS from savings on alternative timing infrastructure also stem from avoided capital costs of conditioning. Conditioning refers to the cost of connecting these atomic clocks to a reliable alternative source of synchronised time, and includes labour, the cost of cabling, and maintenance.

Economic benefit

The annual economic value generated by GNSS in infrastructure (conditioning) is estimated at **£1.4m**.
These benefits reflect saved capital costs in the conditioning of the aforementioned atomic clocks. GNSS clocks are synchronised as part of operation and would not require this periodic synchronisation. Using the same ratio of ratio of atomic clock benefits to capital investment reduction benefits as derived for Energy (Section 4.8.5) and Telecoms (Section 4.8.7) of 4.5x[77], the savings on conditioning are estimated to be **£1.4m.**

[77] This figure is maintained from the 2017 London Economics report 'The economic impact on the UK of a disruption to GNSS'. It reflects the relative cost of connecting and maintaining cable, which is necessary for the operator to provide an alternative delivery mechanism of precise time (e.g. using synchronised Ethernet), to each node in the network, in the absence of GNSS.

Economic loss

The economic impact of loss of GNSS in atomic clock infrastructure (conditioning) is estimated at **£0.** This figure corresponds to the £0 loss figure for the atomic clock infrastructure, as consultations have suggested holdover capacity across the sector in the event of a 7-day outage is sufficient. There are no additional conditioning requirements or costs during the outage period.

Drivers of change

In the previous iteration of this report, the estimates of economic benefit were (**£0.5m**) and loss (**£0**) while the updated estimates presented in this report are **£1.4** (benefit) and **£0** (loss).

4.5 Rail

A wide array of core functions in the UK rail network rely on knowledge of train position to manage operations safely and efficiently. GNSS is widely utilised to support positioning, navigation, and timing-dependent applications that create increased safety for passengers and workers, financial and environmental efficiencies for operators, and heightened security for commercial users.

While rail is an area of high interest for developers of applications that utilise GNSS, a number of applications are not monetised in this report. Some of these applications are not monetised separately to avoid double-counting: Passenger Information systems, Train Monitoring and Diagnosis, and Signalling are considered captured by other, monetised applications. Further, emerging applications such as management of emergencies on rail are covered in Emergency Services (Section 4.3. Finally, the benefits of a GNSS-enabled Track Access Billing system are not monetised due to low uptake of this application at the time under consideration.

The applications that are considered in this section are shown below in Table 9. The annual economic value they generate and the estimated economic losses due to a one-week loss of GNSS are summarised for each.

Table 13 Rail applications

Application	Economic benefit (annual, £m)	Economic loss (7-day, £m)
Driver Advisory Systems	2.9 (*-73%*)	0.1 (*-62%*)
Fleet Management	1.7 (*+1,419%*)	0.0
Cargo Monitoring	0.1	0.0
Infrastructure Monitoring	14.8	0.9
Automatic Selective Door Operation	Not assessed	38.7 (*+94%*)
Train Cancellations	Not assessed	100.1 (*+11%*)
Total	**19.5 (*+79%*)**	**139.9 (*+27%*)**

Note: Values of "0.0" represent non-zero quantities that are less than 50,000. *(+%) and **(-%)** indicate the variation in economic benefits and loss since the 2017 iteration of this report.*
Source: London Economics analysis

4.5.1 Driver Advisory Systems

UK train drivers are guided by a number of automatic measures and advisory systems. One key type, Driver Advisory Systems (DAS), allow intelligent driving of high-speed and freight trains via the use of GNSS-provided data. This reduces traction energy consumption as well as wear and tear on brakes. Furthermore, connected driver advisory systems (C-DAS), which are implemented in the UK, allow a higher throughput of trains on the same rail network. The connected systems therefore use GNSS to improve utilisation of existing rail network capacity.

Economic benefit

The annual economic value generated by GNSS in Driver Advisory Systems is estimated at **£2.9m**.

Driver Advisory Systems and the intelligent driving they allow mean drivers and their employers save fuel and reduce wear-and-tear as they optimally make adjustments throughout the journey. C-DAS introduce a communication link to the area traffic management system, facilitating a reduction in stops at red signals, even less energy consumption, and further efficiencies in brake wear-and-tear. The share of these cost savings that can be attributed to GNSS are estimated at a little over £1.1m. C-DAS also allows greater throughput on the existing rail network as adherence to traffic management is more accurate. The share of benefits of these capacity improvements attributable to GNSS is estimated at £0.6m. Finally, the GNSS-induced reduction in fuel use due to improved efficiency in train operation results in environmental benefits as less CO_2 is emitted. Pricing this using a measure of the Social Cost of Carbon results in a value of almost £1.2m.

Economic loss

The economic impact of loss of GNSS in Driver Advisory Systems is estimated at just **£56k**.

Both DAS and C-DAS are dependent on high-frequency position and timing information to remain connected to traffic management and to determine their location and velocity in order to facilitate optimal operation. The marginal benefits of the systems is therefore all lost over the seven day period, as there are no direct back up systems that can be put in place within the seven day outage.

Drivers of change

In the previous iteration of this report, the estimates of economic benefit (**£10.8m**) and loss (**£148k**) differ from the updated estimates presented in this report of **£2.9m** (benefit) and **£56k** (loss).

The benefits value has most significantly been impacted by two key updates. First, the dependency on GNSS among Driver Advisory Systems has decreased as alternatives with a lower reliance on GNSS have come to market. This results in a reduced GNSS share of benefits for brake wear-and-tear and capacity increases. Next, an increase in the scientific consensus on the Social Cost of Carbon actually results in an increase in the environmental benefits from reduced CO_2 emissions.

The estimated value of economic impact of loss of GNSS, measured in both cases as a loss of benefits for the outage duration, has been impacted by two changes. First, the reduction in benefits outlined above means that the economic losses are also smaller. Second, the change in outage period implies an increased loss as DAS would be offline for longer.

4.5.2 Fleet management

The ability to accurately track the location of the locomotives and wagons that make up a rail fleet generates a range of benefits for operators. GNSS-based fleet management systems are widely used in the UK to monitor, plan, and optimise rail transportation for both passengers and goods.

Economic benefit

The annual economic value generated by GNSS in fleet management is estimated at **£1.7m**.

A further portion of economic benefits are generated in a similar manner to Driver Advisory Systems, though at a higher level of train management. While DAS optimise the operation of individual trains, GNSS-based fleet management systems can optimise operations of the entire fleet. Greater overall efficiency leads to reduced CO_2 emissions, the social benefits of which are monetised at £1.7m. Furthermore, there are further, though relatively small, cost savings for operators due to more efficient use of their rail fleet, resulting in an estimated saving of £51,000 on rolling stock maintenance. Finally, a small reduction in serious accidents such as derailments, can be credited to successful fleet management that is underpinned by GNSS. The benefits of a slight reduction in the expected number of lives lost in derailments each year that can be attributed to the GNSS component of fleet management systems are negligible due to the rarity of such events. While any individual event that is prevented is extremely valuable, the annualised value is close to zero.

Economic loss

The economic impact of loss of GNSS in fleet management is estimated at just **£33,000**.

GNSS-based fleet management systems improve operational efficiency across the rail network, but are not essential to operation. During a GNSS outage the marginal benefits they create would be entirely lost, and it is unlikely that the demand for an immediate replacement would be sufficient for investment in an alternative method of fleet tracking and management. The estimated figure therefore comes from the seven-day equivalent (pro rata) of estimated annual benefits.

Drivers of change

In the previous iteration of this report, the estimate of economic benefit (**£0.1m**) differs from the updated estimate presented in this report of **£1.7m**. The economic loss from an outage was not monetised previously, and so the loss estimate (**£33k**) is entirely additional to the Rail sector's total.

The benefits value has most significantly been impacted by a notable increase in the scientific consensus value of the Social Cost of Carbon, which in turn results in an increase in the environmental benefits from reduced CO_2 emissions.

4.5.3 Cargo monitoring

Rail plays an important role in UK freight logistics: 2016 estimates[78] put rail's share of the UK's freight market at 9%. One trend that is spreading across all modes of transportation in logistics is the ability to track freight, with major investments into GNSS-enabled monitoring technologies that provide real-time rail wagon location updates. The logic for these investments is captured by GE Transportation's chief digital offiver Laurie Tolson, who explains "If you can track it, you can count on it".

Economic benefit

The annual economic value generated by GNSS in cargo monitoring is estimated at **£0.1m**.

Cargo monitoring generate benefits for customers of rail freight who can track their goods and gain peace of mind. GNSS supports these benefits by providing accurate, cost-effective, and high-frequency information on the location of rail freight. The benefits are estimated by considering what it is they are primarily gaining peace of mind from: theft. Data from the Transported Asset Protection

[78] Government Office for Science, MDS Transmodal. (2019). 'Understanding the UK Freight Transport System'.

Association on UK cargo crime frequency, value, and rail's share of these allow modelling of the rail cargo theft that is prevented or recovered due to GNSS-enabled cargo monitoring.

Economic loss

The economic impact of loss of GNSS in cargo monitoring is negligible.

The additional security afforded by GNSS-enabled cargo monitoring operates on two different levels. First, an improved ability to recover stolen goods and reduced response times to unusual rail freight movements are wholly dependent on functioning GNSS. A 7-day outage, then, would render this extra layer of security over and above existing physical security checks entirely ineffective and a portion of the benefits generated would be lost. However, a second effect of cargo monitoring technology is as a deterrent. Some would-be-thieves who are aware such systems are in place may have been dissuaded from targeting rail cargo, leading them to develop skills and knowhow relevant to other targets. The news that a GNSS outage was underway would not necessarily lead them to immediately switch to targeting rail cargo that is now without GNSS-enabled cargo monitoring in place. This means that some portion, assumed to be 50%, of the pro rata economic benefits of cargo monitoring systems would remain during the outage period. The resulting value is marginal at best, due in part to the resilience to an outage in terms of outcome (if not in terms of continued technical functionality).

Drivers of change

This application was not modelled in the previous iteration of this report, and so the estimates of economic benefit (**£0.1m**) and loss are entirely additional to the Rail sector's total.

4.5.4 Infrastructure monitoring

The UK rail network consists of over 10,000 miles of track[79], 2,567 stations[80], almost 11,500 locomotives[81], and countless other components. To ensure safe and efficient operation across the network this infrastructure must be maintained at an acceptable standard, which in turn requires monitoring to identify issues in a reliable and timely manner. Historically this monitoring task has been completed by workers manually inspecting infrastructure, but GNSS can alleviate the need for some portion of this effort by automatically collecting data on infrastructure performance and thus highlighting anomalies as they arise. A key technology underpinning this automation is Plain Line Pattern Recognition (PLPR), which uses cameras mounted underneath trains to capture GNSS-geotagged high-frequency images of the track to identify potential defects for manual review. PLPR-equipped trains have replaced manual inspections on thousands of miles of UK track, with plans for the technology to annually survey almost one million (975,000) miles of railway track across Britain until 2024.[82]

[79] UNECE. (2018). 'United Kingdom'. Available at: https://w3.unece.org/CountriesInFigures/en/Home/Index?countryCode=826 [accessed July 2021].
[80] Office of Rail and Road. (2020). 'Estimates of Station Usage'. Available at: https://dataportal.orr.gov.uk/media/1906/station-usage-2019-20-statistical-release.pdf [accessed July 2021].
[81] European Commission. (2020). 'EU Transport in Figures - Statistical pocketbook 2020'.
[82] Network Rail. (2019). 'How cutting-edge track technology is reducing delays for passengers'. Available at: https://www.networkrail.co.uk/stories/how-cutting-edge-track-technology-is-reducing-delays-for-passengers/ [accessed July 2021].

Economic benefit

The annual economic value generated by GNSS in infrastructure monitoring is estimated at **£14.8m**.

Benefits are generated in part due to cost savings for infrastructure owners. In Great Britain, Network Rail spent more than £1.5bn on maintenance in the 2018/19 financial year, while NI Railways in Northern Ireland spent an estimated £14m on their comparatively smaller rail network. With a conservative assumption that these costs would be 0.5% greater without GNSS inputs into infrastructure monitoring, an economic benefit of £7.7m is estimated.

A further source of benefits is the greater protection of human health that properly maintained infrastructure brings. The Department for Transport records injury numbers and severities in UK rail accidents.[83] Conservative estimates of the proportion of accidents due to infrastructure defects and the share of infrastructure issues that are remedied before they cause accidents because of GNSS, validated by stakeholder interviews, are used to model the number of prevented rail injuries and casualties. The benefit of these avoided injuries and deaths is monetised at £7.1m using time-adjusted economic values for individuals in accidents provided by the Department for Transport.[84]

Economic loss

The economic impact of loss of GNSS in infrastructure monitoring is estimated at **£0.9m**.

The benefits generated are intrinsically linked to the high-frequency and wide-coverage monitoring that GNSS enables. For this reason no immediate and cost-effective backup system exists, meaning that all of the seven-day pro rata benefits, estimated at £0.3m, are lost during outage period.

Network Rail's Kelley Quirk[85] estimates that PLPR technology reduces passenger train delays nationally by around 500,000 minutes per year. It is assumed that these train delays would materialise during a GNSS outage as the geotagging functionality of PLPR renders its fault alerts unusable due to uncertainty over the fault locations. Over the course of a 7-day outage this materialises as just under 10,000 minutes or 160 hours of train delays across Britain. With an average of around 120 passengers per train[86,87], the total passenger time lost to delays is almost 20,000 hours over the outage period. It is assumed that that 2/7 of the journeys during the outage period are for leisure purposes[88]. Furthermore, the value of leisure time is assumed to be one third of 'business time', with the value of business time measured at the average hourly pay rate for UK workers. Valuing leisure time at one third of this average hourly pay rate yields a conservative estimate of £28,000 of lost utility value due to train delays caused by a 7-day GNSS outage. As well as lost leisure time, businesses also suffer losses as their workers are delayed. Assuming that 90% of the delays are lost productive time (some workers may be able to work remotely from platforms or will work later to cover their delayed time once they do arrive), and that 5/7 of the journeys are for business purposes, the equivalent full-time equivalents (FTEs)[89] lost is equal to 6.52. Valuing this

[83] Department for Transport. (2021). 'Rail statistics'. Available at: https://www.gov.uk/government/collections/rail-statistics [accessed July 2021].
[84] Department for Transport. (2012). 'Reported Road Casualties in Great Britain: 2012 Annual Report'.
[85] Network Rail. (2019). 'Efficient and dependable partner'. Available at: https://www.networkrail.co.uk/industry-and-commercial/efficient-and-dependable-partner [accessed July 2021].
[86] Eurostat. (2021). 'Train-movements, by type of vehicle and source of power; RAIL_TF_TRAVEH'.
[87] Eurostat. (2021). 'Passengers transported; RAIL_PA_TOTAL'.
[88] This value is a combination of the observation that two of the outage period's seven days are weekend days and hence traditionally leisure-oriented, and the understanding that while many individuals do work during weekends, these weekend-worker journeys are approximately counterbalanced by leisure journeys taken during the 5-day traditional work-week period.
[89] One FTE is equivalent to the number of hours in a full-time workweek.

resulting loss in productive time using the 2019 average UK labour productivity of slightly more than £50,000 gives an estimated £330,000 in lost productive output. The total loss generated from additional delays, then, is estimated at £0.4m.

Maintenance costs increase as either manual checks are done or they are skipped for the week, increasing maintenance costs in the long run as problems have longer to escalate. The loss of one week of proactive monitoring-informed maintenance work is assumed to increase long run maintenance costs by the proportion of one week's normal spend that is informed by GNSS infrastructure monitoring (0.5%), so that the equivalent of an extra week of maintenance work has to be funded on top of the missed week's work being completed at a later date. One average week's spend on UK rail infrastructure maintenance that is informed by GNSS infrastructure monitoring is equal to 0.5% of £29.5m, or approximately £0.1m.

The risk to human health is similarly increased both during and immediately following the outage period as potential infrastructure problems go undiscovered and have time to escalate to dangerous levels before maintenance can be carried out. Assuming that the risk is increased in proportion to the outage period and a subsequent one-week backlog period before monitoring and maintenance can be brought back up to date, an additional one-week (or 1/52) increase in health incidents is monetised at approximately £0.1m.

Drivers of change

This application was not modelled in the previous iteration of this report, and so the estimates of economic benefit (**£14.8m**) and loss (**£0.9m**) are entirely additional to the Rail sector's total. Note that the aggregated loss figure does not precisely equal the sum of its described parts due to rounding.

4.5.5 Automatic selective door operation

Passenger trains must open their doors to allow passengers to embark and disembark at each station the train calls at. In many cases it is only appropriate to open doors on one side of the train to allow safe exit to the platform, and where the platform is shorter than the train some doors on the correct side must remain closed. In the UK, a mature application of GNSS is an input into a system that determines the station location, looks up the correct doors to open in a database, and automatically opens them without human intervention. Human drivers are still able to open train doors, but only after a system restart and manual input of the station name, entailing an estimated one-minute delay per station.

Economic benefit

The annual economic value generated by GNSS in door control is not monetised in this report.

Economic loss

The economic impact of loss of GNSS in door control is estimated at **£22.6m**.

In the case of a GNSS outage, the one-minute delay for a manual override by a driver described above would occur at every single station a train stops at. Using government data on rail stations[90]

[90] Office of Rail and Road. (2020). 'Estimates of Station Usage'. Available at: https://dataportal.orr.gov.uk/media/1906/station-usage-2019-20-statistical-release.pdf [accessed July 2021].

and passenger behaviour[91] we model that the average rail journey takes a passenger through 7 stations in addition to their origin and destination stations, bringing the total to 9 stations where they would experience delays due to failure of the door control system. There were slightly more than 1.75 billion rail journeys in 2019[92], which combines with the proportion of track served by driver-only operations (30%) to give a loss of passenger time equivalent to 1.2m passenger hours over the outage period. The economic loss is then calculated based on the value of this time, noting differences in the value of time for both leisure and work activities.

Considering leisure activities firstly, 2/7 of journeys during the outage period are for leisure purposes. Following Section 4.5.4 and therefore valuing leisure time at one third of 'business time', and hence at one third of the average hourly wage rate, yields a conservative estimate of £1.8m.

In addition to the passenger leisure time that is lost, the wider economy also suffers as workers are delayed and hence prevented from working by the duration of the delays. Again following the methodology in Section 4.5.4, the equivalent FTE of the remaining 5/7 of the 1.2m lost passenger hours is 644. Furthermore, we assume that only 90% of this time is truly lost productivity, as some workers will be able to work productively while delayed (e.g. by making calls or working on laptops) and some workers will make up for lost time once they eventually arrive at their place of work.[93] Valuing the resulting loss in productive time using the 2019 average UK labour productivity of slightly more than £50,000 gives an estimated £20.9m reduction in output due to lost productive time.

Drivers of change

In the previous iteration of this report, the estimate of economic loss (**£19.9m**) differ from the updated estimate presented in this report of **£22.6m**.

The estimated value of economic impact of loss of GNSS has been impacted by a shift in consumer behaviour: the average rail journey is now longer, passing more stations and hence being more impacted by station-by-station delays. Of further note is the impact of lengthening the outage period under consideration. Many workers, such as those in the retail sector or Emergency Services, continue to work on weekends, meaning that productivity losses continue to accumulate throughout the entire 7-day period.

4.5.6 Train cancellations

For ordinary people, the clearest impact of a GNSS outage in the UK would be in the form of cancelled trains. Cancellations are inevitable as inefficiencies combine across the sector due to GNSS-based systems failing, resulting in increasing delays and ultimately cancelled trains. The economic impact would be felt both by businesses in lost value and by private individuals in lost personal time.

[91] Department for Transport. (2020). 'National Travel Survey'.

[92] Department for Transport statistics. (2020). 'Length of national railway route at year end, and passenger travel by national railway and London'.

[93] The long-term effect of the Covid-19 pandemic on UK working practices may be such that the workforce is far more resilient to transport delays such as those described here, due to an increase in flexible working and newly-developed 'working from home' capabilities. Whether the technology infrastructure that underpins this way of working would be impacted during a GNSS outage remains a topic for future research, as the 2019 'business-as-usual' working practices that this study focuses on do not include the changes described.

Economic benefit

As this application is constructed as a general category for the ultimate impact of a number of GNSS outage effects on the Rail industry, there are no monetised benefits.

Economic loss

The economic impact of loss of GNSS in reducing train cancellations is estimated at **£189.2m**.

The losses that private individuals experience are estimated using the financial value they would be owed for their time from rail companies. The estimated average price of a single UK train ticket in 2019 was £5.79[94] and we assume that the GNSS outage event causes a reduction in rail network efficiency such that 10% of trains are cancelled. These combine with the total number of rail journeys expected in a typical week to give an estimated loss for rail operators of £16.0m over the outage period.

In addition to this private individual loss, there are further economic losses due to delayed workers. Utilising the same ratio of wider economy losses to private individual losses as identified in Section 4.5.5 (£20.9m:£1.8m, or approximately 12:1), the value of lost production from these train cancellations is estimated at £189.2m.

Drivers of change

In the previous iteration of this report, the estimate of economic loss (**£90.4m**) differ from the updated estimate presented in this report of **£189.2m**.

The estimated value of economic impact of loss of GNSS has been impacted by three key changes. First, by taking the share of passenger journeys that are for leisure and business into account (assumed at 2/7 and 5/7 respectively – see footnote 88 for more detail) the ratio of business to leisure losses has almost doubled. Second, pre-Covid-19 shifts in passenger behaviour to longer and more rail journeys mean the impact of cancellations is felt by more people and hence has a larger economic impact. Finally, small increases in average economic productivity since 2017 have a meaningful effect on the total estimated value when tens of millions of journeys are affected by the GNSS outage.

4.6 Maritime

The maritime sector is one of the most GNSS-dependent sectors. Position, Navigation, and Timing (PNT) data are used at all stages of marine journeys for navigation and safety purposes, from oceanic and coastal navigation to manoeuvres in ports. On the shore, GNSS is used to manage cargo (handling and customs operations) and keep track of vessels.

GNSS is the principal source of PNT for ships and most vessels include several GNSS-integrated systems. These include Automatic Identification Systems (AIS) used to locate ships at sea, radar, and gyrocompasses.

[94] The value was identified as £5.46 in 2017 in: National Rail. (2017). 'About your rail fare'. This figure has been adjusted to 2019 prices.

Ports and logistics operations heavily rely on GNSS that enables the efficiencies that allow UK retailers and manufacturers to operate with limited warehousing facilities using 'just-in-time' and saving costs.

Our study of the maritime sector includes 28 current GNSS use cases and 3 future use cases. The applications of GNSS underpinning these use cases are used to support critical national infrastructures and professional and industrial activities as well as support search and rescue operations. Some use cases are not evaluated in detail as they are less vulnerable to GNSS outages.

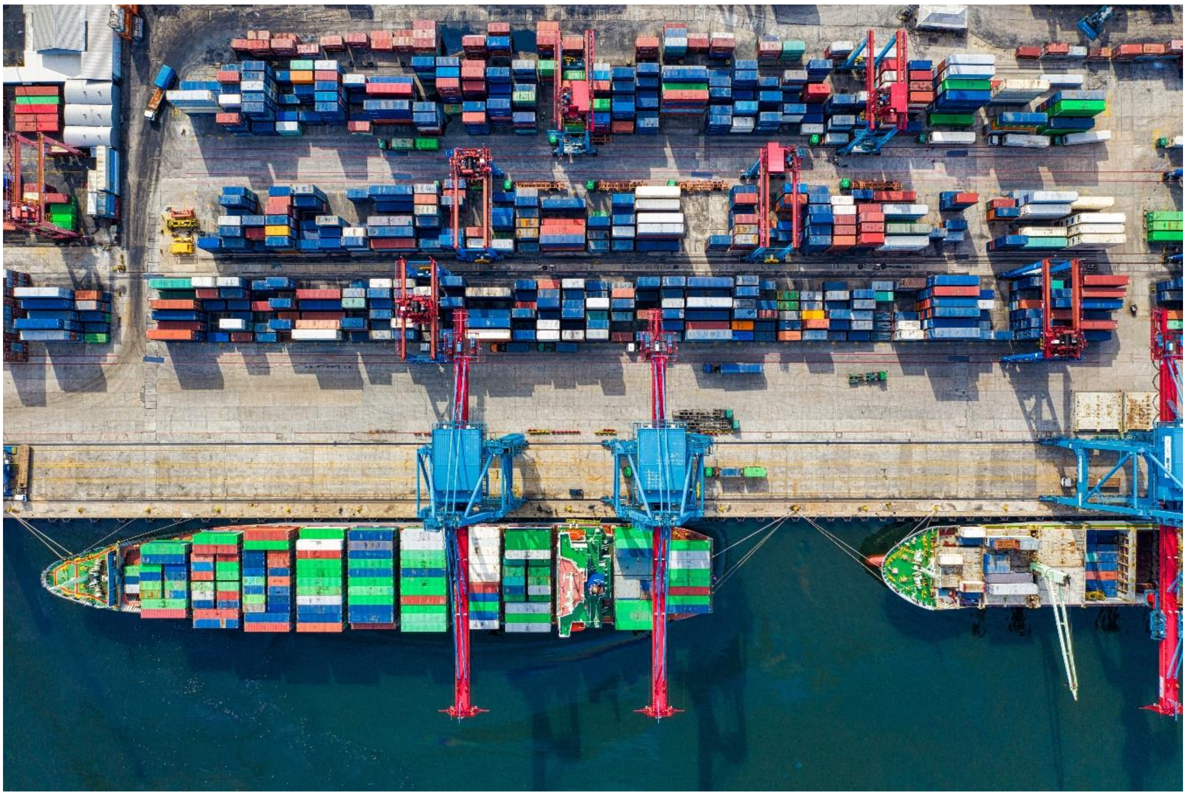


Photo courtesy of Tom Fisk. Available at: https://www.pexels.com/photo/birds-eye-view-photo-of-freight-containers-2226458/.

Current use cases (included in GNSS Loss 1.0)

The majority of current applications are mostly found in navigation. A typical example is providing aid to navigation management (buoys and lighthouses) to help maritime pilots navigating in congested areas. Buoys define shipping lanes and use GNSS timing information to synchronise their lights, offering visual support to navigators.

Throughout the whole journey, AIS data is sent and collected by all vessels and coastguards to maintain safety at sea. The AIS data collected on the shore helps to monitor the flow of vessels, and avoid accidents.

At sea, ships receive similar data to increase the awareness of navigators. PNT data provides information about the relative location of other ships as well as critical information about the seafloor and the presence of offshore infrastructures. This data is even more important when weather and visibility deteriorate.

As a ship approaches the coastline, AIS information about other ships becomes increasingly important. Higher congestion increases the risk of collision. Close to landmasses, traffic is essentially parallel to coastlines forcing all navigators to use the same route and increasing the density of vessels. The ocean depth also reduces while ships are closer to land, and precise location information used in conjunction with maps of the seafloor is required to avoid damage to ships, crew, and the ecosystem (such as oil spills)[95]. Traffic routing systems and scientific or industrial activity (Blue Economy) on the continental shelf are encountered frequently in the coastline approach phase of navigation, including increases in the presence of marine protected areas.

In the case of merchant navigation (container ships, bulk carriers, etc.), the port approach phase marks the transition between open waters and narrow shipping lanes. The nature of the waterway, the physical characteristics of the vessel, the need for frequent manoeuvring of the vessel to avoid collision, and the greater risk of grounding danger impose more stringent requirements for accuracy and for real-time guidance information than for the coastal phase. The fundamental problem is that of precise navigation of large seagoing vessels in narrow channels between the transition zone and their intended mooring. In certain approaches the services of a maritime pilot are required.

Experienced pilots usually board the ship to support navigators with portable pilot units (PPU). These units provide critical information about the surroundings of the ship. The pilot of a vessel in restricted waters or within a port must direct its movement with great accuracy and precision to avoid running the ship aground in shallow water, hitting submerged or partially submerged obstacles, or colliding with other craft in congested waterways. Unable to turn around and severely limited in the ability to stop to resolve a navigation problem, the pilot of a large vessel may find it necessary to hold the total error in navigation within limits on the order of a metre while navigating in this environment.

The berthing and mooring of merchant ships is usually accompanied by tugs and pushers. Tugs and pushers provide additional manoeuvring capability to large vessels in port operations. They require precise positioning data for similar reasons to the pilotage phase. Shallow waters represent a great danger to infrastructure and crew, and manoeuvring support must be carried out with extreme precision.

The cargo handling operations depend on the type of cargo as well as the port. In larger ports, container terminals can be automated, and the cranes used in this automated process rely on GNSS for precise positioning of containers.

Vessel traffic services (VTS) use PNT data to improve safety and efficiency of maritime activities. By providing continuous information about the status of shipping lanes, congestion, and potential accidents, VTS contributes to maximising the economic throughput of the shipping industry. It also keeps track of movement of unauthorised cargo, making waterways safer and keeping them under control of governments. VTS always keeps track of vessels, making it an additional source of safety.

All UK commercial fishing vessels of length 12m or more must be fitted with a government-approved GNSS tracking device. The device allows a vessel to be automatically located and identified through a vessel monitoring system (VMS) by transmitting position data every two hours when at sea. It also allows the Fisheries Monitoring Centre (FMC) to track and monitor fishing vessels.

[95] Acil Allen Consulting. (2013). 'Precise positioning services in maritime sector'. Available at: http://ignss.org/LinkClick.aspx?fileticket=b%2f3x6KEaFS4%3d&tabid=56 [accessed 05/07/21].

Current use cases (new in GNSS Loss 2.0)

Autonomous technologies have emerged in recent years and are now a visible part of the maritime industry. Technologies such as track control are used to maintain ships on shipping lanes, with a role played in correcting trajectories using GNSS input data on position and navigation. In congested zones, automatic collision avoidance and electronic decision-making support the automatic alerting of potential collisions with other vessels, or the automatic manoeuvring of a vessel due to a collision alarm.

On the shoreside, new terminals are now equipped with automatic docking devices. This technology requires a high level of position accuracy and improves the safety and efficiency of docking.

Applications not considered

Marine construction and engineering operations require precise PNT solutions. For instance, clearing the bed of a harbour, river, or other area of water by scooping out mud with a dredge. This process maintains the depth of water required for port approach channels or the installation of sub-sea cables by trailing a dredge behind a navigating vessel. These solutions usually use GNSS inputs augmented by real time kinematic (RTK) data, providing one-metre precision.

Oceanography, the study of the physical, chemical, and biological features of the ocean, relies on positioning data to support mapping studies. Further academic applications include archaeology, hydrography, and the surveying and charting of bodies of water, such as seas, lakes, and rivers also rely on GNSS positioning data.

During winter and in northern latitudes, GNSS assistance in ice breaking is required. Ice breaking assistance can be indirect**,** by directing a vessel towards lighter ice conditions (requiring navigation with high accuracy and integrity), or direct, where the ice breaker and assisted vessel operate near one another (requiring relative accuracy to the one-metre level).

These use cases are not accounted for in this study because in the case of marine construction and engineering, most activities can be postponed in case of a signal disruption. Marine construction usually involves very large infrastructures (e.g. offshore wind turbines) and even if precise positioning is required for installation, the loss of signal would only cause construction efforts to be postponed by a week. The research showed that financial consequences for marine construction were not sufficiently substantial to be included. The same reasoning applies to oceanography activities.

Summary of results for maritime applications

Table 14 Maritime applications

Application	Economic benefit (annual, £m)	Economic loss (7-day, £m)
Shipping industry	450.9 (*+30%*)	182.8 (*+272%*)
Port operations	*Not monetised*	1,309.2 (*+29%*)
Fishing industry	98.7 (*+27%*)	7.9 (*+104%*)
Preventing fatalities – SAR	18.1 (*+104%*)	0.3 (*+186%*)
Total	**567.8 (*+31%*)**	**1,500.2 (*+41%*)**

Note: *(+%) indicates the variation in economic benefits and loss since the 2017 iteration of this report.*
Source: London Economics analysis

4.6.1 Shipping industry

The shipping industry encompasses activities related to the transport of goods and passengers and covers at domestic and inland waterways as well as international transport.

The shipping industry is the subsegment that relies on the largest number of GNSS use cases. From the 28 current use cases identified, 12 serve this segment. Those applications however can be grouped into a handful of wider applications. For instance, navigation support is one of the most important applications: it is an essential element of maritime navigation and precise navigation through open oceans can decrease the overall journey time.

The importance of navigation support depends on the navigation phase (ocean, coastal, port approach, etc.). Assuming the case of a ship navigating from ocean to berth in a UK port, the shipping lane becomes progressively more congested, and the water depth decreases. Each of these developments increases the risk of collision and grounding. GNSS offers critical information for situational awareness and the closer a vessel comes to berthing the higher the reliance on GNSS (see MarRINav[96]). GNSS data are used to maintain navigation safety on shipping lanes, AIS data informs navigators about the presence of other ships, and sea traffic management systems are critical to the safety in maritime transportation.

Economic benefit

The economic benefits provided by GNSS in the shipping industry are estimated at **£450.9m** annually.

The benefits are monetised as the efficiency gain from GNSS applications, reflected by the time savings on maritime journeys. The ONS input-output table estimates the contribution of maritime shipping to GDP at £6,488m[97]. Estimates from EUSPA's GNSS market report[98] show that maritime transportation time and fuel use decrease by 6.7%, using GNSS. Note that the shipping industry is the subsegment that relies the most on GNSS, and so it is possible that GNSS-enabled benefits are greater than what is presented in the model. This results in a conservative estimate of economic benefit of £434.7m in 2019.

Aid to navigation and automatic collision avoidance systems increase the safety at sea and in ports. The precise location of ships allows navigators to make better informed decisions and anticipate potential risks. GNSS contributes to these benefits by providing position precision at sub-metre level. The number of avoided accidents provides an additional £16.2m to the economic benefits of the shipping industry.

Economic loss

The economic consequence of the GNSS disruption in the maritime shipping industry is estimated at **£182.8m**, of which £174.2m is due to a consequential loss of GDP from reduced activities, £8.3m is due to the loss of benefits linked to saved time and fuel, and a further £0.3m is attributed to accidents. This loss is the consequence of 14 days of reduced activities: the 7-day outage will create

[96] Please see: https://marrinav.com/
[97] Office for National Statistics. 'Input-output supply and use tables'. Available at: https://www.ons.gov.uk/economy/nationalaccounts/supplyandusetables/datasets/inputoutputsupplyandusetables
[98] EUSPA. (2019). 'GNSS Market Report Issue 6'.

a backlog of ships on shipping lanes, and it could take up to 7-days to return to the normal flow of operations.

Water transportation is the subsegment that relies the most on GNSS applications. Any signal disruption would affect the efficiency and safety of navigators, forcing them to adapt their speed and modify their routes. 14 use cases are associated with water transportation. Most resiliency applications meet the minimum criteria to deliver the required service but there will be an immediate impact on costs and efficiency of operations. For instance, VTS alternatives include shore-based radars which have limited coverage. In the absence of alternatives, navigators will mostly rely on visual tools. This issue can be exacerbated in poor weather conditions caused by rain, mist, and haze.

During the first days of the outage, ships would slow down, and bottlenecks would be created at harbour entrances, increasing the size of backlogs. After a few days, alternative loading and unloading means would be in place and the flow of cargo handling could restart at minimum capacity. The recent blockage of the Suez Canal[99] has shown that after a week of interruption, the flow of merchandise took one week to normalise. Although a signal disruption is less likely to cause an equivalent chaos, the water transportation sector would be severely affected for 14 days.

As mentioned in this Section's economic benefits analysis, water transportation contributes to £6,488m to the UK annual GDP. We assume that over the 14-day disruption activities will slow by 70%. All modes of water transportation (container, bulk, etc.) can be affected with a different magnitude depending on the degree of reliance on GNSS. The MarRINav[100] study shows that most commodity trading will be reduced by 70% (up to 100% for container ship mooring at automated terminals – see Section 4.6.2).

The impact on passenger transportation is uncertain. Without GNSS, some interviewed stakeholders believe that ferries could be grounded for the duration of the outage if navigation conditions are very bad (weather, visibility, etc.), but otherwise able to continue service in normal conditions.[101] Overall, the impact on transit time would be negligible: there would be no or few scheduling issues at port entries, no cancellations, and no safety issues. The economic impact also depends on the time of the year at which the outage occurs. The impact would be maximised during peak tourist season but modelling this nuance is out of scope and hence is not considered in this study.

It is assumed that water transportation will be affected up to 70% over 14 days, yielding a loss of £174.2m.

The ability to avoid accidents and collisions depends on the level of situational awareness required in a given use case. Situational awareness is typically provided by AIS and VTS agencies. In the absence of AIS data all ships would have to rely on semaphore mode of operations[102]. Without VTS, most activities would need to be based on visual observations, reducing the situational awareness of navigators and increasing the risks of collisions or accidents during navigation in coastal zones,

[99] LaRocco, L. A. (2021). 'Suez Canal blockage is delaying an estimated $400 million an hour in goods'. Available at: https://www.cnbc.com/2021/03/25/suez-canal-blockage-is-delaying-an-estimated-400-million-an-hour-in-goods.html [accessed July 2021].
[100] European Space Agency. (2020). 'MarRINav'. Available at: https://marrinav.com/
[101] NIST. (2019). 'The economic benefits of the GPS'. Available at: https://www.nist.gov/system/files/documents/2020/02/06/gps_finalreport618.pdf [accessed July 2021].
[102] Semaphore: A device using visual signals, usually bodies of defined shapes or positions or both, by which information can be transmitted. From IALA: https://www.iala-aism.org/wiki/dictionary/index.php/Semaphore [accessed July 2021].

ports, or inland waterways. Assuming a uniform distribution of the probability of accidents over a year, the loss of benefits sums up to **£0.3m** over a 7-day outage.

Drivers of change

There are three components to the difference in benefits: first, the time saving factor has been revised and reduced. The model historically used road transport time and fuel savings as a basis for calculating the benefits of improving efficiency and thus saving time, and has been updated to use a maritime-specific factor. Second, the GDP contribution of the shipping industry is higher than in the source used in the prior version of this report. Finally, accidents avoided are newly monetised benefits and hence their value is entirely additional to the previous iteration of this report.

The difference observed between this study and the previous iteration is explained by two factors. First, the contribution of water transportation to GVA has more than doubled since 2017 as with the second point above for changes in the benefits section. Furthermore, the outage duration being considered has increased by two days, meaning that a total of four additional days are included in the disruption (due to the combination of outage period and backlog clearing period).

4.6.2 Port operations

Port operation include all activities concerning commodities handling. Ports are very central to the UK economy given that more than 90% of goods are imported through ports (as measured by weight). GNSS contributes to a varying extent with respect to different cargo types.

Container handling operations require precise position and timing inputs to efficiently manage containers; automated terminals depend on PNT data to operate; a disruption to GNSS would force cranes to shut down after a few minutes after using dead reckoning fail safe systems to operate in that lapse. The impact would therefore be immediate and noticeable. However, other types of cargo are not as vulnerable as automated container terminals. Bulk, Roll-on Roll-off (RoRo) and non-automated container terminals could continue to operate, though this would still be below full efficiency.

The economic impact of reduced port operations is split between imports and exports, and this section estimates the knock-on impacts on the global supply chain.

Economic benefit

The benefits from GNSS are **ambiguous and unmonetized**. McKinsey published a study showing that there is a great difference between perceived and actual impact of automation in ports. The report shows that automation can reduce the efficiency of ports by up to 15%[103] in practice. The survey shows that the while safety improves and performance becomes more predictable, expected cost savings are not met and that efficiency declines versus non-automated counterparts.

The major contributor to this shortfall is a shortage of people with necessary skills and expertise in automation: 75% of survey respondents identify such a shortfall. Data quality and analysis capability are also cited as contributors to the failure of automation:

[103] McKinsey. (2018). 'The future of automated ports'. Available at: https://www.mckinsey.com/industries/travel-logistics-and-infrastructure/our-insights/the-future-of-automated-ports [accessed July 2021].

> *"The first reason is that the lack of a structured, transparent data pool makes it hard to monitor and diagnose the operations and performance of equipment quickly. Second, the standards, formats, and structures of the data may be misaligned or even wholly absent, so ports can't collect and exchange data efficiently."*

Other types of cargo are a lot less reliant on GNSS. Dry bulk depends on straddle carriers that are not critically dependent on GNSS. The main impact on other cargo is traffic congestion, both for ships and lorries / trains used to distribute cargo and commodities to the mainland. This part of the logistic chain is further analysed in the logistics Case Study on page 48.

Economic loss

Maritime shipping is the cheapest mode of transportation, and 95% (91%) of UK imports (exports) are facilitated by maritime shipping[104]. HMRC estimates the value of imports at **£504bn**, and exports at **£373bn** in 2019 (all means of transport). The economic contribution of commodities flow differs with respect to the economic sectors and their relative dependencies on those commodities.

The loss attributed to imports is estimated at **£892m** (where £97.1m is due to warehousing and supporting activities and £795m is due to manufacturing activities) and exports at **£417m**.

Imports and knock-on effects

The disruption of signal will affect the various cargo types differently, depending on the mean of transport and handling. The MarRINav study shows that the reduction of efficiency is maximised for automated terminals, where cranes would shut down completely after a few minutes. Other types of cargo are mostly subject to congestion impacts and the efficiency loss is estimated as 70%.

Table 15 MarRINav efficiency loss

Cargo type	Reduced efficiency
Bulk	70%
RoRo	70%
LoLo (automated terminal)	100%
LoLo (Non-Automated terminal)	70%
Other	70%

Note: LoLo = Lift-on Lift-off

Source: MarRINav – Cost benefit analysis. Available at: https://marrinav.com/wp-content/uploads/2020/04/D8-20-02-21-D8-Cost-Benefit-Analysis-Report-v2.0.pdf

Warehousing activities play a central role in all transportation sectors and are subject to reduction of activities. With fewer goods arriving, fewer staff are needed, and shifts will be shortened. Conversely, if goods are held for too long in warehouses this can increase the operational costs and increase risks of deterioration (perishable goods), loss due to hoarding, or theft.

The warehousing industry contributed £22bn to UK GDP in 2019. Overall, this includes contributions to water, air, road, and rail transport. The contribution of maritime transportation to warehousing activities is estimated at 16.4% (proportional to the share of maritime contribution to GDP). It is also assumed that activities are reduced by 70% following the shipping congestion model presented in

[104] Department for Transport. (2020). 'Transport Statistics Great Britain'. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/945829/tsgb-2020.pdf [accessed July 2021].

MarRINav[105] (lower bound estimate) over 14 days (7-days disruption, and 7-days backlog clearance). This gives an estimated loss of **£97.1m** for maritime warehousing activities.

The manufacturing industry represents **£188bn** of UK GDP and is highly dependent on imports of commodities such as bulk goods and manufacturing parts like electronics. Manufacturing plants will have to slow if not shut down their activities during the outage.

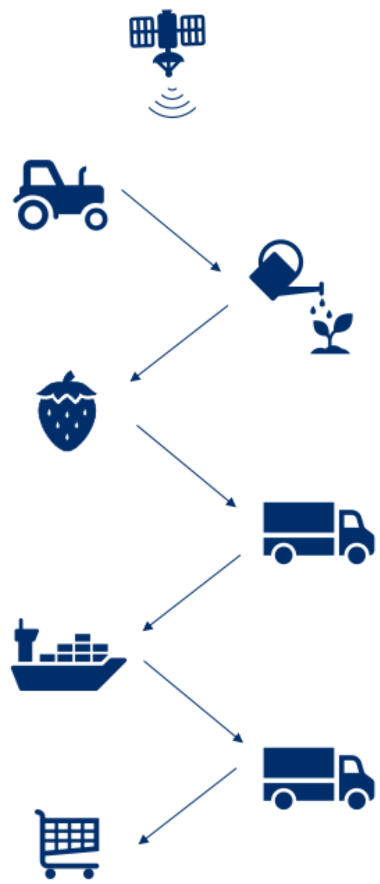
To illustrate the impact of GNSS loss on food imports the case study below charts the journey of a strawberry from Spain to the UK.

[105] ESA. (2020). 'MarRINav'. Available at: https://marrinav.com/

Case Study: logistics of fresh food imports

The import of fresh food into the UK provides a powerful illustration of the integration of GNSS across sectors in the modern UK economy. Likewise, the market for fresh food demonstrates the cascading effect a GNSS outage could have across a variety of applications. To illustrate this, the section below considers the cascading effects of GNSS loss on the logistics involved in the importation of strawberries from Andalusia (Spain) to London (UK).

The journey of a strawberry: Andalusia to London



- Colder weather forces Britain to rely on imports from abroad to meet its strawberry demand. **95%** of soft fruits are imported in the month of January from countries such as Spain.
- GNSS is employed before a single strawberry ripens, as it guides farm tractors to form precise and orderly beds for planting, increasing eventual yield and minimizing soil compression.
- As the strawberries grow, GNSS enables the execution of precision irrigation techniques which leverage agro-climactic and soil data to increase yields and use water more efficiently in sandy soils.
- At harvest, the strawberries are packaged and loaded onto a truck which uses GNSS to chart its journey through traffic and diversions across Spain, into France, and ultimately to the port at Calais.
- Here the strawberries follow the "roll on-roll off" transport method of most food imports into the UK, as the truck drives onto a GNSS-guided ferry, arrives at the port of Dover, and 'rolls off' onto the UK's roads. GNSS also assists in port arrival and departure procedures, aiding in berthing and mooring.
- GNSS then facilitates last mile delivery to a distribution centre or supermarket.
- The strawberry, which was ripening in Spanish sun on Monday, is displayed for sale at a local Tesco on Thursday. Its entire journey has been facilitated by GNSS.
- Many journeys are more complex, offering further touch points with GNSS. Food may be loaded onto rail or other modes of logistics transportation from to a distribution centre, or delivered directly to consumer ("Last Mile" delivery).

Fresh food logistics: value at risk

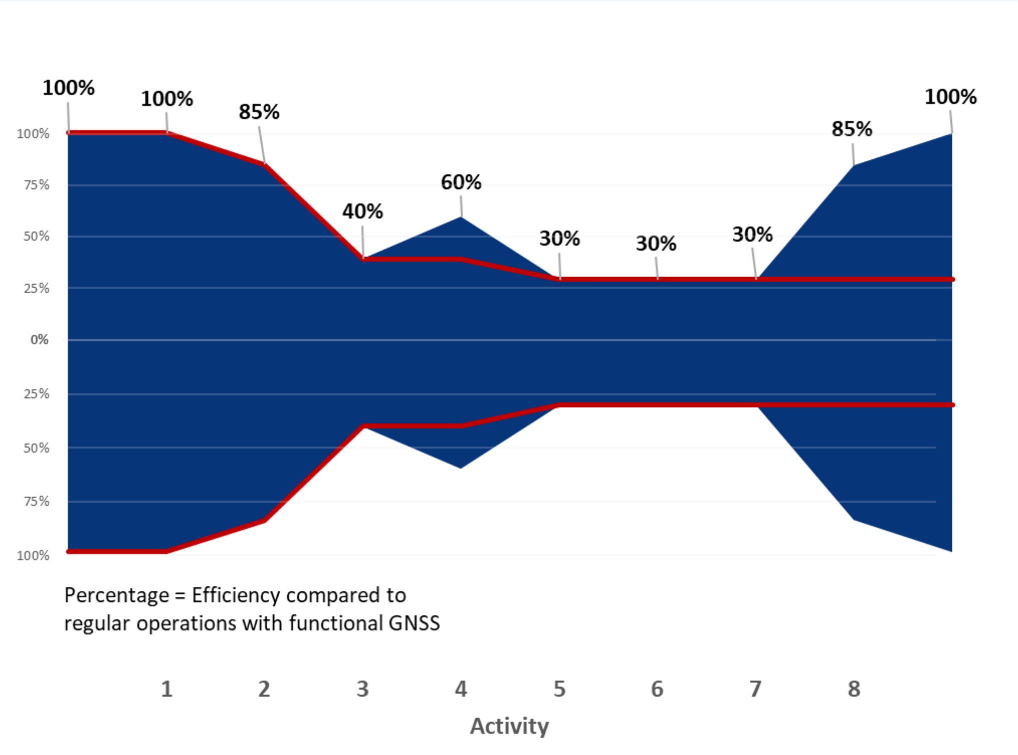
A loss of GNSS would have an impact on logistics, which impacts fresh food imports. The following is an effort to quantify the **value at risk during a 7-day GNSS outage**. According to DEFRA, in 2019 only 55% of all food consumed in the UK was produced in the UK[106]. **£47.8 billion of food imports per annum** account for the remaining 45%[107]. Approximately **£24.9 billion per annum of this is considered perishable.**[108] Of this, **£2 billion** is frozen[109] and, as a percentage of food sales in retail, 1% of all food is wasted[110]. Together, these figures **suggest £22.7 billion in value at risk annually, or £436 million at risk during a 7-day outage period.**

Value at risk = £24.9bn perishable food imported – £2bn frozen – 1% of all food wasted

value at risk = £22.7bn

The following flow diagram illustrates potential pinch points along the journey for fresh food imports in the case of a GNSS loss scenario. It captures potential efficiency losses at each juncture of the logistics journey given an outage affecting that application. The percentage at each point in the diagram refers to the relative efficiency of each activity in the absence of GNSS compared to normal operations. The blue area shows each activity's efficiency loss in isolation, while the red line shows the cascading effect as efficiency loss across successive activities compound each other and form a bottleneck.

Figure 7 Logistics Flow Model



[106] Office for National Statistics. (2021). 'UK trade: goods and services publication tables'. Available at: https://www.ons.gov.uk/economy/nationalaccounts/balanceofpayments/datasets/uktradegoodsandservicespublicationtables [Accessed July 2021].

[107] Department for Environment, Food and Rural Affairs. (2020). 'Food Statistics in your pocket: Global and UK supply'. Available at: https://www.gov.uk/government/statistics/food-statistics-pocketbook/food-statistics-in-your-pocket-global-and-uk-supply [accessed July 2021].

[108] Assuming Fruit and Vegetables, Meat, Fish, Dairy & Eggs are most plausibly perishable on our 7-day GNSS outage timeline. (Other categories include: Beverages, Cereals, Animal Feed, Oils, Sugar, Miscellaneous, and Coffee, Tea, Cocoa, Etc.)

[109] This likely represents a lower bound for frozen otherwise-perishable food. Trade import data does not offer sufficient granularity in some import categories. Sources: https://www.trademap.org/ and https://comtrade.un.org/data

[110] WRAP. (2020). 'Food surplus and waste in the UK – key facts'. Available at: https://wrap.org.uk/sites/default/files/2021-05/WRAP-food-surplus-and-waste-in-the-UK-key-facts-jan-2020-update.pdf [accessed July 2021].

Corresponding Activity
Activity 1 – Goods are transported by road from point of harvest to port
Activity 2 – Vessel approaches UK coastline, entering coastal voyage phase
Activity 3 – Vessel approaches UK coastline, entering coastal voyage phase
Activity 4 – Vessel arrives at anchorage, or a pilot station (if pilot required)
Activity 5 – Vessel enters port approach voyage phase (w or w/o pilot)
Activity 6 – Vessel enter port phase and manœuvres
Activity 7 – Vessel arrives at berth
Activity 8 – Goods are transported by road from port to destination/distribution centre

Fresh food logistics: expert consultations

Expert consultations sought to identify key pinch points in the transport of fresh food via "roll-on-roll-off" (RoRo) transport. The rigidity of the ferry booking system was identified a potentially problematic area. Consultees stated that booking appointments for inbound lorries are 30-60 minutes in length. If a GNSS outage caused a driver to miss their appointment due to navigation challenges or increased road congestion the rebooking process would likely result in a full day delay. This full day delay could become problematic in the case of a just in time supply chain, or the delivery of food which is only a few days away from expiration. As a result, a portion of the value at risk identified above could be lost.[111] However, future applications of GNSS might enable more dynamic systems. Currently, transport/logistics companies have GNSS tracking data on their drivers, but this is not shared with fleet managers at a port. As a result, ports do not have overview of a given driver and their cargo until they arrive at the port gates. Improvements in technology might integrate information streams, enabling a port to adapt to a driver's delay and assign a new ferry booking accordingly. This adaptation would thus reduce the potential economic loss by reducing overall delay.

Experts were also consulted as to whether a GNSS outage would encumber the process of loading and unloading a ferry. In the case of cargo transport, a GNSS outage may have dramatic effects on crane operations. However, unlike cargo, the navigation and sequencing of RoRo lorries within a port immediately before and after transport on a ferry does not depend on GNSS. Traffic flow is usually managed through signals, gates, and RFID tags.

There are 43 manufacturing sectors included in the ONS IOAT[112] (Input Output Analytical Tables). Each sector depends on a varied proportion of inputs and the model we developed to compute the economic loss assumes the impact is greater for sectors with higher dependency.

Depending on the cargo type, sectors are affected to different extents. Container traffic would stop completely where automated, while bulk cargo and roll-on/roll-off (RoRo – i.e. lorries) would 'only' be severely delayed and disrupted.

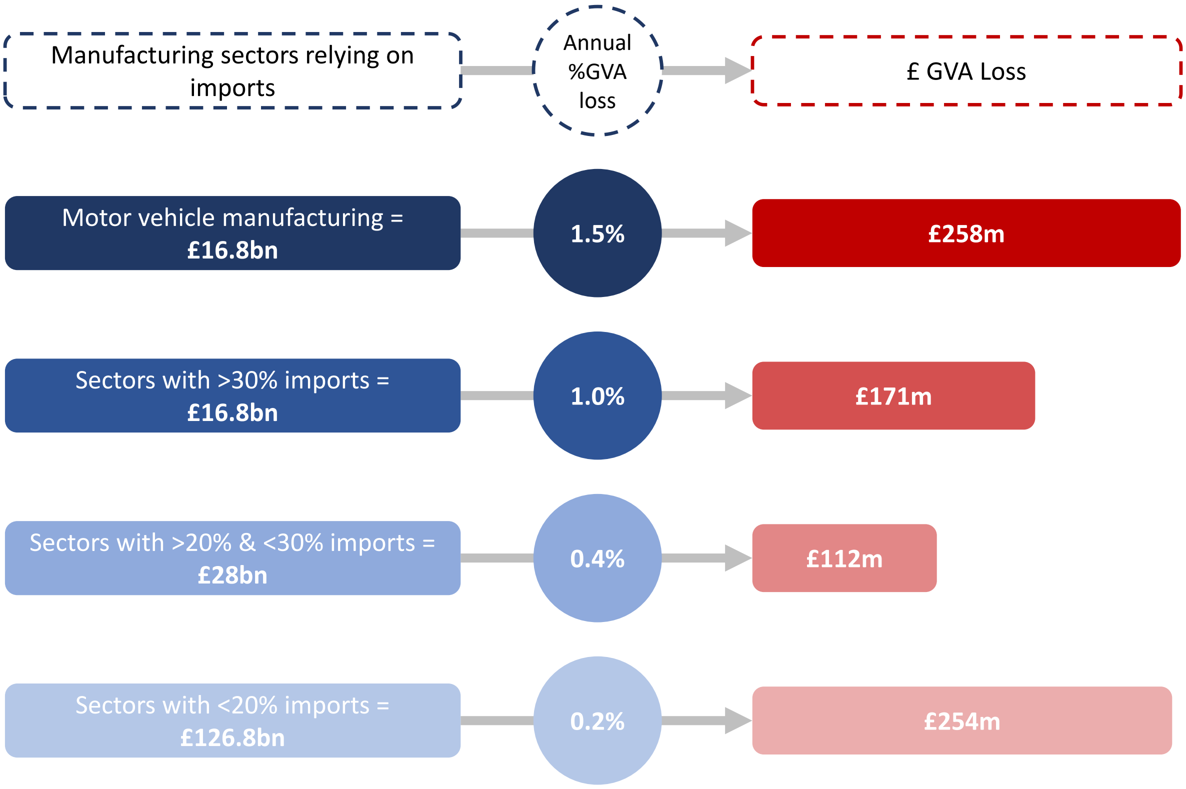
It is assumed that, due to the effects of the GNSS outage, manufacturing factories will slow down after four hours on the first day and workers will be sent home. Some inputs may arrive via RoRo over the outage period considering that some lorries might have been stuck in traffic, and partial production is possible. Post disruption, substantial overtime will be required from the sector's

[111] A detailed decomposition of potential value destroyed by specific good, transport method, and transport route is beyond the scope of this report. This case study serves merely to illustration a possible pathway of economic loss in the case of a GNSS outage.
[112] Office for National Statistics. 'Input-output supply and use tables'. Available at: https://www.ons.gov.uk/economy/nationalaccounts/supplyandusetables/datasets/inputoutputsupplyandusetables.

employees to make up the delay which will lead to extra-time pay increase and increased operational costs at the various plants.

The model assumes that all sectors importing intermediate inputs are highly vulnerable to a delay, and therefore need to substantially slow down production during the seven-day GNSS outage. Assuming the GVA impact is increasing with the need for inputs, each manufacturing sectors have been placed in a category of importers and a share of GVA loss is used to estimate the loss. These shares follow the initial assessment of loss[113]. The diagram below presents the results.

Figure 8 GNSS Loss impact on manufacturing



Source: London Economics analysis (inputs from ONS)

Motor vehicle manufacturing is the only sector among the top importers that has been deemed to rely exclusively on container traffic. The impact on motor vehicle manufacturing is assumed to be 80% over the period, which yields a **1.5%** loss of GVA (see the previous iteration of this report for a detailed methodology[114]).

Exports

The economic value of export loss is estimated at **£417m**.

Overall, the UK exported £373bn worth of commodities in 2019. Not all goods are transported via ships. For instance, pharmaceutical goods and jewellery are still generally transported via plane. The preference for air transport is due to the relative reliability and speed which allow for faster international deliveries, as seen during the Covid-19 vaccination campaign. This trend however could change in the future given progress made in cold chain logistics and the cost savings offered

[113] London Economics. (2017). 'The economic impact on the UK of a disruption to GNSS'.
[114] London Economics. (2017). 'The economic impact on the UK of a disruption to GNSS'.

by container shipping. So, pharmaceuticals and jewellery remain transported by plane and ocean transport mostly covers low-value, high-demand products[115].

Using UK Trade data, it is estimated that 86% of exports are via maritime shipping, in value[116] and that the seven most important export ports are responsible for 65% of the value exported, following the methodology developed in the initial study. It is further assumed that delayed or cancelled exports are responsible for a 0.2% loss in GVA per day (equivalent to the lower estimate of the impact of imports). This is a conservative estimate as other studies have shown that, under Covid-19 measures, an increased stringency on maritime transport by 10% could reduce daily exports value by 0.4%[117].

Drivers of change

The change in warehousing activities is due to three factors. Firstly, the share of activities attributed to maritime transport nearly doubled from 8.9% to 16.4%. This owes to a greater contribution of maritime transport to UK GDP. Second, the GNSS reduced activity was revised to include the most up to date estimates of the disruption, growing by 10% since the previous iteration of this report. Finally, the disruption length increased by two days, inducing a total of 4 days increase due to the backlog effect. In total, the loss associated with warehousing activities increased by **150%**.

Most changes in the value of imports are due to a change in manufacturing needs between 2017 and 2019. The manufacturing sectors contribution to GDP grew from £152bn to £188bn over the same period, resulting in a 28% loss increase.

The methodology to assess the loss of exports changed slightly since the previous iteration of this report, though yielding similar orders of magnitude. Still using the same top export ports, the impact on UK GDP is now based on a factor mirroring the impact of imports.

4.6.3 Fishing industry

In the UK, all fishing ships larger than 12m in length must be equipped with GNSS receivers, as per Safety of Life at Sea (SOLAS) regulation. Fishing ships use GNSS applications to locate fish spawns and to avoid underwater obstacles. Bottom trawling highly relies on GNSS input data since there is a need to know precisely what the seafloor is made of to avoid damage to equipment. Trawlers also use GNSS to identify whether the vessel is tilting or at danger of capsizing. Mid-water fishing equipment also relies on GNSS positioning data. Fishermen use GNSS to locate their fishing nets and pots which allows them to cover more surface and increase the potential catches, fixed gears highly rely on GNSS too to tag the coordinates of nets and pots, and long line and mid water trawling also uses GNSS to locate equipment and to find specific locations with historically high catch success. In most cases, fishermen would simply avoid fishing during outage (due to safety concerns)[118].

[115] Biopharma International. (2018). 'Poseidon takes on the pharma supply chain'. Available at: https://www.biopharminternational.com/view/poseidon-takes-pharma-supply-chain [accessed July 2021].
[116] UK Trade Info. (2021). Available at: https://www.uktradeinfo.com/trade-data/ [Accessed July 2021].
[117] Vershuur, et al. (2021). 'Global economic impacts of COVID-19 lockdown measures stand out in high-frequency shipping data'.
[118] National Institute of Standards and Technology. (2019). 'Economic benefits of the GPS'.

Economic benefit

The economic benefits to fishing are estimated at **£98.7m** in 2019. The value of all landings in 2019 was estimated at £987m by the MMO.[119] For fishing vessels, it is assumed that GNSS increases fish catches by 10%, resulting in the estimated benefits.

Economic loss

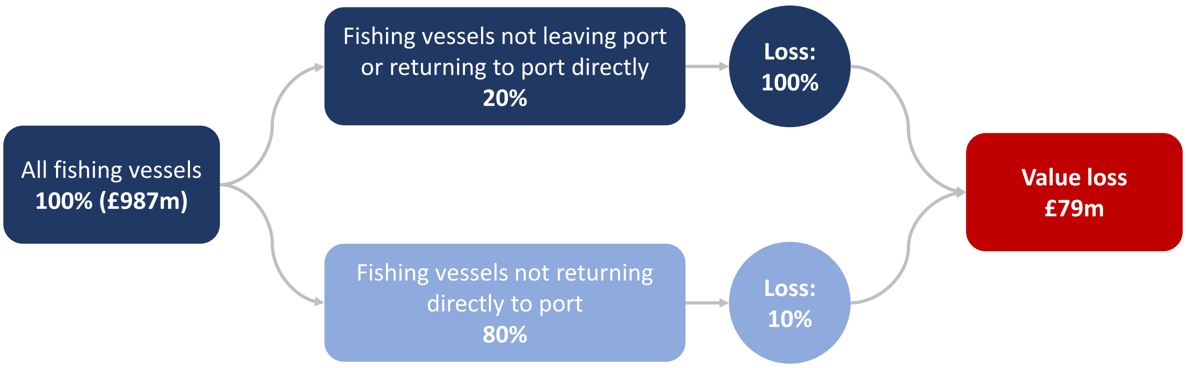
The loss attributed to the fishing industry elevates at **£7.9m** over 7-days.

The loss of GNSS for fishing vessels would require the fisherman to be able to navigate to destination waters using conventional methods. All UK commercial fishing vessels of 12m or greater overall length must be fitted with a government-approved GNSS-tracking device. The device allows a vessel to be automatically located and identified through a vessel monitoring system (VMS) by transmitting position data every two hours when at sea. It also allows the Fisheries Monitoring Centre (FMC) to monitor fishing vessels. In the absence of GNSS, the monitoring of fisheries would be carried out by maritime or air patrols which would severely affect the industry, slowing down controls. .

There are two components to this loss. The direct loss due to missed catches and reduction of activities yields a loss of **£5.3m**, and the indirect knock-on effects on the hospitality and retail industries would cause a loss of **£2.6m**.

As presented in the initial study, the greater impact on fishing vessels is linked to the VMS requirements to report position information based on GNSS. The requirements stipulate that the VMS device must transmit positional fixes every hour and that the position is accurately timestamped with respect to UTC. This would cause a fraction of vessels to return to port (assumed at 20%) losing 100% of daily catches, while others (assumed at 80%) would remain at sea, losing 10% of their catches.

Figure 9 Loss attributed to fishing vessels



Source: London Economics analysis

This value can be considered an upper bound. Some interviewees have said that most fishing crews and companies work on annual quotas. A 7-day disruption would not greatly impact their own revenue as activities could be postponed, causing very small disruption in the GVA generated annually.

The impact of a smaller daily catch would impact the hospitality and retail industry relying on fresh catches. According to the ONS, the UK domestic demand for processed fish and crustaceans totalled

[119] Marine Management Organisation. (2019). 'UK Sea Fisheries Statistics 2019'.

£631m in 2019. It is assumed that 22% of inputs come from aquaculture and imports[120], leaving the remaining 78% to seagoing vessels. Using the same system showed in Figure 9, the total loss over a 7-day outage equals **£2.6m**.

Drivers of change

The changes in both benefits and loss are driven by organic increase in the value of catches for the direct impacts (+£212m, +27%) and the value of domestic fish demand (+£326m, +107%).

4.6.4 Leisure

Maritime UK estimates there are 4,600 companies providing marine leisure services in the UK[121]. The dependency of leisure activities on GNSS is unclear and information is limited. The Royal Yachting Association indicates that GNSS dependent instruments are not mandatory on any type of recreational boats, although GPS chart plotters and NAVTEX instruments are recommended. Lifejackets are mandatory on ships >13.5m length but not all are equipped with personal distress beacons, which are GNSS-enabled.

A US based analysis indicates that recreational boaters rely on GNSS for navigation in open seas, once they are far away from landmarks. But the degree of use is very difficult to estimate[122]. The impact of a loss of GNSS would be greater for boats which are already far from land; assuming they typically rely upon GNSS-enabled instruments they would have to revert to compass and paper charts to try to find their way home. This could represent a challenge for boaters inexperienced in this type of navigation method, increasing the likelihood of getting lost – especially if the weather deteriorates while at sea. Getting lost and the increased likelihood of accidents will increase the long-term impact on recreational boating (e.g., accidents impacting on willingness to access more boating recreation activities). Accidents could further generate increased costs of maintenance or insurance claims.

Depending on the number of recreational boaters at sea during the disruptions, the number of emergency calls could increase, increasing the workload of coastguards and the costs of operations if Search and Rescue actions are required.

However, interviewees have indicated that losing the signal would not necessarily stop recreational boaters but could affect fishing activities. Again, the degree of impact is unknown and given the seasonality of recreational activities, the impact of a GNSS disruption is challenging to estimate.

These findings suggest there is a lot of uncertainty in the assessment of benefits and loss in this application. Hence, the benefits and loss are not monetised in this case.

4.6.5 Search and rescue (SAR)

Emergency beacons are GNSS-enabled and thereby share the location of a person in distress with emergency services. Three types of emergency beacons are used in the maritime domain, namely Personal Locator Beacons (PLB), Emergency Position-Indicating RadioBeacons (EPIRB), and AIS-

[120] Based on: Eurostat. (2016). 'Fishery statistics'. Available at: http://ec.europa.eu/eurostat/statistics-explained/index.php/Fishery_statistics [accessed July 2021].
[121] Maritime UK. (2021). 'Leisure'. Available at: https://www.maritimeuk.org/careers/explore-sector/leisure-marine/ [accessed July 2021].
[122] National Institute of Standards and Technology. (2019). 'Economic benefits of the GPS'.

SART, which uses the AIS system to transmit emergency signals to nearby vessels. COSAPS-SARSAT is the international organisation that operates the emergency beacon system.

The annual Beacon Manufacturing Survey reported that in 2018 (last year of data available), nearly 1.9m beacons were in use globally, a 1% increase since 2017. The survey reported that an additional 200,000 new beacons were manufactured, representing an 8.4% decrease compared to the previous year[123].

Economic benefit

The total GNSS-enabled benefits for SAR activities elevates at **£18.1m**.

Benefits are measured using the actual number of SAR missions carried at sea and involving UK ships or crew or taking place in UK national waters. The relevant COSAPS-SARSAT report on SAR operations indicates that 38 individuals were saved at sea thanks to beacon activations[124]. The number of lives saved estimation is based on UK-owned beacon activations and operations in UK waters.

The number of lives saved is multiplied by the average value of preventing fatalities. The value is extracted from the Department for Transport's transport appraisal guidance tables which gives an estimated value of reducing fatalities of £1.9m per life saved[125].

The total value of lives saved is then multiplied to a GNSS multiplier measuring the efficiency gain of SAR due to GNSS data. This value is extracted from data collected for the GNSS Market Share report[126] and shows that 25% of successful activities.

Economic loss

The loss is estimated at **£0.3m**, capturing the loss of benefits.

Search and rescue operations at sea depend on distress beacons. These beacons are part of the COSPAS-SARSAT system, which uses doppler to locate distressed individuals as a primary source. GNSS is incorporated in an increasing proportion of beacons, which ensures the distress signal is localised faster and more accurately. Without GNSS, the COSPAS-SARSAT system reverts to doppler. In poor weather conditions the reduced accuracy and longer time to localisation means the search effort is prolonged. . Benefits from preventing fatalities and faster rescues will therefore be lost. It is further assumed that the probability of an accident to occur is uniformly distributed in one year, hence the loss of benefits is simply 7 times the daily benefits.

Drivers of change

The loss increased by £0.2m since 2017. This can be explained by an increase in the value of preventing fatalities, the number of lives saved, and increased contribution of GNSS to SAR missions. Compared to 2017, 12 more persons were saved thanks to beacons. The value of lives saved

[123] COSPAS-SARSAT. (2018). 'Results of the 2019 beacon manufacturers survey'. Available at: https://www.sarsat.noaa.gov/BMW%202019_files/2019%20BMW_Results%20of%20the%202019%20B-Mans%20Survey%20%28A.Zhitenev%20CSS%29_20%20Sep%2019_c.pdf [accessed July 2021].

[124] COSPAS-SARSAT. (2018). 'COSPAS-SARSAT report on system status and operations'. Available at: https://vnmcc.vishipel.vn/images/uploads/attach/R007-NOV-22-2019.pdf [accessed July 2021].

[125] Department for Transport. (2020). 'Transport Appraisal Guidance tables'. Available at: https://www.gov.uk/government/publications/tag-data-book [accessed July 2021].

[126] EUSPA. (2019). 'GNSS Market Report Issue 6'.

increased by **£0.2m** between 2017 and 2019, and the share of GNSS-enabled benefits increased by 5% over the same period.

4.7 Road

GNSS is used on roads extensively for its positioning and navigation information. Drivers use GNSS for turn-by-turn navigation. Logistics and fleet management companies use it to keep track of the location and use of their vehicles. Insurance companies use it to obtain information on their clients' driving behaviour that would be otherwise difficult. Emergency and breakdown call use it to locate incidents and send help quickly. These benefits derived from GNSS for these applications are monetised in this chapter, as well as the value of economic losses in the event of GNSS outage.

Other road applications, including autonomous vehicles, Intelligent Speed Assistance (ISA), Cooperative Intelligent Transport Systems (C-ITS), Next Generation Road User Charging, Vehicle to Everything (V2X) Communications, Smart Parking, and Intelligent Salt Spreading/De-Icing, make use of GNSS too. However, these applications currently have a low penetration rate in the UK market. Therefore, their benefits and value of GNSS loss are likely small and not monetised.

The applications that are monetised in this section are shown below in Table 9. The annual economic value they generate and the estimated economic losses due to a one-week loss of GNSS are summarised for each.

Table 16 Road applications

Application	Economic benefit (annual, £m)	Economic loss (7-day, £m)
Road navigation	3,956.4 (*+26.1%*)	1,599.4 (*-15.6%*)
Logistics and fleet management	375.5 (*+143.5%*)	60.2 (*+148.8%*)
Insurance telematics	1323.8 (*+8122.4%*)	Not estimated
Emergency and breakdown call	18.6 (*+24.0%*)	0.4
Total	**5,674.3** (***+70.8%***)	**1,659.9** (***-13.6%***)

Note: *(+%) and* ***(-%)*** *indicate the variation in economic benefits and loss since the 2017 iteration of this report.*
Source: London Economics analysis

4.7.1 Road navigation

Navigation devices and systems use GNSS signals and track the location of the driver. This gives the drivers directions for the selected route continuously – an application also known as turn by turn navigation. Connected devices also receive further advice on routes with shortest travel time based on live traffic and other road events. Navigation can be offered by smartphones or in-built devices, though it is increasingly offered by smartphones.

Economic benefit

The annual economic benefits generated by GNSS in road navigation are estimated at **£3,956.4m.** These benefits come from several sources. Firstly, drivers are able to follow turn by turn navigation instructions and not rely on a paper map. Drivers subsequently make fewer errors and are less likely to get lost. Secondly, time savings are valued at the average UK salary. Shorter travel time means that fuel is saved. Thirdly, pollution and carbon emissions are reduced. These are also monetised.

Economic loss

The economic impact of loss of GNSS in road navigation is estimated at **£1,599.4m** over 7-days.

Road navigation devices would start to fail very soon after GNSS signals were lost. Simple dead reckoning from inertial sensors in combination with snap-to-map software solutions could keep devices in progressively declining service for a limited period – until the vehicle is turned off at the latest. On-board sensors would continue to estimate the current position of the vehicle using the previous determined location, combined with the vehicle's speed and direction. However, this capability would progressively decline, and be entirely lost when the vehicle is eventually turned off.

Smartphones would continue to derive position from all available sources (e.g. WiFi hotspots and cell towers). The impact of loss of GNSS on handheld smartphone users would therefore depend on the availability of alternative sources of positioning.

Given the short holdover capability of devices used in the sector, it is reasonable to assume all time, fuel, and emissions savings made possible by GNSS would be lost for the duration of the outage. However, because of this holdover capability, the likelihood of a sudden spike in accidents when all drivers lose GNSS simultaneously is limited. The loss of benefits over 7-days amounts to £75.8m.

The economic cost would not be limited to the loss of benefits. This is because the behaviour of one driver on the road affects the rest of the road users (network effect). GNSS reliant drivers would spend more time navigating and make wrong turns. They would also need to stop from time to time to read their map and work out where they are on the map. The entire flow of the road network would be affected and see more congestion, affecting even drivers who can navigate without GNSS.

The economic cost in addition to the loss of benefits is estimated to be £1,523.6m over 7-days. This is calculated by modelling the increase in travel time over the course of the 7-days. The increase is assumed to be largest in the first day and then gradually decrease as drivers learn to adapt. Different types of local authorities in England are assumed to see different increases in traffic. Table 17 presents the modelled percentage increase in travel time.

Table 17 Modelled percentage increase in travel time, by type of local authority classification

	London[1]	Urban local authorities[2]	Rural local authorities [3]
Day 1	60.0%	30.0%	20.0%
Day 2	51.0%	25.5%	17.0%
Day 3	43.4%	21.7%	14.5%
Day 4	36.8%	18.4%	12.3%
Day 5	31.3%	15.7%	10.4%
Day 6	26.6%	13.3%	8.9%
Day 7	22.6%	11.3%	7.5%

Note: [1], [2], and [3] : for definition, see footnotes 127, 128, and 129.

Source: London Economics

London[127] is assumed to see 60% increase in travel time in day 1. This impact then gradually decreases to 23% in day 7. Other urban areas[128] in England are assumed to experience a smaller increase in travel time, starting from 30% in day 1. The rural areas[129] are assumed the smallest increase in travel time, starting from 20% in day 1.

127 This includes all local authorities in London.

128 This is defined as the local authorities that Defra defines as "Major Urban", "Large Urban" or "Other Urban". For more see https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/137659/la-class-intro.pdf.

129 This is defined as the local authorities that Defra defines as "Significant Rural", "Rural – 50" or "Rural – 80". For more see https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/137659/la-class-intro.pdf.

These percentages are applied to the 2019 driving time. The increase in driving time is then monetised by the value of time at £18.85[130] per hour and fuel cost per hour at £2.21[131].

Scotland, Wales and Northern Ireland do not publish traffic data at the local authority level. These countries are therefore modelled by assuming an average of 18% increase in travel time every day over the 7-day period. The increase in travel time is also monetised by value of time at £18.85 per hour and fuel cost per hour at £2.21.

Drivers of change

In the previous iteration of this report, the estimates of economic benefit (**£3,138.7m**) and loss (**£1,896.0m**) differ from the updated estimates presented in this report of **£3,956.4m** (benefit) and **£1,599.4m** (loss).

The benefits value has most significantly been impacted by a number of key updates. First, the volume of traffic has increased since the last report. Second, penetration rate of GNSS navigation devices have also increased. The growth in benefits value is therefore mostly from organic growth of the market.

The estimated loss in this report is lower than in the 2017 report. Since 2017, a growing number of drivers have shifted towards using smartphones for navigation. This is illustrated by navigation applications such as Apple Carplay and Android Auto. Both have had an increase in market share since 2017. Smartphones are more resilient against GNSS loss than traditional on-board navigation systems, as they can leverage more alternative sources for positioning, for example, using Wi-Fi hotspots and cell towers. Therefore, there were more navigation devices with stronger holdover and resilience in 2019 than 2017. This reduces the economic loss in this application.

4.7.2 Logistics and fleet management

Logistics companies and businesses that run a fleet of vehicles track their vehicles to improve their operation efficiency. This tracking uses GNSS.

Economic benefit

The annual economic benefits generated by GNSS in logistics and fleet management are estimated at **£375.5m**. The benefits accrue from different sources. Firstly, tracking of fleets allow companies to monitor the use of the vehicles at ease. This enables fleet operators to undertake pre-emptive vehicle service in advance of a breakdown. Constant tracking also allows the head office to respond to orders using the closest vehicles. This reduces idle time, optimising fleet use.

The improvement in fleet maintenance enabled by GNSS is monetised in the form of reduction in maintenance cost. The increase in fleet use efficiency is monetised in the form of time and fuel savings, and the associated carbon emissions reduction.

Economic loss

The economic impact of loss of GNSS in logistics and fleet management is estimated at **£60.2m**.

[130] Parameter used in *London Economics. (2017). 'The economic impact on the UK of a disruption to GNSS'* – value is inflation adjusted.
[131] Parameter used in *London Economics. (2017). 'The economic impact on the UK of a disruption to GNSS'* – value is adjusted by growth in UK fuel price between 2016 and 2019.

The annual economic benefit over the 7-day period would be lost, which amounts to £7.2m. The skills required to track fleets' location, destination and status manually are unlikely available at the call centre. ETA (estimated time of arrival) would become difficult to derive without GNSS. This would affect just in time operation greatly.

To indicate the cost of losing GNSS to monitor fleets, the labour cost to monitor fleets can be estimated. Assuming 6,000[132] large fleet licence holders in the UK, each requiring 3[133] people in 2 shifts, working 8 hours a day at minimum wage[134], over the 7-day period the labour cost would be £19.3m. It would be unlikely to be able to assemble the number of staff needed in the event of a GNSS loss on short notice, and competition from other sectors that would seek to increase staff numbers could mean wage pressure. Nevertheless, this is to indicate the cost of not being able to monitor fleets using GNSS.

Moreover, the reduction in efficiency in the sector could lead to delayed or missed deliveries entirely. The companies affected would most likely be those with large fleets. Because it would be difficult to manage a large fleet without GNSS. The share of GVA (Gross Value Added) by large fleet operators is assumed to be 61%.[135] GVA in the freight transport sector amounts to £14,412.8m in 2019.[136] This implies that the large fleet operators account for £8,791.2m in 2019. Assuming an economic loss of 20% due to missed or delayed deliveries, this would result in an annual loss of £1,758.2m and an implied loss of £33.7m over 7-days. Note that this does not include the knock-on impact further down the supply chain, such as shortage in goods and panic buy. The logistics Case Study on page 48 provides more discussion on the logistics sector and how it could be affected by GNSS loss.

Drivers of change

In the previous iteration of this report, the estimates of economic benefit (**£154.2m**) and loss (**£24.2m**) differ from the updated estimates presented in this report of **£375.5m** (benefit) and **£60.2m** (loss).

The benefits value has most significantly been impacted by growth of the sector since the last report. The sources of benefits are the reduction in maintenance cost, fuel consumption and CO_2 emissions. The valuation metrics that are used to assess these benefits have also increased, for example, fuel price and the Social Cost of Carbon.

The estimated value of economic impact of loss of GNSS has also been impacted by the growth of the sector in terms of GVA. This means more value of GVA is now at risk if deliveries are missed or delayed. Furthermore, wages have also increased. Should the sector need to hire additional staff to manage fleets manually, the labour cost would be higher.

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132 Traffic Commissioners. (2016). 'Traffic Commissioners' Annual Reports 2015-16'. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/567036/tc-annual-report-2015-2016.pdf [accessed July 2021].
Note that while more recent data is unavailable, other sources ('Domestic Road Freight Statistics 2019', available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/898747/domestic-road-freight-statistics-2019.pdf) indicate that while the number of large license holders has decreased, the number of vehicles per license has increased. The assumed number of licenses has thus been held steady at 6,000.

133 In 2017 London Economics assumed 3 staff. This has been grown in line with the growth in tonne-kilometres of goods moved.

134 Current minimum wage for 23 and over as of 16 July 2021.

135 Assumption from the last iteration of this report.

136 Taken from ONS (2017) Annual Business Survey for 2018. As the figure for 2019 was not available, the compound annual growth rate in GVA between 2013-2018 was 9.4%, this was applied to the £13,173.0m figure, arriving at £14,412.8m

4.7.3 Insurance telematics

Insurance telematics refers to insurance products that are offered at a reduced premium, and in exchange, the insurance company fits a black (telematics) box to the driver's car. The box measures the driver's behaviour behind the wheel. The box then sends the data to the insurance company, which are used to assess the riskiness of the driver. A personalised renewal quote can then be offered to the driver.

Economic benefit

The annual economic value generated by GNSS in insurance telematics is estimated at **£1,323.8m**. Two benefits are monetised.

The first type of benefit is accident reduction. According to the British Insurance Brokers' Association, telematics-based insurance is mostly taken up by young drivers.[137,138] The association also points out that the accident rate of young drivers with a telematics black box reduces from 1 accident in 5 drivers to 1 accident in 19 drivers.[139] In 2019, it has been estimated that there were 1.3m live telematic based policies.[140] Using the assumption from the previous GNSS loss report that 76.9% of the policies were held by young driver, there are over 1.0m young drivers with a telematic based policy in 2019.

Assuming that without the telematic black box, 1 in 5 of those drivers would have an accident – 204,742 drivers. With the telematic black box, it's down to 1 in 19 – 53,880 drivers. This implies a reduction of accidents involving a young driver of 150,863. The Department for Transport estimates the average value of preventing a road accident in 2019 at £8,667.[141] This implies the value of accident prevention thanks to young drivers having the telematic black box to be £1,307.6m.

The second type of benefit is insurance fraud reduction. Information on a vehicle's location at all time means that if a driver damages their vehicle on purpose and claim it was an accident, the insurance companies can look at the data and assess the validity of the claim. This makes pay-outs to insurance fraud less likely. Assuming a 60.0% reduction[142] in insurance fraud, applying to LE's database on the amount of UK insurance paid out and the amount of which is fraudulent, the annual value of insurance fraud reduction amounts to £16.2m in 2019.

Economic loss

The economic impact of loss of GNSS in Insurance telematics is not estimated.

[137] British Insurance Brokers' Association. (2018). 'BIBA research reveals telematics based policies almost reaches one million mark'. Available at: https://www.biba.org.uk/press-releases/biba-research-reveals-telematics-almost-reach-one-million-mark/ [accessed July 2021].

[138] British Insurance Brokers' Association. (2020). 'BIBA renews Marmalade's young driver telematics scheme'. Available at: https://www.biba.org.uk/press-releases/biba-renews-marmalades-young-driver-telematics-scheme/ [accessed July 2021].

[139] It is difficult to determine categorically whether this effect is causal or a result of selection into different types of policies. For new drivers there probably is a significant effect on behaviour and habits, but as long as it is affordable to buy a non-telematics insurance policy it is likely the safer drivers that select this.

[140] London Economics estimate: Footnote 137 indicated that there were one million live policies in 2018, with an implied compound annual growth rate of 33% between 2012 and 2017. This rate is applied to the one million figure, yielding 1.3 million live policies in 2019.

[141] Department for Transport. (2021). 'Reported road accidents, vehicles and casualties tables for Great Britain - RAS60002'. Available at: https://www.gov.uk/government/statistical-data-sets/reported-road-accidents-vehicles-and-casualties-tables-for-great-britain [accessed July 2021].

[142] Established through stakeholder consultation.

The economic benefits of this application come from the behaviour change in the drivers as a result of having the telematic box on their cars. The impact of a GNSS loss on these drivers depends on whether they would take the event as a free pass to drive recklessly and make fraudulent claims. However, it is not possible to determine whether drivers have adopted safer habits and therefore maintain a mental "holdover", which is unaffected by the loss of GNSS. In the absence of better evidence, this economic loss is not estimated.

Drivers of change

In the previous iteration of this report, the estimate of economic benefit (**£16.1m**) differs from the updated estimate presented in this report of **£1,323.8m**. Loss is not estimated in both reports.

The benefits value has most significantly been impacted by the increase in the size of the market. At the time of writing the last report, there were 455,000 live telematic policies.[143] The number of live policies is estimated to be 1.3m in 2019 as above. The increase in the live policies means that more drivers benefited from the reduction in accident. Insurance companies also benefit more from insurance fraud prevention.

4.7.4 Emergency and breakdown call (eCall and bCall)

Emergency call (eCall) automatically makes a call to emergency services if the car's airbags are triggered. The call derives the driver's location via GNSS signals and shares it with the emergency services. eCall also allows the driver to manually trigger the call. A related onboard system is breakdown call (bCall), which routes the call to a help centre that can then send for assistance from break-down assistances companies. eCall and bCall are considered together.

Economic benefit

The annual economic value generated by GNSS in eCall and bCall is estimated at **£18.6m**. The benefits come from lives saved and reduced congestion – accidents located and managed faster will free up traffic.

The number of cars with eCall and bCall in the UK in 2019 is estimated to be 2.3m.[144]. In 2019, the estimated number of fatalities per car was 0.000045.[145,146] If it is assumed that the 2.3 million cars with eCall and bCall would have this fatality rate in the absence of eCall and bCall, these cars would see 105 fatalities in 2019. eCall aims to reduce fatalities on road by 10%. Saving 10% of those 105 lives would mean saving 10.5 lives. Department for Transport values each prevented fatality at £1.8m[147]. This implies the total value saved by eCall and bCall comes to £18.6m.

[143] British Insurance Brokers' Association. (2018). 'BIBA research reveals telematics based policies almost reaches one million mark'. Available at: https://www.biba.org.uk/press-releases/biba-research-reveals-telematics-almost-reach-one-million-mark/ [accessed July 2021].
[144] Estimated from London Economics' database on global GNSS based devices.
[145] In 2019, there were 1,752 road deaths reported in the UK (Department for Transport. (2020). 'Reported road casualties in Great Britain 2019: annual report' https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/922717/reported-road-casualties-annual-report-2019.pdf [accessed July 2021].)
[146] There were 38.7 million cars in the UK in 2019, implying 0.000045 fatalities per car when used in conjunction with Footnote 145. (Department for Transport. (2020). 'Vehicle Licensing Statistics: Annual 2019' https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/882196/vehicle-licensing-statistics-2019.pdf [accessed July 2021].)
[147] The value of prevented fatalities was valued at £1.7m in the 2017 iteration of this report. This followed *Department for Transport. (2007). 'Highways Economics Note No. 1 2005 Valuation of the Benefits of Prevention of Road Accidents and Casualties'*, inflated using the GDP deflator (sourced from the ONS). This report simply inflated the £1.7m figure again using the GDP inflator, bringing it to £1.8m.

Economic loss

The economic impact of loss of GNSS in eCall and bCall is estimated at **£ 0.4m**.

A UK car manufacturer told London Economics that the integrity of eCall and bCall would be compromised in the event of a GNSS loss. Whether location information could still be derived would depend on the car architecture. They said that their early generations of eCall and bCall systems would use GNSS inputs only. Their later generations, referring to models introduced to the market in 2019 or 2020, would use inputs from other onboard sensors, for example, dead reckoning, wheel steering angle, on board maps.

New models' eCall and bCall could therefore continue to function in reduced capacity. However, only new vehicles would have this capability and they had only hit the market around 2019. The annual benefits estimated for the application is therefore assumed to be lost in the 7-day period.

Drivers of change

In the previous iteration of this report, the estimates of economic benefit (**£15.0m**) and loss (**not estimated**) differ from the updated estimates presented in this report of **£18.6m** (benefit) and **£0.4m** (loss).

The benefits value has most significantly been impacted by two key updates. First, the number of cars with eCall and bCall have increased since. In the 2017 report, the number of cars were approximated by the number of cars with commercial eCall systems – 1.8m in 2016 (as opposed to 2.3m in 2019 used in this report). Second, valuation per prevented fatality has also adjusted using the GDP inflator.

The estimated value of economic impact of loss of GNSS was not estimated in the last report as the application had a lower penetration rate. The impact of loss therefore would have been small. The penetration rate remains low now, illustrated by the £0.36m of economic loss. eCall became mandatory for all cars type approved since 2018[148]. Hence the penetration rate will increase as the car market cycle gets to those new car types.

4.7.5 Autonomous vehicles

Autonomous vehicles, also known as self-driving vehicles, have a degree of automation by using information from on-board sensors. Examples of these sensors are cameras, radar, LiDAR and GNSS receiver. Inputs from GNSS is used by the onboard computer to compute an estimate of the vehicle's absolute positioning, while the inputs from other sensors is used for relative positioning.

Autonomous vehicles in this report are defined as level 3 or above. At level 3, human intervention may still be needed as a fall back option. Above level 3, driving is performed entirely by the system. This definition is in line with the UK Centre for Connected and Autonomous Vehicles.[149]

[148] European Commission. (2018). 'eCall in all new cars from April 2018'. Available at: https://digital-strategy.ec.europa.eu/en/news/ecall-all-new-cars-april-2018 [accessed July 2021].

[149] Connected Places Catapult. (2020). 'Market forecast for connected and autonomous vehicles'. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/919260/connected-places-catapult-market-forecast-for-connected-and-autonomous-vehicles.pdf [accessed July 2021].

Autonomous vehicles accounted for close to 0% of total new car sales in the UK in 2019.[150] The share is estimated to remain low until 2030, where the share is projected to rise to 4%.[151] As the take up of autonomous vehicles in the UK is still low, the economic benefits and loss are likely to be low. These are therefore not monetised but discussed qualitatively.

Economic benefit

GNSS and other on board sensors all have different strengths and weakenesses. They can therefore complement each other. The value that GNSS brings is the areas in which the other sensors are weak.

Camera would not be effective in detecting surroundings on featureless roads.[152] This means on country roads, or on roads with limited markings, it would need assistance from the other sensors. Its effectiveness would also diminish when visibility is low (such as when the weather condition limits visibility). LiDAR is similar to cameras in that it is not effective at guiding navigation on featureless roads.[153] Radar cannot detect road markings.[154]

In the environments where these sensors are not effective, GNSS remains effective or is in fact most effective.[155] In rural, unobstructed areas, the vehicle is more likely to receive better GNSS signals. The benefits that GNSS brings to autonomous vehicles is therefore the support that GNSS can provide to the other sensors when it is most needed.

Two stakeholders pointed out another benefit that GNSS brings to autonomous vehicles is the timing that it provides. As there are multiple inputs coming from multiple sensors in an autonomous vehicle, these inputs need to be timestamped for processing. The stakeholders indicated that the time source will likely come from GNSS.

Economic loss

The economic loss of GNSS outage would be from the reduction in autonomous vehicles' navigation efficiency when the other onboard sensors have low performance. This would be on rural roads, or in low visbility or dark environments.

However, as autonomous vehicles are still in development, it is unclear what contingency measures developers would have put in place and hence the impact of a GNSS loss on these vehicles is also unclear. One leading UK car manufaturer told London Economics that the research on their autonomous vehicles' dependency on GNSS is still ongoing, in particular in terms of safety implications. However, they are working to make their autonomous vehicles able to function independent of GNSS. A potential solution they provided as an example was the use of high

[150] Connected Places Catapult. (2020). 'Market forecast for connected and autonomous vehicles'. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/919260/connected-places-catapult-market-forecast-for-connected-and-autonomous-vehicles.pdf [accessed July 2021].
[151] Connected Places Catapult. (2020). 'Market forecast for connected and autonomous vehicles'. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/919260/connected-places-catapult-market-forecast-for-connected-and-autonomous-vehicles.pdf [accessed July 2021].
[152] Septentrio. (2019). 'The role of GNSS localization in safe assisted driving'. Available at: https://www.septentrio.com/en/insights/role-gnss-localization-safe-assisted-driving [accessed July 2021].
[153] Septentrio. (2019). 'The role of GNSS localization in safe assisted driving'. Available at: https://www.septentrio.com/en/insights/role-gnss-localization-safe-assisted-driving [accessed July 2021].
[154] Septentrio. (2019). 'The role of GNSS localization in safe assisted driving'. Available at: https://www.septentrio.com/en/insights/role-gnss-localization-safe-assisted-driving [accessed July 2021].
[155] Septentrio. (2019). 'The role of GNSS localization in safe assisted driving'. Available at: https://www.septentrio.com/en/insights/role-gnss-localization-safe-assisted-driving [accessed July 2021].

definition maps with details down to lane level, which would then be coupled with camera and other sensors to guide navigation.

The loss of GNSS would also mean that autonomous vehicles would lose GNSS as a source to calibrate its central timing. This would be particularly an issue for connected autonomous vehicles when vechicles have different timing. The car mannufaturer also confirmed that the clock in the car alone would not be sufficient. Therefore the central timing would need to be calibrated by GNSS.

Drivers of change

This application was not considered in the previous iteration of this report.

4.7.6 Connected road applications

Connected road applications in this context refers the following applications: Cooperative Intelligent Transport Systems (C-ITS), Vehicle to Everything (V2X) Communications, Platooning/Flocking, and Smart Parking.

The common feature among these applications is that they either involve vehicle-to-vehicle communications or vehicle to infrastructure communications. These communications aim to improve coordination among road users, improving traffic flow efficiency.

The economic benefits and loss of these applications are not estimated due to their low penetration rate in the UK market.

Economic benefit

GNSS enables devices in the network of these applications (these could be, for example, a connected car or smart traffic light) to know each other's real time location. A finding emerging from the stakeholder consultation is that these connected devices would need to be time-synchronised. These applications are still being developed, so it is unclear what would act as the time source. One stakeholder suggests that it would likely be GNSS. This is because to cover the connection over a large area it would be expensive to use ground infrastructure to derive the common time source (e.g. fibre). GNSS would be a lower cost option. It is attractive to use GNSS for synchronisation as it is consistent and global. This way, car manufacturers can define a single standard without the need to incorporate idiosyncratic national or regional systems.

Economic loss

These applications could be severely affected by GNSS loss. A real life event in New York City in 2019 demonstrated the consequence of losing GNSS as a time source.[156] The timing in GPS had a scheduled update – the week number in GPS signal reset to zero. This caused the New York City Wireless Network to crash. Traffic lights at 12,389 intersections became disconnected. The city's authority would not know if a traffic light had stopped working unless someone had reported the incident. The cameras that normally record real-time traffic information also became inactive because of the disconnection.

[156] Davis, D. A. (2019). 'GNSS Rollover hamstrings New York city wireless network'. Available at: https://insidegnss.com/gps-rollover-hamstrings-new-york-city-wireless-network-and-a-handful-of-other-systems/ [accessed July 2021].

This event illustrates the impact of losing GNSS as the common time source. Connected devices' timing can drift apart and this could disrupt the certification in the connection process, prompting the connection to end.

Drivers of change

These applications were not considered in the previous iteration of this report.

4.7.7 Other emerging road applications

Other emerging road applications include Intelligent speed Assistance (ISA), Next Generation Road User Charging, and Intelligent Salt Spreading/De-Icing.

Economic benefit

Intelligent Speed Assistance (ISA) uses GNSS to derive the car's driving speed. If the speed is higher than the local speed limit. ISA will issue warning to the driver or limit the engine power to slow down the vehicle. The economic benefits would therefore relate to the accident reduction and prevention associated with speeding, and also potential fuel efficiencies. New cars sold in the UK will be required to be fitted with ISA from 2022. Currently, the share of vehicles with ISA is very low – less than 1%. The economic benefits in 2019 was therefore low and is not estimated in this report.

Next Generation Road User Charging refers to a regime where GNSS is used to track and charge road use. Currently this has not yet been used in the UK but it has been used in several countries, including Belgium, Czechia, France, Germany, Hungary, Slovakia, and Switzerland. These countries have demonstrated the economic benefits of using GNSS to implement road user charging.

The use of GNSS means that less roadside infrastructure is required. Gantries are not required for tolling any more, only for enforcement. It has been estimated that tolling via GNSS saves 80% of infrastructure that would otherwise be required.[157] Furthermore, because less physical infrastructure is required, it can be quick to adopt or extend the road user charging regime. Adding or removing sections of roads in the scheme only requires changes in the back-office system. Slovakia provides a clear illustration. The country uses a GNSS based road user charging scheme. It had around 2,500km of road covered by its road charging scheme, it then extended to nearly 17,800km within one month.[158]

Therefore, there are potential economic benefits associated with using GNSS for road user charging. The UK authorities could save costs from installing less roadside infrastructure. They could also make extend or reduce the scheme's coverage without having to make physical alteration on the roads. Existing road user charging schemes use automatic number plate recognition technology.[159]

Intelligent Salt Spreading/De-Icing is a technology that uses GNSS positioning to automatically spread de-icing salt on the road. The technology also adjusts the spread setting according to the driver's speed and location. This technology allows all activities in a spreading run to be recorded, including spread settings, time spread and where the salt was spread. Such information is useful for local councils if there is a legal action brought against them. The councils could use the information as evidence to prove that the activities were indeed carried out. In addition, the automatic spreading

[157] EUSPA. (2015). 'GNSS adoption for Road User Charging in Europe, Issue 1'.
[158] EUSPA. (2015). 'Slovak Republic embraces European GNSS'. Available at: https://www.gsc-europa.eu/news/slovak-republic-embraces-european-gnss-3 [accessed July 2021].
[159] However, it is not clear whether the technology uses GNSS to timestamp data.

could improve the efficiency of the spread run. Human error would be reduced. The time it takes to finish a spread run would be reduced, saving labour costs. The economic benefits would therefore come from better records on spread runs and increased efficiency during the runs. Penetration rate in the UK is still low[160] and the current benefits are likely to be small and therefore not calculated.

Economic loss

These applications uptake is still low in the UK, as discussed above. The potential economic loss is briefly discussed below.

The UK car manufacturer told London Economics that Intelligent Speed Assistance (ISA) would be compromised but unlikely to fail completely immediately. This is because for ISA to work robustly, there should be on-board maps containing speed data. Therefore, immediately following the GNSS loss, ISA should make use of dead reckoning to work out its position on the map and the relevant speed limit. The manufacture said that however this means if the car goes off road or GNSS loss continues in a prolonged period (such as 7-days), the system would not be able to align the vehicle's location on a map. Nevertheless, if ISA were to fail completely, it is unclear whether drivers would take GNSS outage as a free pass to speed. ISA could have trained drivers to drive safely, so much so that in the absence of the ISA, they continue to do so.

Next Generation Road User Charging would not be able to use GNSS data to collect road user charges. Authorities might not be able to track road use. This in turn would affect the authorities' revenue. The extent of this impact would depend on whether last generation's infrastructure is still in place and ready to be used as back up, such as tolls and cameras with licence plate recognition.

The loss of intelligent Salt Spreading/De-Icing is likely to mean that local authorities would, in the hypothetical case where penetration is higher than it is today, go back to employing more labour to carry out and record the spread run. The increase in labour cost would be one aspect of the economic loss. If the technology tends to make less error than when it's done manually, GNSS loss could mean an increase in accident too.

Drivers of change

These applications were not considered in the previous iteration of this report.

4.8 Other updated sector benefits

This report has focused the attention on seven priority sectors of the UK economy. This section covers the remaining sectors for which economic loss was estimated as a result of a five-day outage of GNSS in the 2017 report. Sectors that were deemed to be resilient to a five-day outage, and which were not prioritised for this report, are assumed to be resilient to a seven-day outage and therefore not analysed. For more information on the remaining sectors, please see London Economics (2017). 'The economic impact on the UK of a disruption to GNSS'.[161]

The benefits of GNSS in these other updated sectors are summarised in the table below and detailed in the text the follows.

[160] Evidence provided by the UK Space Agency.
[161] London Economics. (2017). 'The economic impact on the UK of a disruption to GNSS'.

Table 18 Other updated sector benefits

Sector	Economic benefit (annual, £m)
Offender Tracking	31.5 (*+2.3%*)
Satellite Communications	32.4 (*+2.2%*)
Surveying	27.5 (*+97.8%*)
Location-Based Services (LBS)	209.8 (*+2.4%*)
Energy	4.5 (*+2.3%*)
Fixed line communications	32.8 (*+2.5%*)
Cellular telecommunications	5.1 (*+2.0%*)
TETRA	4.6 (*+2.3%*)
Meteorology	102.0 (*+2.0%*)
Health	291.3 (*+17.6%*)
Total	**741.5 (*+24.7%)***

Note: *(+%) indicates the variation in economic benefits since the 2017 iteration of this report.*
Source: London Economics analysis

4.8.1 Offender tracking

Recent years have seen an increased roll-out of GPS trackers to monitor the movements of criminal offenders throughout the UK. During 2019 it was estimated that around 60,000 offenders were tracked throughout the course of the year, with up to 1,000 individuals monitored at any one time.[162] Newly released burglars, thieves and robbers were fitted with GPS tags to track their movements in what is thought to be a world first scheme aimed at prevention of reoffending within the first twelve months of release from prison.

The present scheme in 2021 is currently targeted within six police forces across the UK, with plans to expand into a further seven regions by the autumn.[163] The primary benefits of adoption of the scheme for the offenders themselves include a greater degree of flexibility of movements, with geo-fenced areas expanded to allow participants to travel to work should this be required or for other essential journeys such as for medical reasons. Whilst RFID tags attached to the offender's ankle remains the primary means of tracking, there is also the potential to track less violent offenders using GNSS tracking via smartphone.

With a slightly increased cost of a prison place in the UK versus the previous study compared against daily operating cost for tracking offenders in the region of £12 per day, there is a slight increase in the previous estimate of £30.8m. With the current estimate of up to 1,000 offenders tracked at any one time, the current benefits are calculated to be in the order of **£31.5m**. This figure represents a slight increase on the 2017 study assessment, which valued benefits at £30.8m.

Offender tracking is particularly vulnerable to jamming and spoofing as that would permit them to leave the legally permitted region that they may occupy within the constraints of geofencing.

4.8.2 Satellite communications

High-throughput mobile satellite communication devices require GNSS fix in order to complete the 'handshake' with the geostationary communications satellite, which allows acquisition of the

[162] BBC. (2019). 'Electronic GPS tags to track thousands of criminals in England and Wales'. Available at: https://www.bbc.co.uk/news/uk-47256515 [accessed July 2021].
[163] Ministry of Justice. (2021). 'GPS tags to hunt burglars and cut theft'. Available at: https://www.gov.uk/government/news/gps-tags-to-hunt-burglars-and-cut-theft [accessed July 2021].

appropriate focused spot beam. Inmarsat have confirmed that GNSS location information is required, and that no alternative means of inputting location information is available on the communication devices.

It is beyond the scope of this study to estimate the benefits of mobile satcoms, however it is noted that SpaceX's Starlink, one of the leading entrants into the new generation of mobile satellite communications, is including GNSS receivers within early versions of their phased array antenna user devices as part of their initial commercial service.[164] It is unclear however to what extent the usability of the device depends upon GNSS availability.

A recent study however estimates annual global benefits of satcoms in aviation of $480m,[165] adjusted to £489.6m based on CAGR (Compound Annual Growth Rate) growth. Benefits mainly accrue to passengers and airlines so the UK share of global benefits is approximated based on the registered country of aircraft. The UK's share of the global fleet is 6.61%,[166] so the annual UK benefits of satcoms in aviation is estimated at **£32.4m**, a slight increase on the value found in the previous study iteration of £31.7m.

Users of fixed satellite communications do not rely on GNSS.

4.8.3 Surveying

Since the potential for the use of GNSS within surveying applications was identified at an early stage within the surveying community, penetration levels have remained steadfastly high within the sector. Indeed, now many surveying applications are typically highly dependent on GNSS, and owing for the need for high levels of precision may incorporate Real Time Kinematic (RTK) systems for additional accuracy. GNSS has fundamentally changed the surveying profession as traditional requirements of clear line of sight between the point of measurement and a known reference point is no longer required. The benefits of GNSS in Surveying are assessed against a counterfactual where GNSS would not have taken the widely pervading role that has been established and an alternative remained. The latest data from Eurostat (special extract request) suggests there are approximately 50,000 surveyors in the UK.

Users can broadly be classified in three categories: users of handheld devices, machine control and marine surveying. Handheld surveying includes cadastral surveying, which deals in the measuring of cadastral boundaries and the resolution of boundary disputes. The benefits therefore materialise in the form of labour cost reductions.

Mapping is a discipline that charts specific points of interest for cartographic, environmental, and urban planning. Generally, the devices used in mapping are the simplest in the surveying domain as the required accuracy is lower than for other applications. Here too, benefits accrue thanks to reduced labour costs.

Mining encompasses all surveying application pertaining to the measurement of mines and associated yields. Generally this is limited to open-pit and surface mining.

164 Nardi, T. (2021). 'Hackaday'. Available at: https://hackaday.com/2020/11/25/literally-tearing-apart-a-spacex-starlink-antenna/
165 Helios. (2017). 'The benefits of satcom to airlines'. Available at: https://www.inmarsat.com/content/dam/inmarsat/corporate/documents/aviation/insights/2017/Helios%20Study%20-%20Airline%20Benefits%20of%20Satcom%20-%20A%20Report%20for%20Inmarsat.pdf.downloadasset.pdf [accessed July 2021].
166 Based on Flightglobal: https://www.flightglobal.com/

GNSS is primarily used for Civil Engineering projects such as road or rail construction. Construction surveying is split between person-based and machine-based, where person-based construction saves labour inputs for the same efficiency reasons as the other handheld applications. Machine control is similar in essence to the applications in agriculture, and manufacturers of equipment report significant benefits. Benefits accrue because an automatic construction machine can apply new concrete or asphalt more precisely than humans, or alternatively saves inputs through the ongoing maintenance of roads. GNSS helps to ensure newly paved roads are accurately located and meets the other junction point where it is intended.

Marine surveying includes hydrographic surveying, which is the charting of the seabed, and a key input in offshore oil and gas exploration, which both require highly accurate location information.

Additional applications in the surveying domain include infrastructure monitoring, which is the study of movements in infrastructure to enable early fault detection and allow faster repair. The Crossrail project is a good example of a construction project that may use GNSS to monitor the buildings above the construction sites (both need to be verified for actual usage). However, benefits are extremely difficult to monetise.

In totality, the assessed surveying benefits have increased to **£27.5m** from £13.9m since the previous iteration.

4.8.4 Location-Based Services (LBS)

Location-based services span a variety of consumer-focused applications that all rely on location. In terms of equipment, the main means of accessing location is via the GNSS chip in an individual's smartphone or tablet, with a significantly smaller proportion of use coming from dedicated devices, mainly in the tracking domain (fitness, smartwatches, wearables etc.). GNSS is the most accurate source of location information outdoors, but the location calculation algorithm within smartphones uses supplementary information from Wi-Fi networks and cell-ID to calculate the location.

For smartphones and tablets, the accessibility of GNSS means that many people use the technology. As per 2018 for example, there were some 5.5m apps available for download across the main app stores which potentially rely on location to varying degrees.[167]

Monetised benefits of GNSS in location-based services include those that are driven by the ability of users to shift from personal cars as the primary means of transport and to identify alternative means of travel. The market leading map applications for smartphones all include a 'public transport' option, which induces a small proportion of users to switch means of transport. Benefits are monetised as fuel consumption reduction and associated reduction in air pollution and CO_2 emissions.

Additional benefits are realised for navigation. Focusing solely on time savings benefits from pedestrian navigation (road-based navigation being considered elsewhere), GNSS helps people navigate through unknown areas and avoid getting lost. Benefits from other applications such as Augmented Reality gaming (Pokémon Go remains by the far the most downloaded example[168]), location-aware social media, and location-based advertisements have not been monetised.

[167] EUSPA. (2019). 'GNSS Market Report Issue 6'.
[168] Tekrevol. (2021). '22 best augmented reality games for 2021'. Available at: https://www.tekrevol.com/blogs/22-best-augmented-reality-games/ [accessed July 2021].

Fitness tracking is accessible through both smartphone applications and dedicated devices. Many smartwatches also feature some level of activity tracking beyond dedicated devices. GNSS enables the user to track their progress and chart their route when running, cycling or undertaking other sporting activities. The total annual economic costs to the NHS due to physical inactivity were estimated to be €14.2bn.[169] The cost savings due to increased physical activity as a direct result of GNSS in fitness tracking devices are calculated to monetise these benefits. Benefits have been monetised using input assumptions that attribute a modest proportion of the increased activity to GNSS.

Beyond location, the time on smartphones is calibrated by derivations from GNSS or networks that have been synchronised using GNSS.

Total LBS benefits have remained relatively consistent since the last iteration, with a slight increase from £204.8m to **£209.8m**.

4.8.5 Energy

The National Grid is the UK's electricity transmission and distribution company. GNSS is not used for distribution, but it is a very important input in transmission.

National Grid's substations monitor the voltage and load on the network, and adjacent substations communicate with each other to identify disturbances. The communication between substations is timestamped using GNSS-time to ensure that the information is identified in the correct order. If there is a fault in the communication link between substations, the information is rerouted, so the time it takes for the information to be received may increase. Without the timestamp, incorrect inferences may be drawn from the information.

In case of disturbance, National Grid are required to shift the load from a disturbed power line to a functioning line within 120ms. This relies on the layout of the transmission grid, which is fully meshed. Benefits of GNSS materialise as GNSS equipment has longer lifetime than atomic clocks, which would be the alternative. Additional benefits are derived because GNSS clocks are synchronised as part of operations, whereas atomic clocks would need to be conditioned periodically.

The benefits arising from longer device lifetime are monetised at **£0.8m** per year based on 337 substations, each using 8 GNSS receivers/clocks on average, at a cost of £2,000 and lifetime of 20 years for GNSS and 5 years for atomic clocks.

The removal of the need to condition atomic clocks through non-GNSS sources brings great benefits, as transportation of accurate time to each substation is a challenging endeavour. Indeed, owing to the remoteness of the network, it is questionable whether a fibre-based time transportation system could be created at all. The National Grid's transmission network is approximately 8,000 km long,[170] and the price of fibre-optic cable ranges from £3.20 to £8.50 per metre.[171] Assuming £3 per metre, and the need for three times the network to ensure resilience, the capital cost for National Grid would be £72m, in addition to which the accurate timescale would come at a cost. Assuming the

[169] Centre for Economics and Business Research. (2015). 'The economic costs of physical inactivity in Europe - An ISCA and Cebr report'.
[170] National Grid. (2017). 'UK Transmission'. Available at: http://www2.nationalgrid.com/Contact-us/UK-Transmission/ [accessed March 2017].
[171] FS.com. (2021). 'Armoured Cable'. Available at: https://www.fs.com/uk/c/armored-patch-cables-220 [accessed July 2021].

lifetime of fibre optic cable is 20 years, this would imply annualised replacement cost of **£3.7m.** With GNSS, these costs have not materialised.

The total benefits are then relatively unchanged at **£4.5m**, an increase of £0.1m from the previous iteration. Additional benefits of using GNSS are derived from convenience. Suppliers of equipment offer a complete solution incorporating GNSS. This removes an obligation on National Grid to offer its own timing solution.

4.8.6 Fixed line communications (including internet)

Fixed-line telecommunications use GNSS as a source of timing information. Following Chronos (2011) three distinct aspects of timing may be considered. These are: i) Traffic Timing (Frequency); ii) Common epoch (usually UTC) time slot alignment (Phase) and iii) Time of day (Time).

Digital telecommunications consist of data packets that flow around the network at a constant rate defined by the bandwidth of the network. In order to ensure the correct packet is 'unpacked' in the correct location, it is necessary to ensure all '(un)packing stations' or switches operate a mutually referenceable time, thereby ensuring that the packets arrive at the correct destination.

The errors that may occur in the telecoms networks are constant traffic speed errors and varying traffic speed errors (wander). Constant traffic speed errors imply that data arrives at the switch either too early or too late compared with expectation. If the problem becomes too large, and the buffer at the switch fills up, the buffer must be emptied, and data is lost. Wander has a similar effect but differs from constant traffic speed errors as the error may cancel out over time.

To reduce the risk of errors, the devices at opposite ends of the network must be synchronised to the same clock.

Telecommunication timing devices have holdover capability whose precision depends on the exact oscillator in use. The use of GNSS enables network operators to calibrate local timing devices using GNSS, and thus save money compared to a setup using atomic clocks conditioned by alternative sources.

Since telecommunications is particularly critical, the core network derives timing information from three independent sources to ensure resilience against outage of one source. Limited evidence suggests switches at the edge of the networks may rely on GNSS to greater extent.

Benefits have been estimated in the order of £5.8m per year from reduced infrastructure costs on atomic clocks (assuming prices are comparable, the savings derive from the longer lifetime of GNSS devices).

Additional benefits are achieved as the GNSS-based solution removes the need for the telecoms company to provide alternative sources of timing in a setup where atomic clocks are used. Base stations are connected by cable or satellite backhaul, so there is an alternative means of distributing timing information, but the required precision of time means that this would require a complicated setup, which is avoided when using GNSS. The UK fixed-line telecommunications networks consists of approximately 100,000 nodes spread all over the UK. Delivering synchronised time to those nodes would involve significant additional effort. Using the same ratio of atomic clock-benefits to capital investment reduction-benefits as derived for Energy the savings are estimated at **£32.8m**, a modest increase of £0.8m against the previous iteration of this study in 2017.

4.8.7 Cellular telecommunications

In addition to the application of GNSS in fixed-line telecommunications, a further layer of complexity is introduced as base station timing for radio frequency stability and call hand-over management are required. Benefits can be estimated from reduced infrastructure costs on atomic clocks (assuming prices are comparable, the savings are derived from the longer lifetime of GNSS devices).

Much greater benefits are achieved as the GNSS-based solution removes the need for telecoms companies to provide alternative sources of timing in an alternative setup where atomic clocks are used. Not all cellular base stations are cabled, so it is necessary for the operator to provide an alternative delivery mechanism of precise time (e.g. using synchronised Ethernet) to the estimated 50,000 base stations in the network. Using the same ratio of atomic clock-benefits to capital investment-benefits as derived for Energy (see section 4.8.5), the savings are estimated in excess of £4.0m, resulting in a total benefit of the order **£5.1m**. This figure represents a modest increase against the total 2017 benefit of £5.0m.

4.8.8 TETRA

The mobile radios of Emergency Services in the UK use the TETRA (Terrestrial Trunked Radio) standard for internal real-time communication. GNSS plays a crucial role in synchronising the network and individual handsets. Expert consultees indicated that resilience to GNSS outages among handsets is minimal, highlighting the importance of GNSS as an input into the system. Benefits have been monetised at **£4.6m** by updating those modelled in the previous iteration of this report according to the UK inflation rate.

The UK's emergency services are in the process of migrating to a different network, though the process has experienced a number of delays. The new, EE (owned by BT) provided, network will provide faster data speeds but requires infrastructure upgrades to achieve the same coverage as the current system which has an approximate 97% geographic reach within the UK.[172] As it is still in progress, the impact of this new network on the UK's reliance on TETRA and hence GNSS is not considered in this report.

4.8.9 Meteorology

The Met Office is the UK's National Meteorological Service and is a Trading Fund within the Department for Business, Energy and Industrial Strategy (BEIS). The Met Office uses GNSS for a wide array of applications including:

- **Radio-occultation**: a technique where the refraction of GNSS signals across the atmosphere is measured by high-quality GNSS receivers on board meteorological satellites hundreds of times per day. This process refines estimates of water vapour in the atmosphere and contributes a couple of % to total weather forecasting accuracy. A similar activity is undertaken a few times per day by ground-based receivers. Using GNSS signals, the Met Office also maps the ionosphere by assimilating data from LEO satellites such as those operated by ESA, EUMETSAT, and since June 2020, commercial operator Spire[173], to inform satellite operators of any anomalies.

[172] ISPreview. (2020). 'New 4G Emergency Services Network Faces Another 2 Year Delay'
[173] Met Office Press Office. (2020). 'The impact of coronavirus on Met Office observations'. Available at: https://blog.metoffice.gov.uk/2020/06/15/the-impact-of-coronavirus-on-met-office-observations/ [accessed July 2021].

- **Positioning of sensors**: The Met Office sources many data points from moving sensors including weather balloons, marine networks (including buoys, Argo floats, and ships), and aircraft with in-built weather sensors. Many of the sensors use GNSS as the only source of position information. In addition, the JASON satellites operated by EUMETSAT (measuring sea level) are GNSS-enabled as the technique requires extremely accurate information on the location of the satellites.
- **Lightning detection network**: Using the time of detection of the radio pulse of lightning strikes at different sites in the network it is possible to accurately estimate the location of lightning strikes. This approach requires very accurate timing and location information, which is sourced from GNSS.
- **Timing and synchronisation:** The Met Office's internal network and supercomputer are synchronised using GNSS clocks on-site. The supercomputer requires timing accuracy of approximately 1s.

A recent London Economics study[174] of the UK Met Office estimates its economic impact at £30bn over 10 years. It has been found that 50% of this value is attributable to observations, where the location of sensors makes a key contribution to the accuracy of the forecasts. This suggests GNSS benefits in weather forecasting upwards of **£102m** per year, of which around 25% are utility benefits to the public and climate change information benefits, and the remaining 75% benefits to businesses. This is a slight increase on the estimation of £100m annually in 2017 based on reappraisal of the inputs to the original study.

4.8.10 Health

The Health CNI does not rely on GNSS at its core. Social carers, district nurses, midwives, etc. that drive from location to location however are considered to use GNSS for navigation purposes. This can be from smartphone-based navigation software for less urgent responses. Similar to emergency services (see standalone section), non-stationary activities are expected to rely on either GNSS-based fleet management solutions to respond to urgent requirements as and when they arise. In the simplest form, ambulance services transport patients to hospitals to allow treatment of ailments, and in some cases, transport patients back home, thereby freeing hospital beds for other patients. GNSS use in ambulance services is extensive, and as a result, the Health CNI has secondary reliance on GNSS.

One primary health application of GNSS is in tracking devices, which has the potential to offer benefits to people with dementia and their carers. The use of this technology can alert carers that an individual has moved outside a set boundary, as well as assisting in locating a person at any time or in any place where GNSS is accessible. This is likely to be associated with significant benefits in terms of reduced search costs. Additionally, the freedom to move more freely provides physical and psychological benefits for people with dementia. There remain however concerns over the ethical and practical use of tracking devices for such patients.

The UK Alzheimer's Society reports that 850,000 patients are diagnosed with dementia with a total economic cost of £34.7bn in 2021.[175] Approximately, one-third live in residential care and the

[174] London Economics. (2016). 'Met Office – General Review'.
[175] Alzheimer's Society. (2021). 'Facts for the media'. Available at: https://www.alzheimers.org.uk/about-us/news-and-media/facts-media [accessed July 2021].

remaining two-thirds at home. McShane el al. (1998) found that 40% of people with dementia get lost outside their home. Therefore, there are approximately 227,800 annual search events.

A Norwegian study[176] estimates that GNSS can reduce the number of search events by half. Moreover, the use of a tracking device is likely to allow dementia patients to stay at home for six additional months, reducing the cost burden faced by the NHS.[177]

The number of dementia patients that are tracked using GNSS is not known, therefore benefits have not been monetised for the UK.

Other forms of trackers include those used by lone workers, whose superiors are able to respond to emergency signals from lone workers and direct search teams to their location. UK company Peoplesafe provides lone worker tracking devices and management solutions to more than 100 NHS trusts to allow district nurses and other personnel to trigger alarms if they face physical or verbal abuse. The company cites a Royal College of Nursing report that states that more than 60% of nurses have been subjected to abuse in a two-year period, with 10% having experienced physical assault.[178] The company also supplies solutions to more than 50% of police forces to be used by people under police protection, witness protection and anyone worried about their safety. Timely response in cases of domestic abuse can make a world of difference to the victim. Other applications of lone worker tracking are in hospitality, where lone hotel workers frequently face troublesome guests. Housing associations, council, and care workers may also find similar solutions beneficial.

The benefits of the GNSS-based solution are both in terms of peace of mind for the individual equipped with an alarm, and for companies who are able to prove that they take the safety of their staff members seriously. The Health and Safety Executive estimates that it costs £17,000-£19,000 to investigate a physical assault, costs that would be payable by the employer if found negligent.

Another UK company, TrackaPhone and the TecSOS project track approximately 15,000 subscribers, with strong growth foreseen over the coming years. The estimated number of lives saved in a year from tracking 15,000 people is 18-20, estimated based on actual alerts and the situations faced. The value of a statistical life is £2.0m according to the Department for Transport,[179] implying benefits of £38.0m. Assuming similar rates for Peoplesafe's 100,000 users, the total benefits are monetised at **£291.3m**, which represents an increase on the value estimated in the previous study of £247.6m. This is owing to an increase in the statistical value of life since 2016.

[176] Helsedirektoratet. (2017). 'Andre gevinstrealiseringsrapport med anbefalinger'. Available (in Norwegian) at: https://www.helsedirektoratet.no/rapporter/gevinstrealiseringsrapporter-nasjonalt-velferdsteknologiprogra [accessed July 2021].
[177] An estimated 25 percent of hospital beds are occupied by people with dementia (Source: Alzheimer's Society. (2009). 'Counting the cost – caring for people with dementia on hospital wards'.)
[178] Peoplesafe. (undated). 'More than one in ten nurses subjected to physical assault'. Available at: https://peoplesafe.co.uk/sectors/nhs/ [accessed July 2021]
[179] Department for Transport. (2019). 'Accident and casualty costs (RAS60)'. Available at: https://www.gov.uk/government/statistical-data-sets/ras60-average-value-of-preventing-road-accidents [accessed July 2021].

4.9 Other updated sector losses

The economic losses associated with a 7-day outage of GNSS in the other updated sectors are summarised in the table below and detailed in the text the follows.

Table 19 Other updated sector losses

Sector	Economic loss (7-day, £m)
Offender Tracking	0.6 (*+50.0%*)
Satellite Communications	32.2 (*+42.5%*)
Surveying	526.5 (*+52.7%*)
Location-Based Services (LBS)	1.6 (*+100.0%*)
Energy	Not monetised
Fixed line communications	-
Cellular telecommunications	-
TETRA	Unknown
Meteorology	2.1 (*+40.0%*)
Health	1.0 (*+42.9%*)
Total	**583.0 (*+50.3%*)**

Note: *(+%) indicates the variation in economic loss since the 2017 iteration of this report.*
Source: London Economics analysis

4.9.1 Offender tracking

The scope of the sector includes the tracking of offenders. If GNSS fails, the application will no longer be viable, and offenders would be able to move uninhibited even if they continue to wear the tag. A tagged offender remains under arrest, so if the positioning information is lost, police forces would be obliged to apprehend tagged offenders even if they are not at fault. This would absorb resources that might be used elsewhere. Generally, lower orders of offenders are deemed to be eligible for release under tracking schemes, but nevertheless any offences committed during an outage would be at cost to society.

The loss of benefits over a seven-day period has increased slightly to **£0.6m** versus £0.4m over a five-day period from the previous study. With the number of offenders tracked remaining constant at around 1,000, a substantially greater impact can be expected from the use of police resources to bring these individuals back into custody.

4.9.2 Satellite communications

Mobile satcoms would be severely impacted by loss of GNSS, as the devices would lose the location information that allows them to acquire the appropriate spot beam from satellites. Inmarsat's isatphone 2 user guide is clear that: *"Before you can make a call, your phone needs a GPS fix so it can be located by the satellite"*[180] and it therefore follows that mobile satcoms from GEO satellites would be lost if GNSS were lost.

The benefits of mobile satcoms are beyond the scope of this study, but applications include maritime and aviation as well as research expeditions and reporters operating in areas of poor cellular coverage (e.g. in conflict areas). Inmarsat's LEO competitor, Iridium, is less forthcoming with information on the GNSS usage of their devices, and choose to promote tracking applications

[180] Inmarsat. (2020). 'IsatPhone2 User Guide'. Available at: https://www.groundcontrol.com/inmarsat/IsatPhone_2_User_Guide.pdf [accessed July 2021]. Note that this finding is backed up by consultation with Inmarsat.

instead, where a user can send a "breadcrumb trail" of recent locations to selected recipients. It is also possible to manually share position information for handset models featuring GNSS receivers.[181] The Iridium constellation is fundamentally different to Inmarsat as overlapping spot beams constantly change positions, meaning multiple satellites are required for a conversation. It therefore appears that the core functionality of the Iridium solution could be maintained even if GNSS were lost.

The degree to which benefits of mobile satcoms would be lost when GNSS is lost therefore depends on the relative market shares of LEO and GEO solutions. While market data on the extent of GNSS reliance is not available, sources suggest the majority of mobile satcoms currently rely on GEO services (for example, leading GEO operator SES states that GPS time synchronisation is need to enable its mobile backhauling[182]), although this is subject to change in coming years with the launch of LEO services from providers such as Starlink and OneWeb.

Inmarsat is the largest UK satellite communications company, and its service is entirely mobile. If GNSS were to be lost for five days, Inmarsat's revenue average daily revenues would be lost for the duration of the outage. Detriment to the company and users is therefore estimated at **£31.6m,** an increase compared against the value from the previous study iteration of £22.1m.

The seven-day equivalent loss of the benefits of satcoms in aviation estimated previously of £32.2m is **£0.6m**, which would all be lost.

The largest user of mobile satcoms is the maritime shipping sector, where mobile satcoms enable accurate scheduling of port operations and allow access to weather forecasts and communication for crew. The impact of the loss of satcoms is nested within the wider impact of loss of GNSS for maritime shipping and considered under maritime transport infrastructure.

4.9.3 Surveying

In surveying, benefits attributable to GNSS would be lost if GNSS suffered an outage. As all relevant surveying equipment integrates GNSS currently, reversal to non-GNSS methods appear infeasible in the short term at least, so not only efficiency benefits, but in fact, all economic activity in the sector would most likely cease during the period of the outage. In total, benefits in Surveying for the average seven-day outage would amount to **£0.5m**, which compares to the estimate of five-day loss of £0.2m.

Detriment beyond those losses (estimated against a GNSS-free baseline) would be felt as the surveying sector would be unable to function. Surveying is contained in the Engineering activities and related technical consultancy, which employed 372,000 people and contributed £28.3bn to GDP in 2019.[183] In 2014, the UK had approximately 53,000 surveyors.[184] Assuming surveyors have the same productivity as the rest of the sector, loss of all activity for seven days would imply loss of GVA of **£77.3m,** an increase on the £50.5m from the previous study iteration.

The sector itself however generates economic activity of much greater magnitude still. Construction activities, for example require inputs from surveyors, and civil engineering projects such as road and

[181] Outfitter Satellite Phones. (2021) 'General Questions about Iridium Handsets'. Available at: www.outfittersatellite.com/iridium-9575-faq.html [accessed July 2021].
[182] SES. (2021). 'Managed Mobile Backhaul'. Available at: https://www.ses.com/find-service/telco-mno/managed-mobile-backhaul [accessed July 2021].
[183] Office for National Statistics. (2021). 'Non-financial business economy, UK: Sections A to S'.
[184] Special extract from Eurostat; reference occupation code, ISCO-08: 2165

rail construction would not be able to continue without inputs from the surveying profession, indicating the loss to society will vastly exceed the modest monetised loss.

In the UK, Civil Engineering contributes £16.9bn to GDP.[185] A loss of GNSS-based surveying inputs is assumed to reduce activity on the first day by 75%, and for the rest of the five-day period, only 5% of activities can be continued. The required effort to rectify the delay imposed on construction projects is assumed to add 50% to costs. The estimated economic impact of loss of GNSS in civil engineering is therefore **£448.7m,** a substantial increase on the 2017 five-day estimate of £294.1m. The majority of other construction activity uses GNSS to very limited extent, and the loss has not been monetised.

In addition to this monetised loss, the oil and gas sector could be affected by loss of GNSS through the loss of marine surveying vessels used for exploration. The impact depends on whether any prospecting activities coincide with the loss and have not been monetised. With daily operating costs thought to exceed £200,000 per day to run a survey vessel, costs could quickly accumulate.

4.9.4 Location-Based Services (LBS)

Loss of GNSS would impact smartphone and tablets users of the wide range of location-based applications. However, depending on the user's environment, the impact may be vastly reduced by the availability of alternative positioning sources, notably Wi-Fi. For fitness trackers, no alternative location source is known. As the benefits from fitness trackers are driven by the inducement of more activity, it could be argued that a certain 'mental holdover' would be present, so the benefits would probably not be lost.

Benefits from inducement to use of public transport rather than personal cars may be considered resilient to loss of GNSS as the primary geographical area for such effects is in cities where Wi-Fi is available in abundance. On the other hand, the strain to rail operations (discussed above) might reduce the desirability of rail solutions significantly. The anticipated increase in congestion on the roads may also make the use of buses less appealing and therefore bring people back to cars. On balance, over a seven-day period the loss estimate for modal shift would double to **£1.6m** against the previous estimate (£0.8m) for a five-day outage with increase in GNSS penetration in recent years.

Benefits of pedestrian navigation would most likely be kept as the majority of instances of pedestrian navigation is in cities, where alternative location sources are available. In fact, the benefits of such navigation may ultimately increase as a result of the congestion that will drive people to walk rather than drive. However, such benefits have not been monetised.

The paragraph above fundamentally assumes that faced with an electronic map on a smartphone, individuals will be able to ascertain their position 'within the light blue circle', and navigate streets based on visual aids, street names and the local environment. This assumption is considered valid certainly for users with experience of navigation prior to the smartphone age, but less so for a younger generation whose ability to use conventional navigation techniques relies on personal interest rather than ever having had to learn it. It is beyond the scope of this study to test the assumption, but future work to ascertain these skills in the population is encouraged.

[185] Office for National Statistics. (2021). 'Non-financial business economy, UK: Sections A to S'.

4.9.5 Meteorology

Loss of GNSS would prevent in-situ measurements being made in LEO in relation to the present composition of the atmosphere using radio occultation payloads on ESA, EUMETSAT and Spire satellites. With many of the Met Office's moving terrestrial sensors also losing their position information there would be no method to compensate for the loss of these datasets. In addition, the lightning detection network would also cease functioning.

The Met Office would be able to continue forecasting the weather, although with some added uncertainty, so the impact of loss is limited. This is because its supercomputer would remain synchronised. Based on the conservative attribution of £102m of Met Office annual benefits to GNSS, the loss of GNSS for five days would account to **£2.1m,** a slight increase on the five-day outage assessment of £1.5m in 2017.

4.9.6 Health

The impact on tracking of lone workers could be mitigated depending on the type of device in use. For smartphone applications, the loss of GNSS would be less critical than dedicated devices, as smartphones can derive position information from Wi-Fi and other signals of opportunity. Assuming 20% of devices would lose position information and assuming lone workers are equally likely to be in distress irrespective of the system in use, less than one incident would go unanswered on average.

Benefits from fleet management operations for carers would be lost, and additional detriment may arise as a result of increased congestion and reduced ability to navigate between sites. The total benefit lost over a seven-day outage amounts to **£1.0m**, an increase on the value from the previous study iteration of £0.7m.

4.10 Economic loss during a 24-hour GNSS outage

The previous sections of this chapter included in-depth consideration of the effects of a 7-day GNSS outage. This section now turns to the impact of a similar UK-wide, instantaneous GNSS outage that instead only lasts for 24 hours and is followed by full restoration of all GNSS.

The total estimated loss is £1.4bn over 24 hours, with most of the losses found in Emergency Services and Road. In Emergency Services, significantly reduced efficiency in call centres and among responders would result in a near-immediate overwhelming of each service, reducing their ability to properly serve and protect the public. In Road, the sudden failure of navigation devices would result in traffic as most drivers are faced with navigation without the aid of GNSS for the first time in recent memory.

It is important to note that the total estimated loss over 24 hours exceeds the result of dividing the 7-day figure into seven equal parts. Detail on the modelling underpinning this result is given in the remainder of Section 4.10.

An outage of such a short period would most likely be interpreted as temporary by individual users. Without specific information regarding a general GNSS outage these individuals would probably assume their specific device was broken and hence move to utilising any immediately available alternative. In some cases, notably maritime and aviation, navigation systems would alert professional crews to the outage and prompt them to use alternatives where possible. In other cases, some productivity would be wasted by users spending time attempting to investigate the source of device fault. In the case where holdover capacity exists, users would not notice the outage.

We therefore expect either no effect over 24 hours, for those applications with sufficient holdover, or a similar but more short-term outcome as with the 7-day outages considered previously.

Table 20 Economic loss during a 24-hour GNSS outage

Sector	Economic loss (24 hours, £m)
Agriculture	-
Aviation	0.5
Emergency Services	883.5
Finance	-
Maritime	95.3
Rail	20.0
Road	341.8
Other updated sectors	83.3
Total	**1,424.4**

Source: London Economics analysis

4.10.1 Agriculture

Interviews with expert stakeholders suggested that one day of outage would likely have no effect. Farmers are capable, and indeed likely, to shift to another task in the interim and simply try to work with their GNSS-dependent machinery the next day. While uncertainty remains over the point in a week at which the risk of cultivation-related loss crystalizes, which drives the economic losses estimated in section 4.1, we assume that this point does not fall within the first 24 hours of a GNSS outage.

4.10.2 Aviation

Aviation would immediately feel the impact of a GNSS outage, meaning that within a 24 hour outage losses would accrue along the same path as a 7-day outage as discussed in Section 4.2. Much of the traditional aviation sector would be largely unaffected, though other drone-related activities (included in Aviation in this report) would be immediately affected. The majority of these losses (97%) come from loss of efficiency in aviation-enabled agricultural productivity enhancements and surveillance.

Interestingly, in contrast to the negligible effects experienced in Agriculture, the aviation-enabled agricultural productivity gains in Aviation considered in this report are largely derived from *timely* soil and crop monitoring. Unlike harvesting and planting that can be deferred, the economic efficiencies enabled in Aviation are lost without constant and timely monitoring. **£434k** of the estimated 24-hour loss comes as a result of this lost productivity.

A loss of GNSS, even for a short period, will result in a loss of ADS-B for surveillance. This means that the minimum safe distance between aircraft in flight corridors would have to be increased, reducing overall efficiency and producing economic losses on an order of **£58k** within the first 24 hours.

4.10.3 Emergency Services

In Emergency Services, it is assumed that the impact of a 24-hour outage would be larger than the naïve pro-rata estimate that one-seventh of the 7-day outage period would result in. As Section 4.3 explains, the losses estimated are based on assumptions of some form of Emergency Services response over the outage period. These responses, such as hiring more Command and Control centre staff, are not considered feasible during the first 24 hours, and thus it is assumed that 25%

of the week's losses fall within the first 24 hours, before the outage's effects are understood and alternatives are brought online.

4.10.4 Finance

Following the negligible estimated losses in Finance over a 7-day period outlined in Section 4.4, the estimated losses over a 24-hour period are also zero. This is due to sufficient holdover capacity in timing from existing atomic clock infrastructure that is distributed throughout the UK's financial institutions.

4.10.5 Maritime

The breadth of applications dependent on GNSS in the Maritime sector result in differing impacts over a 24-hour outage period. A detailed evaluation of the dependencies is available in Section 4.6. The majority of economic losses within a 24-hour period come from Port Operations, which represents over 97% of the total estimated loss.

Holdover is poor in automated container terminals, with shutdowns expected just minutes after a loss of GNSS. These holdover minutes come from cranes using dead reckoning[186], though even this fails to be safe for operation within just a few minutes. Manual and semi-automatic enabled container terminals can maintain operations, though at a slower pace, which will then cause port backlogs within a few hours. On the water, in poor visibility conditions tugs and pushers could be forced to cease operations, creating a traffic jam at the port entrance.

The resulting losses come mostly come from the manufacturing sector (**£51m**) which is heavily dependent on just-in-time delivery from ports. Motor vehicle manufacturing in particular could experience empty warehouses and total shutdowns in a matter of hours, with shutdowns in other industries also highly possible within the 24-hour period. Further losses come from a loss of export value (**£41.7m**) as backlogs grow.

4.10.6 Rail

In Rail, a 7-day outage (analysed in detail in Section 4.5) and a 24-hour outage are similar in that while neither will cause a system shut-down, efficiencies are lost throughout the entire outage period. A loss of GNSS will immediately cause a reversion to manual door operation and loss of efficiencies from Driver Advisory Systems. The pro rata rate of one-seventh of the 7-day outage losses is therefore taken to be valid for a 24-hour outage period. The economic losses from train cancellations (£14.3m) and automatic selective door operation (£5.5m) are notably dependent on the assumption that the 24-hour period could be any day of the week, rather than specifically a weekday or weekend, meaning average weekly travel patterns are used when modelling the impacts of delays on passengers and businesses.

4.10.7 Road

The economic loss in Road experienced in 24 hours is predicted to be larger than the loss over 7 days (analysed in Section 4.7) divided by 7, the naïve pro rata rate.

[186] The calculation of current position by using previous data on position in conjunction with estimations of speed and direction. This method is subject to cumulative errors that quickly result in significant errors.

This is largely because the impact of a loss of GNSS for road navigation is assumed to be largest on the first day. On the first day drivers might not realise GNSS was lost and subsequently take more time to navigate, involving wrong turnings while navigation devices give inaccurate or no responses. The impact would then decrease over the 7-day period as drivers become used to navigating without GNSS and plan their routes in advance without GNSS. Road navigation losses amount to **£333.2m** of the 24-hour losses, or 97%. For a detailed breakdown of the modelled impact per day in Road please see Table 17.

4.10.8 Other updated sectors

Detailed modelling of the day-by-day impact of a loss of GNSS in other updated sectors was not undertaken. It is therefore assumed that the pro rata rate of loss (one-seventh of the 7-day loss estimate, available in Section 4.9) is appropriate.

5 Less than Worst-Case Scenarios

The GNSS Loss estimates that are the focus of this study assume a Reasonable Worst-Case Scenario (RWCS) of 7 days of GNSS outage. In reality, more plausible sources of disruptions are likely to be more limited in both scope and duration than this RWCS. This motivates consideration of the economic losses associated with a more likely 'Less than Worst-Case Scenario (LWCS).

To illustrate more likely scenarios of disruption, two case studies of less than worst case scenario events were proposed by LE and agreed by UKSA. These were chosen to demonstrate the potential high impact associated with disruption to economically important areas:

- LWCS 1: jamming event around the Port of Dover;
- LWCS 2: a spoofing event (i.e. provision of fake GNSS-like signals) around the Heathrow area, between Junction 14 and Junction 15 on the M25 (affecting the flight path into Heathrow and the widest part of the M25, so presumably the busiest).

Jamming and spoofing are criminal offences, and it is therefore the police's duty to identify the origin of the signal and switch it off. The authorities would certainly intervene quickly given the economic significance of the areas covered by the LWCS. This implies a limited duration of an event which needs to be factored into the definition of the LWCS, in addition to the geographical scope and type of disruption outlined above. Furthermore, the likelihood and timeliness of intervention by authorities will be proportionate to the scale / power of the disruption (diameter and height). The duration of the disruption is therefore inversely related to the scale / power of the disruption. For simplicity, a credible duration of interference of up to (but not greater than) 24 hours is assumed for this analysis.

The analysis of the two LWCS case studies (detailed below) considers the impact on a) those GNSS users that observe the disruption directly, and b) economic agents that depend on those users (including businesses depending on air travel and tourism). The geographic location of the user determines the degree to which they directly observe the disruption of their devices, but economic agents across the whole of the UK could be affected by the disruption through downstream dependence on supply chains and services.

5.1 Port of Dover

This case study describes the impact of a scenario in which GNSS signals are jammed for up to 24 hours, around the Port of Dover. Jamming is usually caused by a signal interference at GNSS frequencies. It may be intentional (malicious actions) but may also be caused unintentionally, by space weather for instance. This section is agnostic of the jamming means and only analyses qualitatively the consequences of such event on GNSS dependent activities at the port of Dover. The port of Dover hosts a few Roll-on Roll-off (Ro-Ro) and passenger terminals, one Lift-on Lift-off (Lo-Lo) terminal, and three Cruise Terminals.

A duration of disruption of 24 hours is reasonable because it is assumed that the authorities would likely detect and immobilise any source of interference as a matter of priority, given the economic and strategic significance of the port. Disruptions of greater than 24 hour duration are possible under the LWCS but are less likely to happen and harder to achieve, e.g. by sophisticated malicious actors.

Figure 10 Port of Dover

Source: Copernicus Sentinel data extracted on 17 July 2021 at https://www.sentinel-hub.com/explore/eobrowser/

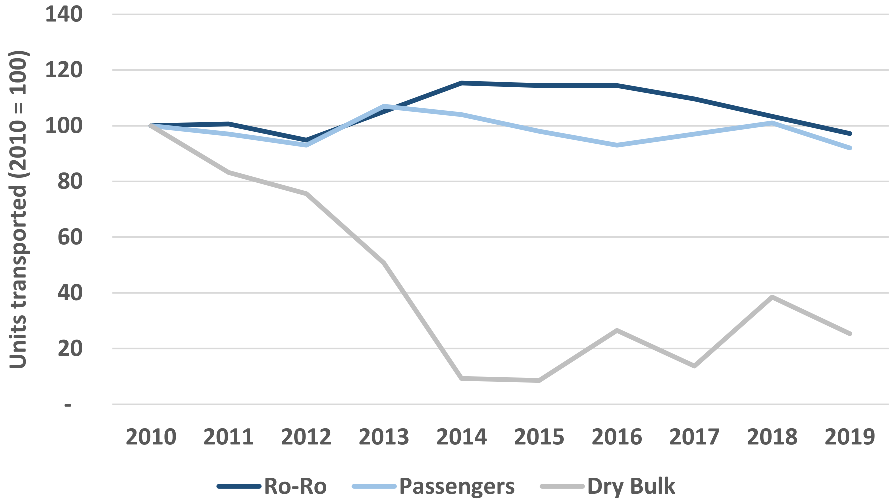
5.1.1 Maritime activities at Dover

Dover ranks first in UK ports in the handling of Ro-Ro commodities (in tonnes). Dover is also the largest passenger port (64% of international passengers transit from Dover[187]) and ensures daily connections with Dunkirk and Calais. Over time, the number of passengers transported through Dover has slightly decreased while Road haulage remained stable despite fluctuations. The volume of dry bulk handled, however, has substantially decreased between 2010 and 2014, while recovering somewhat in recent years. In addition, a small volume of containers are also handled by non-automated cranes. Three piloted Lo-Lo cranes handle 15,000 containers a year; in comparison, the Ro-Ro terminals handle over 4m units a year.

The Port of Dover specialises in the handling, storage and freight forwarding of temperature-controlled commodities. It's closeness to continental Europe offers a strategic advantage for the fast transportation of perishable goods by sea. These commodities are mainly handled by Ro-Ro. In 2019 on average, 6,500 lorries, 30,000 passengers, and 5,500 cars, transited the Channel through the port of Dover, daily.[188] Dover is also directly connected to the M2 and M20 motorways which inter-connect to the M25, giving fast and direct access to central London, the Midlands, as well as all other parts of the UK.

[187] Department for Transport. (2021). 'Sea passenger statistics'. Available at: https://www.gov.uk/government/statistical-data-sets/sea-passenger-statistics-spas [accessed 28/07/21].
[188] Port of Dover. (2021). 'Performance'. https://www.doverport.co.uk/about/performance/ [accessed July 2021].

Figure 11 Evolution of commodities and passenger transport at Dover (2010 = 100)



Source: London Economics analysis (data for DfT and port of Dover).

With such traffic density (at the port and on the roads), it is key for the port authority to maintain fluid traffic within the port, and at the port's gates (road and sea sides).

Figure 10 shows how the port is organised. The image shows that there is unique access to the port allowing lorries, coaches, and cars to get into the port. This one single point of failure is such that traffic congestions could severely impact the flow of vehicles at the port entrance. As presented in Section 4.7, a loss of GNSS signal might force drivers to slow down, resulting in a chain reaction that can cause a traffic jam. At Dover, a traffic jam involving only 10% of daily lorries would result in a 10km-long queue.

The narrow aspect of the channel (between two landmasses in proximity) is such that the annual maritime traffic density is one of the highest in European waters. Many ships transit through the channel, parallel to the coastlines, moving between the North Sea and the Atlantic Ocean. In addition, the connections between France and the UK are perpendicular to this axis resulting in hundreds of ships cross path each day (as illustrated in Figure 12. Sea traffic is vulnerable to GNSS outages (as we have seen in Section 4.6) and congestion would induce ships to slow down, narrowing the space between them and increasing the chances of collisions. For that reason, ships passing through the Dover Channel need GNSS to comply with Traffic Separation Scheme for the few hours they are in the channel.[189]

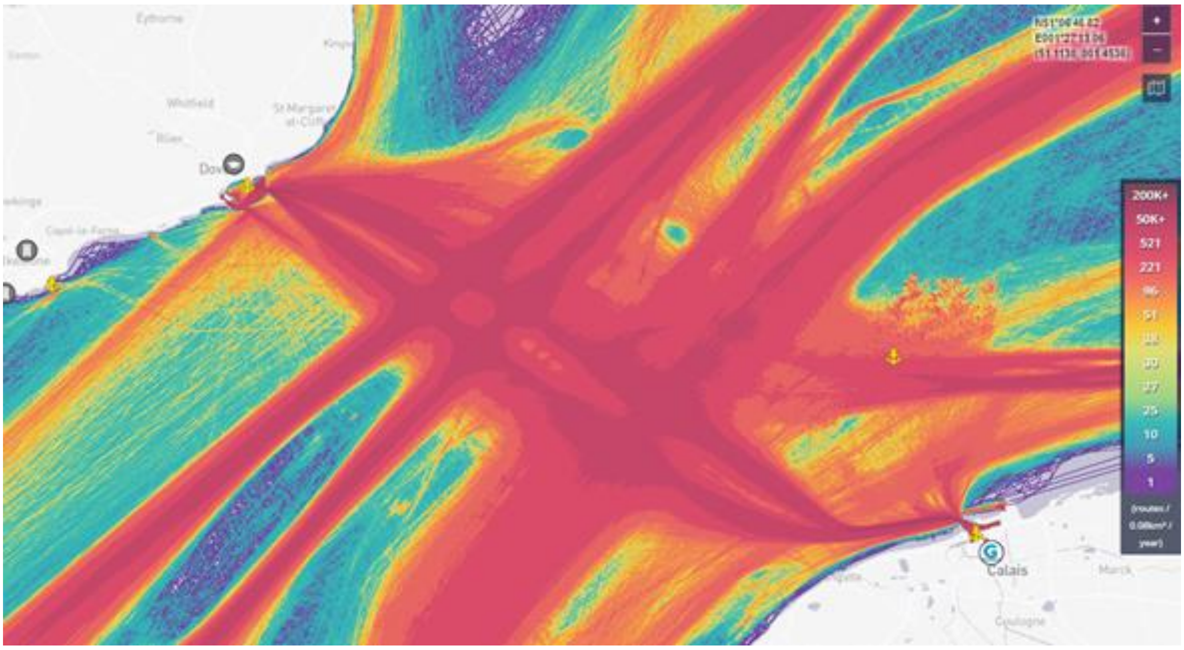
All these aspects are such that the Port of Dover could be subject to a multitude of issues during a jamming event, impacting the port's activities, and rippling to the wider the UK economy.

5.1.2 Impact of Jamming

There are two traffic flows that could be impacted by a jamming event at the port of Dover: maritime shipping traffic, and road traffic. Both are interconnected, so a disruption to either traffic flow implies a disruption to the other.

[189] Knowledge of Sea. (2020). 'Traffic Separation Scheme'. Available at: https://knowledgeofsea.com/traffic-separation-scheme/ [accessed July 2021].

Figure 12 Sea traffic density between Dover and Calais, 2019.



Note: The unit of the legend indicates the traffic density in number of routes, per 0.08km^{2}, per year.

Source: Marine traffic (traffic density, 2019). https://www.marinetraffic.com/en/ais/home/centerx:1.5/centery:51.1/zoom:11

The section will focus on the ferries, passengers and lorries that represent by far the most important element of Dover's activities. Indeed, one container ship moored at the container terminal every 3 days on average in 2019[190], meaning that a 24-hour description of signal is unlikely to cause any congestion at that terminal. Cranes are manually operated to load and unload container ships, which once again means that there will not be any disruption to port operations. In addition, there were 130 calls at cruise terminals that same year, and following the same logic, cruise ships are unlikely to be disrupted.

On the waterside, the disruption could cause ferries at sea to slow down which might cause delays and lorries and passenger cars would start accumulating at the ferry terminals.

Weather conditions could be such that ferries would have to slow down even more, and cancellations could occur. Cancelling one Ferry or more will immediately involve a direct increase in congestion at the port. Ferries take on average 1.30 hours to cross the channel, transporting on average 780 passengers, 140 cars, and 170 lorries.

Table 21 Dover Ferries capacity, in 2019

	Passengers	Tourist Cars	Lorries
Per year (2019)	10,863,262	2,000,966	2,397,270
Per day	29,762	5,482	6,568
Per ferry, per day (assuming 38 a day max)	783	144	173

Source: London Economics analysis (data available at https://www.pofreight.com/SailingSchedules, https://www.doverport.co.uk/about/performance/)

190 Port of Dover. (2019). 'Annual report 2019'. Available at: https://www.doverport.co.uk/administrator/tinymce/source/Annual%20Reports/2019%20Annual%20Report%20%26%20Accounts.pdf [accessed July 2021].

A previous study of the economic impact of delays and disruptions at Dover[191] found that the value of trade passing between Dover and Calais each year was £89bn in the mid-2010s. As a news article at the time[192] argued that disruption to Dover following closure at Calais gives a theoretical "daily bill" of 1/365th of this value: roughly £243m per 24 hours. Of course, as freight traffic has increased this 'back-of-an-envelope figure could be pushed higher'.

We assume a scenario in which a jamming event occur during a day with poor weather conditions, forcing the cancellation of 5 ferries in a row. The consequence would be the accumulation of 865 lorries at the port, creating a queue of over 10 km, and grounding almost 4,000 passengers at the port. The impact would therefore not only be felt over 24 hours during the disruption, but also in the following day(s) due to the need for backlog clearance.

Despite a low likelihood, this kind of scenario can result in a dramatic congestion event with immediate consequences on companies operating at the port such as cargo handling, ferries, and logistics. The Port of Dover now handles £122bn worth of merchandise each year[193] and a single event lasting for 24 hours can be substantial for the UK economy.

Ships that lose signals are not entirely grounded and navigation can continue with other means. Under good weather conditions, ships are unlikely to be disrupted. As seen in chapter 4, the main point of failure is located at the port, where cargo is handled. Due to the nature of operations at Dover, minor delays in scheduling are not likely to disrupt the flow of lorries and passengers.

This port is vulnerable to disruptions because the flow of passengers and lorries is continuous, hence congestion creates a backlog very quickly. This has been seen in the past in events such as counter terrorism actions from the police on the UK side[194], or the French side[195], and even a shift in demand can induce chaos.[196]

The Port of Dover operates 24 hours 7 days a week and holds a schedule of ferries that allow planning in advance. Port community system[197] is advanced, so managers and logistics companies know where the perishable goods are. The reliance of Ro-Ro on GNSS is rather small. It is mostly used for fleet management and route planning (within truck company) but is not an essential element of the supply chain. There is not much crossover between port and road and essentially, port record truck operations (entry, load/unload) and exit and work on an appointment system generally booked for the day. The port authority is well connected with lorries and have a very

[191] Oxera. (2016). 'The Port of Dover ferry operation is of major economic importance to the UK economy'. Available at: https://www.doverport.co.uk/administrator/tinymce/source/Oxera%20Port%20of%20Dover%20infographic%20v10.pdf [accessed October 2021].

[192] The Guardian. (2015). 'Is the Calais Crisis costing the UK £250m a day in lost trade?'. Available at: https://www.theguardian.com/uk-news/2015/jul/30/calais-crisis-cost-uk-250m-a-day-trade [accessed October 2021].

[193] Port of Dover. (2019). 'Annual report 2019'. Available at: https://www.doverport.co.uk/administrator/tinymce/source/Annual%20Reports/2019%20Annual%20Report%20%26%20Accounts.pdf [accessed July 2021].

[194] Kentonline. (2020). 'Operation Stack causes long delays at Port of Dover and Eurotunnel after Counter Terrorism Police request for security checks'. Available at: https://www.kentonline.co.uk/dover/news/freight-chaos-with-delays-at-port-and-tunnel-233845/ [accessed July 2021].

[195] BBC. (2016). 'Dover ferry port chaos leads to 14-hour traffic jams'. Available at: https://www.bbc.co.uk/news/uk-england-kent-36873632 [accessed July 2021].

[196] Teller Report. (2020). 'Due to Brexit, trucks are stuck in a traffic jam of 30 kilometers near Dover'. Available at: https://www.tellerreport.com/business/2020-12-17-%0A---due-to-brexit--trucks-are-stuck-in-a-traffic-jam-of-30-kilometers-near-dover%0A--.S1rL7RXFnD.html [accessed July 2021].

[197] Port community system is a platform that connects systems and users to manage and optimize port activities, as well as communicate between stakeholders. See https://customscity.com/what-is-a-port-community-system-pcs/ for more information.

efficient and strict booking system; if lorries do not turn up in the 20 minutes slot, they are turned away and are not able to pick up / drop the container which might result in the loss of the good.

Lorry drivers are typically very experienced and know the area they are driving through. A loss of signal would disrupt the SATNAV onboard the lorry, but this event is unlikely to affect their arrival time. In other words, the loss of signal is unlikely to create a traffic jam at the entrance of the port of Dover because of lorry drivers. The situation is the same for port employees who do not need GNSS guidance to find their way to work.

However, depending on the timing of the event, the journey could be considerably slower. Other drivers like tourists might detect the issue too which could result in minor disruptions. As drivers are looking at their navigation devices and trying to understand the situation, they are most likely to adopt a risk averse behaviour forcing them to slow down. Some drivers might slow down and move to the slow lane. This in consequence could affect lorries and port staff. A shortage of staff at the port would reduce the efficiency of operations, inducing delays at security gates, customs, etc.

For passenger vehicles, navigation at the entrance and through the port will not rely on GNSS inputs. The road has sufficient signage for tourists to find their way to the ferry.

5.1.3 Summary

This section presents the case of a jamming event at Dover. It shows that the port has two main points of vulnerabilities; the road and port entrances. While experienced drivers and employees with local knowledge would not be directly impacted by the jamming of their devices, tourists might respond to the blackout by reducing their speed, triggering traffic jam events. The loss would be associated with the late arrival of lorries and the reduced efficiency due to less available staff.

On the seaside, delays may occur as ferries would reduce their speed, having to rely on alternative instruments and line of sight for port approach navigation. Given the intensity of road haulage and passenger traffic at Dover, any delays and cancellation would cause lorries to stack up at the port. On an average day, the port of Dover handles £334m worth of commodities per day and a single 24 hour outage could have severe repercussions for the UK economy.

Table 22 Effects of jamming incident

Direct/Indirect Effect	Likely to occur?	Economic loss over 24 hours[1]
Direct effect: Interrupted Lo-Lo activities	No	N/A
Direct effect: Interrupted Cruise activities	No	N/A
Direct effect: Disruption Ro-Ro caused by ferry cancellations	Yes	Up to £334m (or 780 passengers, 140 cars, and 170 lorries per ferry cancelled)
Direct effect: slowed down traffic at port entrance on the roadside	No	N/A
Indirect effect: economic impact on UK supply chain	Yes	Not monetised
Total		Up to £334m

Note: [1] Economic loss on an average day
Source: London Economics

5.2 The M25 motorway

This case study describes a spoofing event between Junction 14 and Junction 15 on the M25. This is the widest part of the M25. As highlighted in red in Figure 13, the driving distance is approximately 4.66km. The shortest, straight line distance is approximately 4.48km. Spoofing involves the broadcast of GNSS-like signals from non-GNSS sources, generally with the intention to fool receivers into thinking they are somewhere that they are not.

Figure 13 Junction 14 and 15 on M25

Source: Copernicus Sentinel data extracted on 17 July 2021 at https://www.sentinel-hub.com/explore/eobrowser/

The duration of the interference is assumed to be 24 hours, as proposed by LE and agreed by UKSA. This is because it is assumed that the authorities would likely detect and immobilise any source of interference as a matter of priority. Disruptions of greater than 24 hour duration are possible under the LWCS but are less likely to happen and harder to achieve, e.g. by sophisticated malicious actors.

As shown in Figure 13, the junctions are near London Heathrow Airport. An interference between Junction 14 and 15 could therefore affect:

1) Road traffic travelling between the junctions; and,
2) Flights operation at London Heathrow Airport

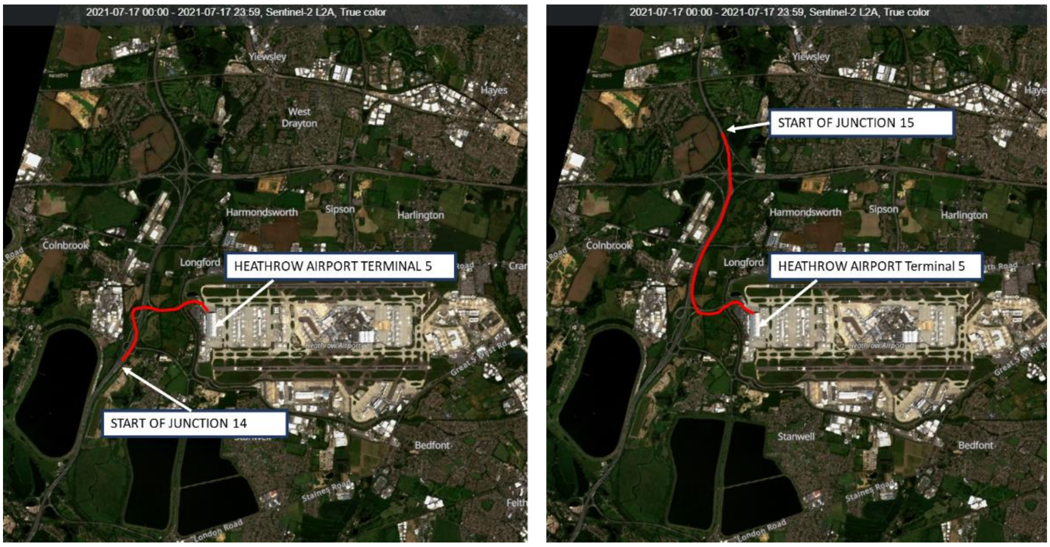
The misleading GNSS signals are likely to be broadcasted as a radius. The size of this radius is assumed to be large enough to cover the entire Heathrow Airport and the surrounding motorways.

5.2.1 Road traffic travelling between the junctions

Junctions 14 and 15 are located on the west end of the M25, passing Heathrow Airport. Therefore, disruptions caused by misleading GNSS information could directly affect:

1) **Traffic travelling in and out of Heathrow Airport**
   a) Junctions 14 and 15 are closest to Heathrow Airport Terminal 5. Unless the driver lives close to the airport, they are most likely to use these parts of the M25 to reach the terminal.
   b) Terminal 5 also homes three car rental agencies (as of July 2021). Drivers that rented cars from these agencies are most likely to leave the airport via the junctions.
      i) Avis Car Hire
      ii) Sixt Car Hire
      iii) Zipcar
   c) As the junctions are to the west of the airport, drivers travelling from the west of the airport are also likely to use the junctions. For example, these drivers could come from Slough, Maidenhead, Farnborough, and Woking.

Figure 14 Route from Juction 14 (left) and Juction 15 (right) to Heathrow Airport Terminal 5



Source: Copernicus Sentinel data extracted on 17 July 2021 at https://www.sentinel-hub.com/explore/eobrowser/

2) **Traffic travelling to the west of Greater London**
   a) As the junctions are located on the west end of the M25, vehicles travelling to the west of Greater London such as Windsor, Reading, Bath and Bristol are likely to go via the junctions.

Stakeholder consultations indicated to LE that GNSS receivers in most navigation devices are not resilient against spoofing. Furthermore, a real life spoofing event[198] in Portland, USA, demonstrated that impact on smart phones when they are spoofed. (This gives a good indication as smart phones are used as navigation devices.) Even if there are alternative positioning sources such as cell towers

198 Inside GNSS (2017). 'Spoofing Incident Report: An Illustration of Cascading Security Failure'. Available at: https://insidegnss.com/spoofing-incident-report-an-illustration-of-cascading-security-failure/ [accessed July 2021]

and Wi-Fi hotspots, smart phones would ignore them and continue to rely on the faulty GNSS signals. Moreover, the aforementioned real life event showed that recovery following a spoofing attack can be slow. An individual said that their phone continued to display incorrect location an hour and half after exposure to the spoofing.

Therefore, in the event of misleading GNSS information between Junctions 14 and 15, it is assumed that road navigation devices would display incorrect positioning information. In addition, some devices might not recover immediately after leaving the junctions.

The effect on drivers and road traffic would depend on the extent to which the spoofer shifts the GNSS location.

Spoofer shifts the GNSS location to somewhere with different roads

The spoofer could shift the GNSS location to a vastly different location, such that the false navigation route looks very different from the roads. In this situation, most drivers in the junctions are likely to realise that they can no longer rely on GNSS navigation.

Although most drivers are likely to detect the incident, it does not mean it would not cause disruptions. As drivers are looking at their navigation devices and trying to understand the situation, drivers are most likely to slow down. Some drivers might slow down and move to the slow lane. Other drivers might continue to drive distracted while they are trying to understand their navigation devices, potentially resulting in road accidents.

Research[199] has demonstrated that when there are enough vehicles on a motorway, minor disruptions to the traffic ahead can cause a chain reaction to the following traffic. The first car slows down slightly. The ones behind it slow down a bit more to avoid collision. The slow down eventually amplifies until a wave of stopped or slowed traffic. The researchers call this phenomenon “phantom traffic jam” (the traffic jam occurs in the absence of any road constructions or major road accidents).

In this situation, the traffic between the junctions would be slowed down. One of the important impacts to consider would be its impact on the commute of Heathrow Airport staff. Airport staff or public transport drivers are less likely to distracted by the faulty navigation instructions, as they travel to the airport on a regular basis and know the route.

However, as the entire flow of traffic between the junctions are affected, airport staff commutes would be affected. This could result in a delay in getting the relevant staff to the airport, such as flight crews and engineers. The knock-on impact could mean delayed or even cancelled flights.

Another important impact to consider is that rented cars leaving Terminal 5 would likely be tourists that rely on GNSS navigation. As soon as they enter the junctions, they would unable to rely on their navigation devices. Some might drive slowly while trying to make sense of their devices. Some might continue driving but make the wrong turns and exit at the wrong junction. (Bear in mind that as discussed, the incorrect location is likely to continue to be displayed after the drivers exit Junctions 14 and 15.) Other drivers that use in-car navigation devices might simply detect the incorrect information and return to the car agency and claim that they have been given a faulty device.

[199] M. R. Flynn, et. al (2009). ‘Traffic Modeling - Phantom Traffic Jams and Traveling Jamitons’. https://math.mit.edu/traffic/ [accessed July 2021]

Moreover, as discussed above, drivers use the junctions to travel to the west of Greater London. These drivers would also likely experience an increase in travel time.

Spoofer shifts the GNSS location to somewhere with similar roads

Alternatively, the spoofer could shift the GNSS location such that the false route looks similar to the roads between the junctions. In this situation, most drivers are unlikely to detect the spoofing. A study[200] conducted an experiment where a spoofer misled drivers so that the incorrect route matched the shape of the roads and triggered physically possible instructions. 95% of the drivers in the study did not realise that they had been misled. They then followed the incorrect instructions and reached the wrong destination.

In this situation the impact is less clear. Drivers that make journeys regularly via these junctions are likely to be less GNSS reliant. Drivers such as bus drivers, flight crews and airport staff should therefore still be able to reach the airport regardless. The impact on the rest of the drivers on the roads would depend on how fast they are able to detect the incorrect information. Some drivers might not realise until they have reached a landmark or a town that they had not planned on arriving. It is likely that tourists driving rented cars would not realise soon. Other drivers might realise sooner. There have been real life examples where drivers blindly follow the instructions from their navigation devices and reach the wrong destination.[201]

Economic cost of slowed down traffic

In the case of the spoofer shifting the GNSS location to somewhere with different roads, the traffic between the Junctions would likely slow down. According to DfT[202], 216,000 vehicles travelled via Junctions 14-15 daily in 2019. The distance between the Junctions is approximately 2.9 miles. It can be assumed that it would take each vehicle 5 minutes to travel across the Junctions (this implies approximately traveling at 35 miles per hour).[203]

As an indication of the economic cost, it can be assumed that each vehicle passing the Junctions that day would see an increase in travel time by 50%. Each vehicle would then take an additional 2.5 minutes to cross the Junctions. Totalling this increase in travel time for all drivers and passengers, it would amount to just under 14,000 hours[204].

Using value of time at £18.9 per hour as per the analysis in Road in Chapter 4.7, the slowed down traffic would cause these road users just over £260,000 in terms of value of time. If fuel cost is taken into account, it would bring in an additional economic cost of just under £20,000[205]. In total the economic cost of the slowed down traffic would be just under £280,000. Therefore, the economic

[200] Zeng et.al (2018). 'All Your GPS Are Belong To Us: Towards Stealthy Manipulation of Road Navigation System'. https://people.cs.vt.edu/gangwang/sec18-gps.pdf [accessed July 2021]

[201] For example, see BBC. (2007). 'Sat nav error puts an end to trip'. Available at: http://news.bbc.co.uk/1/hi/england/hampshire/6483383.stm [accessed July 2021].

[202] DfT (2020). 'Road Traffic Estimates: Great Britain 2019'. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/916749/road-traffic-estimates-in-great-britain-2019.pdf [accessed September 2021]

[203] Most vehicles are likely to travel at a higher speed and travel across the junctions in less than 5 minutes. 5 minutes are nevertheless conservatively assumed.

[204] Number of vehicles (216,000) multiplied by the increase in travel time (2.5 minutes), as well as occupancy rate of 1.55 (as per the analysis in Road in Chapter 4.7).

[205] As per the analysis in Road in Chapter 4.7, fuel cost is valued at £2.21 per hour. Unlike value of time, occupancy rate does not factor in the calculation. As fuel cost is calculated per vehicle, not per passenger.

cost would likely be limited. It is worth noting that even if travel time increases by 100% (i.e. doubles), the total economic cost would still be just under £570,000.

In the case of the spoofer shifting the GNSS location to somewhere with similar roads, the increase in travel time beyond the Junctions cannot be monetised as it is unclear where drivers would ultimately end up.

5.2.2 Flights operation at London Heathrow Airport: inbound flights

Overall, stakeholder consultations indicated that the spoofing would unlikely drive a safety concern for inbound flights.

Flights arriving at Heathrow are unlikely to be affected. Stakeholder consultations indicated that Heathrow Airport uses ILS (instrument landing system) for landing, which does not rely on GNSS. Even if GNSS information was used by the pilot, one stakeholder told us that manned aviation have a number of backup inputs onboard, for example, barometric altimeters, radio altimeters and human monitoring. If GNSS gives information inconsistent with the rest of the inputs, pilots on board are likely to detect the anomaly and ignore the GNSS-based information.

Upon landing at Heathrow, aircraft taxiing is also unlikely to be affected by the spoofing. Stakeholders in the aviation sector told LE that GNSS is not approved for use on the ground at UK airports due to the issues of multipath and interrupted signals. Aircraft thus use other primary systems for ground navigation, including surface movement radars.

Figure 15 Cockpit of a commerical flight: illustration of inputs onboard

Source: https://www.pxfuel.com/en/free-photo-eykge

5.2.3 Flights operation at London Heathrow Airport: outbound flights

The slowed down traffic between the junctions would affect flight passengers and flight crews' travel to the airport, and therefore outbound flights.

Flight passengers

Some passengers might miss their flights due to slower traffic. Firstly, the number of passengers travelling to the airport using road transport needs to be estimated. According to the 2019 passenger survey report (pre-Covid-19)[206], 146,427 passengers travel to and from Heathrow Airport on an average day. 70% of these passengers travel using road transport.[207] This yields over 100,000 passengers. Assuming half of these passengers are those travelling to the airport (and the other half are leaving the airport), over 50,000 passengers travel to the airport using road transport daily.

While not all of those passengers would use the M25, a sizeable portion would. Passengers from London are likely to take the underground or train. The rest of the passengers are then those who come from the west, south and north of the airport, they are likely to use Junctions 14-15 or the surrounding motorways to reach the airport. If 2/3 of the 50,000 passengers are assumed to use the junctions or surrounding motorways, over 30,000 passengers would be affected by the slow down.

However, some of these passengers would make their flights anyway, despite the traffic slow down. This is because most passengers plan on arriving early for their flights. The passengers that would miss their flights would be those who intend to arrive just on time, or only arrive slightly early. Assuming that these passengers make up of 10% of the 30,000 figure, over 3,000 passengers would miss their flights because of the slowed down traffic.

The value of missing these flights can be approximated by the compensation that consumers receive when their flights are delayed or cancelled. Using the EU flights compensation directive[208] as an indication, a consumer is entitled for £220[209] when their short distance flight is cancelled. (The compensation is higher for longer flights; this amount is used as a lower bound for indication.) The total value of missing the flights then amounts to around £0.8m.

Flight crews

The slowed down traffic might also affect flight crews' commute to the airport. However, it is less clear what the impact would be. Flight crews from international airlines are more likely to stay at hotels near the airport. They are then less likely to be affected by the traffic. For the flight crews that who are held up in traffic, it is unclear whether their absence could be filled out by another flight crew member who is already at the airport. Stakeholder consultations told LE that pilots are trained to operate specific types of flights. For example, an Airbus pilot could not fly a Boeing without conversion training. For flight attendants, though to a lesser extent, they are also trained for specific aircraft. This is because flight attendants are required to have operational knowledge of the plane that they work on, for example, operation and storage of equipment onboard and knowledge of seating chart.

Therefore, it can be assumed that if flight attendants were affected by the traffic, some flights might be delayed. Passengers might be asked to board later than the scheduled time. If pilots were late, it would then depend on the whether there were any suitable stand-by pilots at the airport.

[206] Civil Aviation Authority. (2019). '2019 Passenger survey report'. Available at: https://www.caa.co.uk/Data-and-analysis/UK-aviation-market/Consumer-research/Departing-passenger-survey/2019-Passenger-survey-report/ [accessed July 2021].
[207] This includes car, taxi/minicab/Uber, and bus/coach.
[208] European Union. (2021). 'Air passenger rights'. Available at: https://europa.eu/youreurope/citizens/travel/passenger-rights/air/index_en.htm#compensation-cancellation-1 [accessed July 2021].
[209] EUR 250 converted to GBP at 1 Euro = 0.8817 GBP. HMRC (2021). 'HMRC yearly average and spot rates: average for the year to 31 December 2019'. https://www.gov.uk/government/publications/exchange-rates-for-customs-and-vat-yearly [accessed July 2019]

Nevertheless, the portion of flight crews which travels to the airport by road is unknown. It is difficult to then assert the number of flight crews that would be affected by the slowed down traffic.

As an indication, it can be assumed that 1% of the outbound flights at Heathrow would be delayed due to late arrival of flight crews. Approximately 650 outbound flights operate at Heathrow daily.[210] This implies 7 flights might be delayed or cancelled. Eurocontrol values the cost of cancelling a commercial flight on the day at £21,954[211] for a flight of 180 seats.[212] The cost of cancelling the 7 flights would come to approximately £0.2m.

5.2.4 Summary

If a spoofing event is launched between Junction 14 and 15 on the M25, it could have a number of direct effects and indirect effects on the surrounding area. Table 23 summarises these effects and the likelihood of occurring.

It is highly likely to cause noticeable disruptions to the motor vehicle traffic passing these junctions. This is estimated to bring an economic cost of approximately £0.28m.[213] However, inbound flights are unlikely to be affected as landing procedures at Heathrow do not use GNSS. Taxiing is also unlikely to be affected.

As indirect effects of the slowed down traffic, flights operations would then be affected. As flight crews and passengers are held up by traffic, some passengers might miss their flights and some flights might not be able take off and some. The economic cost is estimated at approximately £0.80m for the passengers missing their flights and £0.20m for the flights not being able to take off.

Overall, the total economic cost of this spoofing event has been estimated at around £1.28m.

[210] Heathrow Airport. (2018) '2018 Statistics'. Available at: https://www.heathrow.com/company/about-heathrow/performance/airport-operations/traffic-statistics [accessed July 2021].
[211] EUR 24,900 converted to GBP at 1 Euro = 0.8817 GBP. HMRC. (2021). 'HMRC yearly average and spot rates: average for the year to 31 December 2019'. Available at: https://www.gov.uk/government/publications/exchange-rates-for-customs-and-vat-yearly [July 2021]
[212] Eurocontrol. (2020). 'EUROCONTROL Standard Inputs for Economic Analyses'. Available at: https://www.eurocontrol.int/sites/default/files/2021-03/eurocontrol-standard-inputs-economic-analysis-ed-9.pdf [accessed July 2021].
[213] Assuming 50% increase in travel time.

Table 23 Effects of spoofing incident

Direct/indirect effect	Likely to occur?	Economic loss over 24 hours[1]
Direct effect: slowed down traffic between the junctions	Yes	Approx. £0.28m
Direct effect: disruption to flights landing at Heathrow	No	N/A
Direct effect: disruption to flights taxiing at Heathrow	No	N/A
Indirect effect: slowed down traffic beyond the junctions	Yes	Not monetised
Indirect effect: passengers missing flights due to slowed down traffic	Yes	Approx. £0.80m
Indirect effect: flight crews missing flights due to slowed down traffic	Yes	Approx. £0.20m
Total		Approx. £1.28m

Note: [1] Economic loss on an average day.

Source: London Economics

6 Alternative and potential future mitigation strategies

This chapter aims to identify options available to GNSS users who wish to mitigate their reliance on GNSS for everyday operations. The analysis considers the full value chain of services enabled by GNSS: Position, Navigation and Timing (PNT), and it is useful to consider available options for users of each capability. It is important to note that while satellite signals directly provide Position and Timing information, Navigation information is provided through the infrastructure that allows users with a compatible device to determine their position, velocity, and time by processing signals from satellites.

Many users will rely on two or more capabilities depending on environment of use, but some generalisation is feasible:

- Users of **positioning** range from *consumer electronics* (smartphones, fitness trackers), insurance telematics, and non-safety critical rail and maritime applications; over *safety and Search and Rescue* applications (such as emergency beacons under the COSPAS-SARSAT programme); to *high-accuracy applications* including precision agriculture (variable rate technology) and construction applications.
- Similarly, for **navigation**, users of GNSS range from consumers and transport professionals for road transport over transport operations and approaches, to automatic steering for agriculture and unmanned navigation for RPAS (Remotely Piloted Aerial Systems).
- **Timing** users have significant overlap with the critical national infrastructures and include communication, power distribution and financial operations.

6.1 Traditional/current methods

Prior to the wider adoption of GNSS devices, navigation relied on the use of clocks and sextants, or radar systems to determine position at sea, and the use of paper maps on the road. Reverting to these methods could be a solution in the absence of signal but there are multiple reasons to believe this will not be as efficient. There is currently no *universally applicable* alternative to GNSS for the case of positioning and navigation, and many of the traditional means of navigation might not be readily available or useable by users as the capabilities and equipment to use these alternatives have been degraded or lost.

For example, for **pedestrian and road navigation,** it is likely that few delivery or taxi drivers carry maps in their vehicles, and the ability of drivers to navigate successfully based on maps is likely to be weaker. For other industries, e.g. **agriculture** and **surveying**, no comparable traditional mitigation strategies exist.

In the **maritime** industry, many stakeholders have mentioned that visual information remains very important for navigators, but in narrow or congested channels, it becomes increasingly difficult to interpret all visual signals. New mariners are trained mostly on new technologies and the provision of traditional navigation skills might be insufficient if the signal disappeared. The development of automated container ports also means that GNSS-based systems have replaced manual labourers, and large ports would not be able to revert to barcode-based identification of containers.

Loss of the timing capabilities of GNSS can be mitigated by using adequate oscillators in the GNSS timing receiver that can hold time for a certain holdover period, ranging from a few minutes to months, or through the use of caesium or rubidium clocks.[214] However, higher quality equipment with longer holdover periods are more expensive. Hence, loss of GNSS signal will still affect sectors relying on timing capabilities, and the extent of the impact of this loss will depend on the quality of the oscillator used as well as other mitigation strategies that are in place.[215]

6.2 Current and future technologies

This section summarises the current and future technological solutions to mitigate the risks associated with loss of GNSS and considers the costs and effectiveness of mitigation against the loss estimated in the preceding chapters.

The coverage, dimension, and accuracy of potential alternative technologies identified are summarised in the table below.

Table 24 Accuracy and coverage of positioning (and navigation) mitigation technologies

Technology	Potential Coverage	2D/3D Positioning	Accuracy
eLoran	National / Global	2D	30m – improving to <10m with eDLoran
Locata	Local / Regional	3D	< 3cm
Omnisense S500	Local	3D	20cm-2m
Iridium STL service	Global	3D	Horizontal: 20m-50m unassisted and 10m in augmentation scenarios (1σ)
Ultra wideband	Local	2D	<30cm
VDES-R Mode	Local	3D	20m

Source: London Economics research based on sources referenced in this section.

In addition to the positioning and navigation-relevant technologies, additional technologies have been identified specifically for the Timing property of GNSS. Table 25 summarises the findings for all technologies that are discussed in turn in this section.

Table 25 Timing accuracy of mitigation technologies

Technology	Accuracy
NTP timing servers (NPL)	≤ 1ms – 30ms
NPL MSF 60 kHz radio signal	10ms
PTP	10ns (1*10^-5ms) – 100ns (0.0001ms) – but dependent on network setup and clock used as a timing source
NPL-*Time*	100ns (0.0001ms)
eLoran	100ns (0.0001ms)
Locata	2.5ns (2.5x10^{-6}ms) – potentially much better
Omnisense S500	100µs (0.1 ms) – possibly up to 10ns (1*10^-5ms) in the future
Iridium STL service	Compatible with IEEE-1588 standards: 10ns-100ns

Source: London Economics research based on sources referenced in this section.

[214] The Royal Academy of Engineering. (2011). 'Global Navigation Space Systems: reliance and vulnerabilities'.
[215] See Curry, C. (2010). 'Dependency of Communications Systems on PNT Technology', *Chronos Technology*.

6.2.1 eLoran

Enhanced Long range navigation (eLoran) is a low-frequency, long range Terrestrial Radionavigation System, capable of providing a two-dimensional PNT service for use by many modes of transport. eLoran transmits pulsed groundwave signals with a central frequency of 100kHz.

Positioning and navigation performance of eLoran is similar to GNSS[216]. However, since it is a ground-based system that operates independently of GNSS, eLoran is not exposed to the same risks as GNSS. Because of this, eLoran could work as a complementary source of PNT and mitigate the risks associated with loss of the GNSS signal.[217] Properties of the eLoran signal mean it could be used in areas where GNSS does not provide sufficient signal strength, for example in buildings or underground. eLoran's transmitted timing signals allow easy translation to Coordinated Universal Time (UTC) with measured timing errors of less than 100 nanoseconds in a 2014 test.[218] This is better than the current timing accuracy requirements of major timing applications.

In addition, the accuracy of eLoran makes it unsuitable for certain GNSS applications. Since the 2017 study, the antennae required to receive eLoran has reduced from approximately the size of a Frisbee to 2" by 2" by 0.75",[219] making eLoran a viable option for infrastructure timing users, vessels, aircraft, and larger road vehicles. However, road vehicles face another obstacle as the interference is likely stronger in the environment where navigation is required, namely cities.

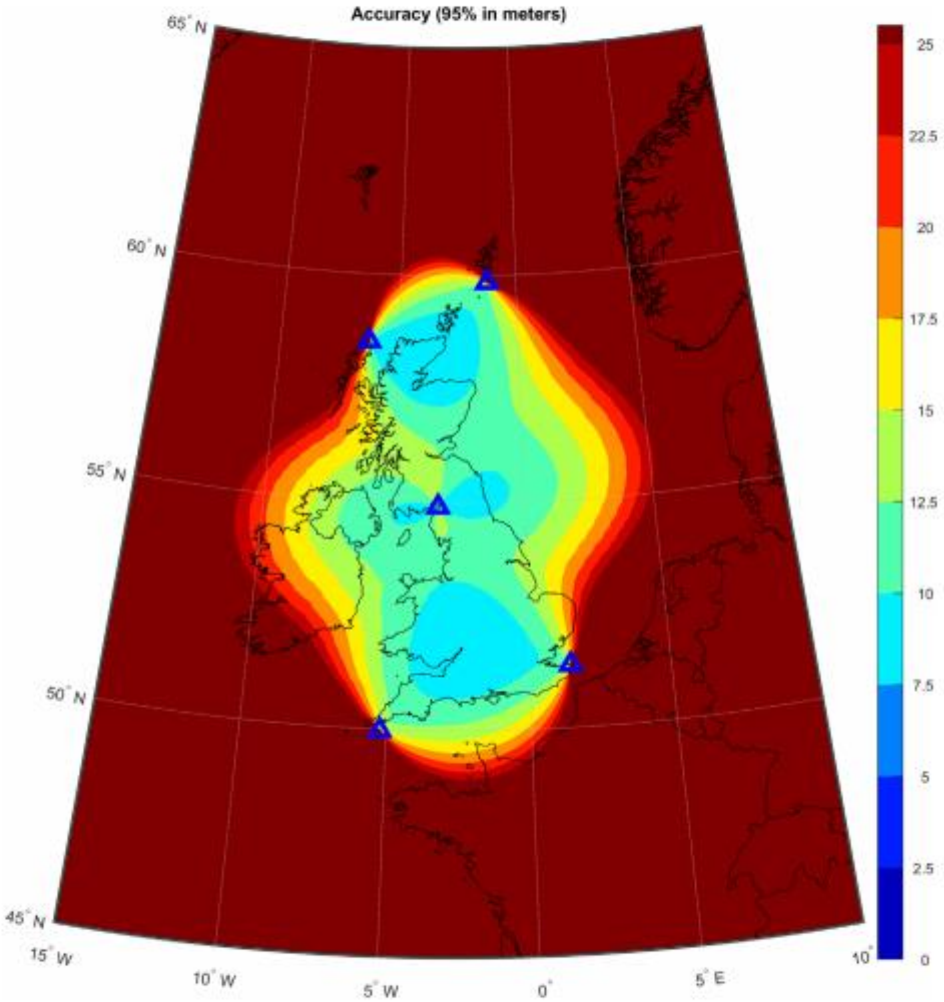
The coverage area of the system depends upon the location of the eLoran transmitters, their Effective Radiated Power (ERP) and Signal to Noise ratio (SNR) at the intended point of use of the signals. A 250 kW ERP transmitter has an approximate range of 1000 km. At least 3 transmitters are required to allow positioning, with 5 required to be received to provide integrity, via solution separation, within a user's receiver[220].

The user cost of an eLoran solution is currently higher than GNSS, but leading manufacturers have confirmed that receiver prices would reach a competitive level within one year of firm Government commitment to continuing the eLoran service.[221] Additional costs of a combined eLoran and GNSS solution at that point in time will therefore be the additional antenna.

In order to meet positioning requirements, like 10m required by the IMO in port approach phases of maritime navigation, the use of differential Loran (eDLoran) stations will be required. However, as eLoran is ground-based and therefore offers two-dimensional positioning and navigation, it is not well-suited to aviation.

[216] Cameron, A. (2014). 'GNSS Backup Delivers 5-Meter Accuracy'. Available at: https://www.gpsworld.com/gnss-backup-delivers-5-meter-accuracy/ [accessed July 2021].
[217] International Loran Association. (2007). 'Enhanced Loran (eLoran): Definition Document'. Available at: https://www.loran.org/otherarchives/2007%20eLoran%20Definition%20Document-1.0.pdf [accessed July 2021].
[218] Curry, C. (2014). 'Delivering a National Timescale using eLoran'. Available at: https://rntfnd.org/wp-content/uploads/Delivering-a-National-Timescale-Using-eLoran-Ver1-0.pdf [accessed July 2021].
[219] UrsaNav. 'eLoran Points of Light'. Available at https://www.ursanav.com/wp-content/uploads/eLoran-Points-of-Light_04APR2016.pdf [accessed July 2021].
[220] MarRINav. (2019). 'PNT, RI, Technology and Integration'. Available at: https://marrinav.com/2019/11/14/pnt-ri-technologies-and-integration/ [accessed July 2021].
[221] MarRINav. (2020). 'D8 Cost Benefit Analysis'. Available at: https://marrinav.com/wp-content/uploads/2020/04/D8-20-02-21-D8-Cost-Benefit-Analysis-Report-v2.0.pdf [accessed July 2021].

Figure 16 Example of eLoran accuracy performance coverage with 5 stations



Source: MarRINav. (2020). 'D5 – Conceptual PNT Infrastructure'. Available at: https://marrinav.com/marrinav-reports/

6.2.2 Satcom spacecraft

The provision of GNSS-like signals from LEO constellations is currently being explored by several companies. While there is promise of some performance enhancements which can complement existing provision (e.g., stronger signal strength, potentially for indoor penetration), there are some technical challenges and drawbacks in terms of receiver design, signal handover, among others whose technical feasibility is still being tested.

For example, the dual payload on the most recent Iridium Constellation (Iridium Next) demonstrates the concept of using satcom spacecraft to support PNT via LEO (Iridium STL). The growth of LEO constellation offers an alternative to GNSS signals that are increasingly vulnerable to jamming events[222]. PNT services could piggyback megaconstellation infrastructures and given the number of satellites launched, the accuracy of the signal could rival GNSS.

[222] GPS World. (2021). 'Editorial Advisory Board PNT Q&A: Promising alternatives to GNSS'. Available at: shorturl.at/fiERX [accessed 14/07/21].

On the one hand, LEO signals are much closer to earth so are stronger / subject to less attenuation, which means that the PNT signal may be available indoors, enabling many new applications[223] such as location-based advertising, improving the accuracy of the vertical location of emergency calls, and accurate asset or people tracking that require seamless positioning both indoor and outdoor or in the urban environment.

On the other hand, the need for receivers to constantly handover signals from hundreds / thousands of satellites that are moving position continuously adds significant cost, complexity and power consumption which is hard to miniaturise in receiver form.

This idea is being considered by the UK Government to meet national PNT requirements and appears to have been a motivation for their acquisition of OneWeb[224]. The dual-use LEO system could support resilient PNT and may supersede the need for a UK sovereign GNSS-like system, although this is only likely to be tested in future generations of the system.

The Iridium STL service provides PNT information through Iridium's satellites at much greater signal strength than GNSS (300-2400 times the power), offering a resilient back-up to GNSS for critical national infrastructure. Satellite Time and Location can achieve timing accuracy of 10ns-100ns and horizontal position accuracy of 20m-50m (10m with augmentation). Such performance would make STL attractive for critical infrastructures and transport applications.

Iridium communications also announced recently that they were awarded a US Army grant of $30m to develop a payload that could be used to send PNT data in support to GPS signals for military use[225].

The suitability of timing from sources like STL depends on the confidence users place in the resilience of the timing source, and crucially, the degree to which this timing source is itself GNSS dependent. Sources suggest STL is GNSS dependent, but that its internal holdover capacity would ensure continuity of service for approximately one day.

6.2.3 Locata

Locata is another potential alternative to GNSS that could be used at a local level. It is a terrestrial positioning technology that utilises a network of small, ground-based transmitters (LocataNet) providing a robust radio-based positioning signal within a specific area. Instead of using satellites, Locata works by creating local hotspots on the ground that transmit radio-positioning signals.

To provide nano-second level synchronisation Locata uses a patented synchronisation method called TimeLoc that allows internal synchronisation without the need for precise oscillators such as atomic clocks. This enables the Locata network to provide accurate position solutions utilising one-way ranging signals.

[223] Goulding, T. (2020). 'Untangling the OneWeb web', *Space in Focus.* Available at: https://londoneconomics.co.uk/blog/publication/untangling-the-oneweb-web/. [Accessed July 2021].
[224] Goulding, T. (2020). 'Untangling the OneWeb web', *Space in Focus.* Available at: https://londoneconomics.co.uk/blog/publication/untangling-the-oneweb-web/. [Accessed July 2021].
[225] Space News. (2021). 'U.S. Army selects Iridium to develop payload for low Earth orbit satellite navigation system'. Available at: https://spacenews.com/u-s-army-selects-iridium-to-develop-payload-for-low-earth-orbit-satellite-navigation-system/#:~:text=navigation%20system%20%2D%20SpaceNews-,U.S.%20Army%20selects%20Iridium%20to%20develop%20payload,Earth%20orbit%20satellite%20navigation%20system&text=He%20said%20the%20company%20will,satellites%20in%20low%20Earth%20orbit. [accessed July 2021].

The Locata concept was designed to overcome the limitations of GNSS, as well as other pseudolite-based positioning systems, to provide high accuracy and reliable signals, in all environments at an affordable cost.

Locata transmitters, known as LocataLites, transmit multiple GPS-like code and phase signals, in the 2.4 GHz licence-free ISM (industrial, Scientific and Medical) band. The system provides single-point positioning, meaning that a decimetre to centimetre-level positional fix can be obtained without the need for a reference (base) station. Locata can operate on its own, but it can also integrate with external systems including GNSS or IMU.

Locata orbs and transmitters have been deployed in the port of Auckland as a test bed a few years ago and is moving to full automation of straddle carrier and cranes in 2021. The port of Auckland stated that the success of the demonstrator allowed to integrate this new system and intends to double the throughput of containers within the year[226].

6.2.4 VDES-R Mode

VHF Data Exchange System (VDES) is a radio communication system that operates between ships, shore stations and satellites on Automatic Identification System (AIS), Application Specific Messages (ASM) and VHF Data Exchange (VDE) frequencies in the Marine Mobile VHF band.

The R-mode refers to “Ranging mode” or the addition of a ranging capability to existing or new data transmissions. Ranging systems work by measuring the time of flight, or time of arrival, of radio signals to estimate the distance between the user and multiple known base stations. If sufficient stations are available, the user’s position can be calculated by measuring time of arrival of energy waves.

Two concepts for R-Mode are currently being studied by the international maritime community, based on the medium-frequency signals of the IALA Marine Beacon DGPS system, and the use of base station networks of the Automatic Identification System (AIS) and its planned successor, the VHF Data Exchange System (VDES).

6.2.5 Radar absolute positioning

A radar system works by emitting short chirps of high-intensity GHz-frequency radio energy via a transmitting antenna. The pulses propagate through air until they encounter a radio-reflective target, and a certain amount of the radio-frequency energy is directed back towards the radar antenna, providing information about obstacles surrounding the radar. By measuring the elapsed time between emission and reception of a pulse, the range to the radar-reflective object can be determined.

Typically, marine radar systems operate a rotating radar antenna, which continually radiates radar pulses and measuring the time of the radar returns with the angle of rotation of the antenna provides relative-bearing information to the vessel. If signals are received, they are usually plotted on a circular display showing the range of the object’s detection.

[226] Sofranec, D. (2021). ‘Robots emerge from stealth: Locata’s PNT orbs provide port guidance’, *GPS World.* Available at: https://www.gpsworld.com/robots-emerge-from-stealth-locatas-pnt-orbs-provide-port-guidance/ [accessed July 2021].

The use of radar is already widespread in some sectors. In the maritime industry for instance, the SOLAS convention[227] requires that all marine vessels of 300 gross tonnes and upwards (and all passenger vessels) be equipped with one radar operating in the X-band (9 GHz, or 3 cm wavelength). All vessels of 3000 tonnes and upwards shall also equip one S-band (3GHz, or 9 cm wavelength) radar.

The purpose of equipping radar is to **provide situational awareness** to the users. In maritime navigation, skilful use of radar can allow navigating a vessel 'blind', i.e., in situations of extremely low optical visibility, collision avoidance can be achieved using radar alone. However, radar is not used as a primary means for position-fixing and these techniques are applied manually and are primarily used as a fail-safe backup to conventional radionavigation such as GNSS.

To continuously fix a vessel's position using radar and plot these fixes on a navigational chart would constitute a great deal of manual effort and would not be practical on a typical commercial vessel. The GLA investigated and developed techniques that allow a marine radar to perform absolute positioning, determining the latitude and longitude of own vessel using radar return information. For instance, modified radar transponder beacons (racons), called **eRacons,** can communicate their precise location and can be used to automatically estimate their position.

Additional Dead-Reckoning sensors, such as speed-log and gyrocompass, can be integrated into the solution since 'traditional' log-and-gyro based dead reckoning shows very slow and steady error-growth over time, potentially making it much more reliable over long-term GNSS-outages than an inertial system based on Inertial Measurement Units (IMU). This means combining technologies could provide short-term solution.

6.2.6 Omnisense SP500 System

A further potential GNSS alternative at a local level is the **Omnisense S500 Cluster geolocation system**. The Omnisense system is a full 3D positioning system that, similarly to Locata, works by deploying several mobile beacons that periodically broadcast navigation signals, forming a wireless network of beacons.

According to Omnisense, their system is portable (no fixed infrastructure requirement), easy to install and competitively priced and can be used in industrial settings for tasks such as site logistics, yard management, construction, fleet management, etc.; agriculture for cow tracking/monitoring and environmental monitoring; emergency services for firefighters, first responders, police, etc.; healthcare for dementia tracking, sports and fitness training, etc.; and defence for soldier training, GPS-denied situations, etc.[228] The Omnisense system could thus be a viable GNSS backup solution for very localised tasks that require a rapid and easy deployment.

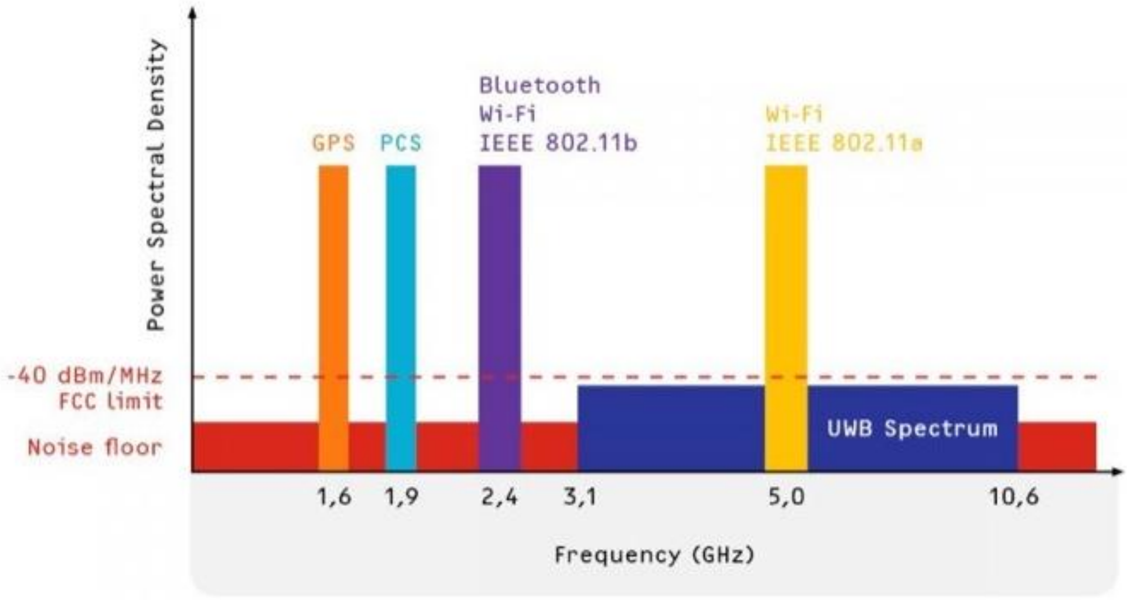
Omnisense is market ready and a system can be acquired from Omnisense. In terms of coverage, it is targeted towards local applications such as the use on a farm for tracking of cows. Given this, the system would not act as a large-scale backup of GNSS PNT information, but rather as a local alternative / backup. Omnisense uses ultra-wide band and 'Wi-Fi' frequencies to deliver its solution.

[227] International Maritime Organization. (1974). 'International Convention for the Safety of Life at Sea (SOLAS), 1974'.
[228] See Omnisense 'Market Sectors / Applications' for more details: http://www.omnisense.co.uk/markets.html [accessed July 2021].

6.2.7 Ultra Wideband (UWB)

The UWB technology can be used for low range radio communications. The technology uses very low energy level high bandwidth radio waves for communications over a wide range of the radio spectrum. It is mostly used for data transfer between devices.

Figure 17 UWB spectrum



Note: PCS = Personal Communication Services (e.g. mobile phone communications)

Source : TechPP[229]

Since 2002, the FCC authorised unlicenced use of UWB frequencies. Before that it was only used by the US military to support radar applications. UWB has gained popularity in recent years with the development of IoT and connected objects. Recent applications in the car industry shows that UWB provides a more secure service than traditional RF or Bluetooth devices[230]. UWB can be used in many applications including augmented reality (AR), navigation, mobile payments, vehicle access, indoor navigation, asset tracking, automotive industry, medical applications.

More recently, Apple launched a device capable of tracking objects lost or stolen[231]. The airTag uses a combination of crowdsourced Bluetooth pings and UWB frequencies to locate objects with precision of a few metres. The device works by sending Bluetooth signals to surrounding devices to indicate its relative position. Using other's devices position the network of objects can triangulate the position of the airTag device and provide users with the last known location. This method creates a moving grid that updates itself, sending regular pings to other users.

[229] Wate, Y. (2020). 'Ultra Wideband (UWB) and its significance', *TechPP*. Available at: https://techpp.com/2020/08/14/ultra-wideband-uwb-explained/ [accessed July 2021].
[230] Hall, C. (2021). 'Tesla thought to be looking at ultra wideband technology for future car unlocking', *Pocket-lint*. Available at: https://www.pocket-lint.com/cars/news/tesla/155588-tesla-thought-to-be-looking-at-ultra-wideband-technology-for-future-car-unlocking#:~:text=Tesla%20thought%20to%20be%20looking%20at%20ultra%20wideband%20technology%20for%20future%20car%20unlocking&text=It's%20a%20common%20method%20for,method%20that%20most%20probably%20use. [accessed July 2021].
[231] Skinner, C. (2021). 'Apple AirTag review', *TechRadar*. Available at: https://www.techradar.com/reviews/apple-airtag-review [accessed July 2021].

6.2.8 Atomic and quantum technologies

Atomic technology is already used to maintain the international atomic time, combining measurements of 400 clocks spread over 50 laboratories around the world.

The National Physics Laboratory (NPL) are developing and characterising a new generation of optical atomic clocks which are based on laser-cooled trapped ions and atoms. The stability and accuracy of these clocks are improving, and they already surpass the performance of existing caesium primary standards. In collaboration with European labs, work carried out on these next generation atomic clocks intend to redefine the "second" at the international system (SI) level. Optical atomic clocks have the potential to improve satellite navigation systems and measurements of the Earth's gravity potential, as well as test fundamental physical theories.

The NPL is also developing new techniques that underpin atomic clocks to develop new quantum sensors such as **atomic magnetometers** and **atomic inertial sensors**.

Atomic magnetometers are chip-scale magnetometers able to detect faint variation of magnetic field within a cubic metre scale vacuum chamber[232]. This method consists of a cell of glass containing rubidium atoms the spin of which is measured to identify the direction of the magnetic field. An atom's spin is random, but electromagnetic interference can influence its direction, and using lasers it is possible to orientate the spin. When an external magnetic field is sensed, the spin deviates from the laser's guidance which decreases the amount of light transmitted. Measuring the amount of light allows to precisely measure the magnetic field's characteristics.

While at early stages, atomic magnetometers could be used in a variety of applications including battery-powered mobile computers, wireless communications and GNSS components, and industry.

Inertial navigation systems are typically corrected by GNSS data which makes those systems vulnerable to a disruption. Atomic inertial sensors can solve the problem of drift by providing measurements of acceleration and rotation with very low bias instability and random walk, using wave-particle duality measurements.

These techniques are not only increasingly precise, but they also remove the need for correction as the measurement error is linear (as opposed to quadratic for traditional systems). This means they are more reliable, for longer. In addition, such an advanced technology is no longer vulnerable to jamming and spoofing attacks.

6.2.9 Precision Time Protocol (PTP)

If a higher accuracy is required, the **Precision Time Protocol (PTP)** can be used for synchronisation. Similarly to NTP, PTP is a network based timing protocol. However, unlike NTP implementations that generally perform timestamping on the software level, PTP implementations use dedicated hardware for timestamping in order to minimise network path issues. PTP can be used within local area networks using a local grandmaster clock as a timing input.[233] The use of dedicated hardware

[232] NIST. 'Chip-scale magnetometers'. Available at: www.nist.gov/noac/technology/magnetic-and-electric-fields/chip-scale-atomic-magnetometers [accessed July 2021].
[233] It should be noted that PTP can also be used without dedicated hardware using software timestamping. However, in this case accuracies are lower, typically around 10 to 100 microseconds. For more information see: EndRun Technologies. 'PTP/IEEE-1588 Frequently Asked Questions'. Available at: https://endruntechnologies.com/pdf/PTP-1588.pdf [accessed July 2021].

allows PTP to achieve accuracies of 10 to 100 nanoseconds[234, 235], although the accuracy depends on the type of clock used as a timing source and the setup of the network. It is crucial that the timing source used as an input to the PTP network does not depend on GNSS or provides sufficient holdover capabilities in the case of a loss of GNSS.

Similarly to NTP, the Precision Time Protocol can also be used as a synchronisation protocol over longer distances. However, performance is dependent on the network configuration[236].

6.2.10 NPL*Time®*

The National Physical Laboratory offers a paid for timing service that is delivered entirely over optical fibre, **NPL*Time®*,** which is certified to meet timestamping standards set by MiFID II on financial transactions. The requirement on timestamping is such that "timestamping accuracy must be within one millisecond for standard electronic trades, while high-frequency trades need accuracy within 100 microseconds, synchronised with and traceable to Coordinated Universal Time (UTC)".

NPL*Time®* uses atomic clocks accurate to within one second every 158 million years, and **PTP**, which can deliver synchronised timestamping through fibre networks thanks to what the vulnerabilities of GNSS are avoided.

6.2.11 What3words

What3words is a London based company which split the surface of the world in 3x3m cells and attributing each of them a unique, semi-random series of 3 words. This is presented as an alternative address system which can lack in precision when accessing complex buildings, with many entrances. It also supports developing countries where address systems simply do not exist.

The company also presents itself as an alternative to complex reading of GNSS coordinates. The 3 words sequence can be critical in search and rescue applications, where time matters and reading and communicating words can be simpler, saving time and lives.

The technology is well integrated in smartphones and has penetrated the car industry in recent years[237]. However, the technology still relies on GNSS signal to locate individuals on the map which does not make it an alternative per se. But the system could be integrated with one or many of the alternative sources of PNT described above. If the maps were made available for local download like open street maps, it could easily replace the need to paper maps already in decline and would add a level of safety for its users, removing the need for internet connectivity.

[234] EndRun Technologies. 'Precision Time Protocol'. Available at: https://endruntechnologies.com/pdf/PTP-1588.pdf [accessed July 2021].
[235] Symmetricom. (2010). 'NTP and PTP (IEEE 1588) - A Brief Comparison'. Available at: http://www.en4tel.com/pdfs/NTPandPTP-A-Brief-Comparison.pdf. [accessed July 21].
[236] EndRun Technologies. 'Precision Time Protocol'. Available at: https://endruntechnologies.com/pdf/PTP-1588.pdf [accessed July 2021].
[237] The AA. (2019). 'AA drives innovation with location technology what3words'. Available at: https://www.theaa.com/about-us/newsroom/what-3words [accessed July 2021].

6.3 Summary of mitigating strategies

Table 23, presented in this section, summarises the mitigation strategies discussed in this chapter, and identifies useful candidates for mitigation of problems, where 'traditional methods' are considered a default mitigation and not mentioned in the tables.

The solutions presented in Sections 6.1 and 6.2 are unlikely to be widely adopted individually. Most of them would only be able to procure PNT data at a local level and in most cases remain short range. As the MarRINav study shows, a reliable source of alternative PNT data is likely to come from an integrated system-of-systems. Taken alone, the technologies are unable to supply continuous position and timing data for an extended period of time, at large scales.

This implies the capital expenditures required are likely to be high but could greatly outweigh the loss if no alternative are provided. This study shows that the loss of signal would induce a loss of over £7.6bn over a 7-day period. The development of a resilient PNT infrastructure that employs the appropriate mitigation technology might contribute to reducing this loss by almost 50%.

Table 26 Effectiveness of Mitigation

Sector	Application	Economic loss (7-day, £m)	Mitigation Technology	Mitigated Loss
Agriculture	Cultivation	223.6	Locata/Omnisense**	
Aviation	Navigation	0.1	none	
	Surveillance (communications)	0.4	none	
	Safety	0.5	STL*	0.5
	Environmental	Not assessed	n/a	
	Productivity	3.0	Locata/Omnisense**	
Emergency Services	Public-safety Answer Point (PSAP) caller location	1,560.2	none	
	Automatic vehicle and personnel location	1,968.7	STL, eLoran, Locata/Omnisense**	1,968.7
	Medical delivery and critical supplies	4.9	STL, eLoran, Locata/Omnisense**	4.9
	Security and surveillance robots	0.1	Locata/Omnisense**	
Finance	Infrastructure (atomic clocks)	-	NPL Time, eLoran, STL	-
	Infrastructure (conditioning)	-	NPL Time, eLoran, STL	-
Rail	Driver Advisory Systems	0.1	STL, eLoran	0.1
	Fleet Management	0.0	STL, eLoran	0.0
	Cargo Monitoring	0.0	STL, eLoran	0.0
	Infrastructure Monitoring	0.9	STL*, eLoran*	0.9
	Automatic Selective Door Operation	38.7	none	
	Train Cancellations	100.1	STL, eLoran	100.1
Maritime	Shipping industry	182.8	STL, eLoran*, VDES-R Mode, Radar Absolute Positioning	182.8
	Port operations	1,309.2	Locata/Omnisense**	
	Fishing industry	7.9	STL, eLoran*, VDES-R Mode	7.9

	Preventing fatalities – SAR	0.3	none	
Road	Road navigation	1,599.4	STL	1,599.4
	Logistics and fleet management	60.2	STL	60.2
	Insurance telematics	Not estimated	n/a	
	Emergency and breakdown call	0.4	STL	0.4
Government	Offender Tracking	0.6	none	0.6
	Meteorology	2.1	none	
Space	Satellite Communications	32.2	NPL MSF, STL, eLoran	32.2
Surveying	Surveying	526.5	Locata/Omnisense**	
Location-Based Services	Location-Based Services (LBS)	1.6	none	
Energy	Energy	Not estimated	n/a	
Communications	Fixed line communications	Not estimated	n/a	
	Cellular telecommunications	Not estimated	n/a	
	TETRA	Not estimated	n/a	
Health	Health	1.0	none	
	Total	**7,644.5**		**3,958.7**

Note: * in the column of mitigation assumes the form factor of the listed mitigation technologies is such that they are useful for the application. ** refer to Locata/Omnisense solutions and indicate coverage is local to the area where devices will be installed. When no asterisk is included, this is considered certain. Total in brackets indicate the mitigated loss independent of form-factor assumptions.

7 Summary of results

This research is a refresh of the June 2017 London Economics report "The economic impact to the UK of a disruption of GNSS" on behalf of the UK Space Agency (UKSA).

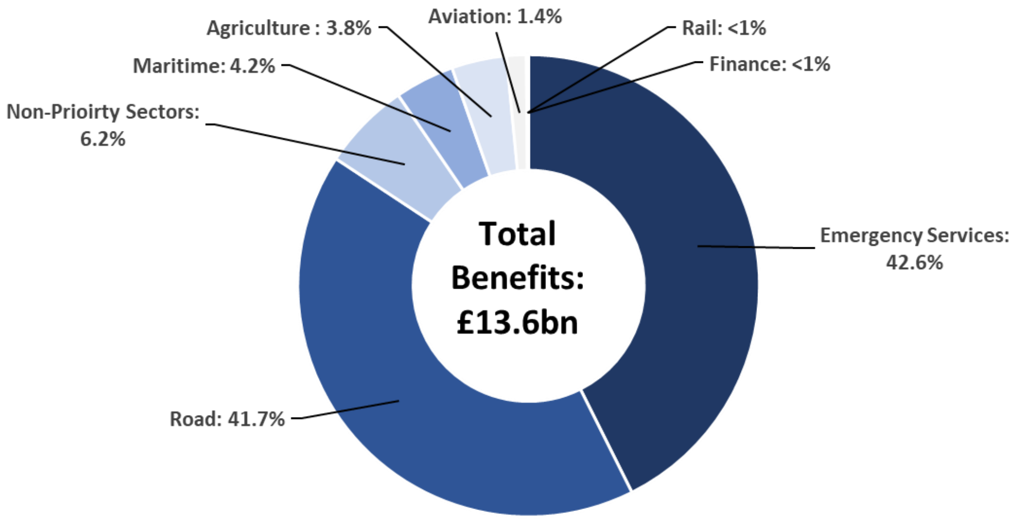
The objective is to improve the accuracy and scale of GNSS benefits and estimated losses for seven priority sectors: Agriculture, Aviation, Emergency Services, Finance, Maritime, Rail, and Road, as well as a more general update of all other updated sectors covered in the previous study.

The research also provides an updated assessment of current and future mitigation strategies.

7.1 Economic benefits

The economic benefits to the UK from the use of GNSS have been monetised at **£13,622.2m per annum**. Benefits are estimated against a counterfactual scenario in which GNSS had not been developed or chosen as the primary source of PNT in the applications covered by this study.

Figure 18 Share of economic benefits from GNSS, by sector



Source: London Economics

Most of the economic benefits are estimated to come from Emergency Services (43%) and Road (42%) (Figure 18). The Emergency Services sector benefits from efficiency gains due to improved navigation and general resource management, which translate both into direct cost savings and into improved health outcomes for UK citizens. The road sector benefits from efficiency gains due to GNSS in the form of time and fuel savings, and the associated environmental benefits.

Overall, compared to the 2017 report, the total estimated economic benefits have increased by 102% (Table 27), more than doubling in magnitude. A majority of this change is due to increases in the Emergency Services and Road sectors. In each sector an increase in device penetration (smartphones, satnavs, and insurance telematics devices) explain much of the growth.

Table 27 Annual economic benefits estimated in 2017 and 2021 (current) report

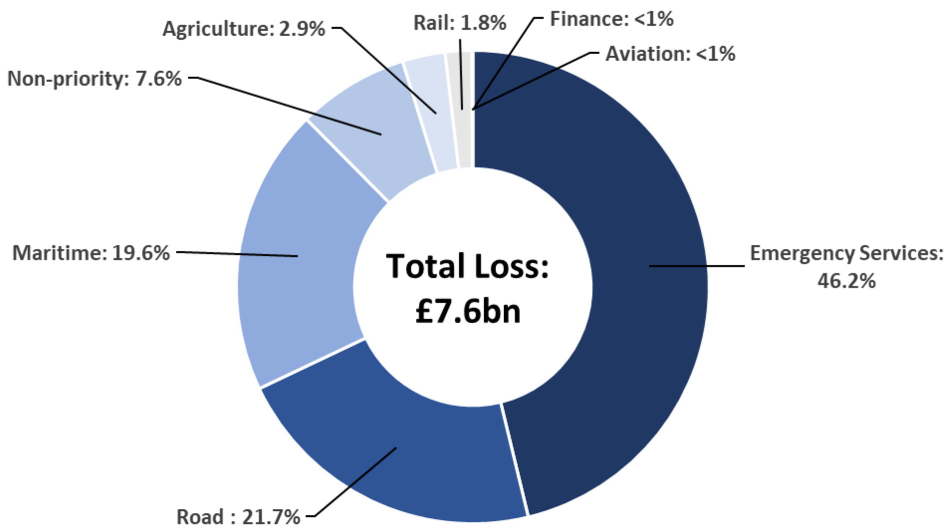
Sector	Annual benefits in 2017 (£m)	Annual benefits in 2021 (£m)	Change
Agriculture	284.4	524.4	*84%*
Aviation	3.4	187.9	*5426%*
Emergency Services	2,021.8	5,805.1	*187%*
Finance	0.6	1.7	*183%*
Maritime	434.0	567.8	*31%*
Rail	10.9	19.5	*79%*
Road	3,322.2	5,674.3	*71%*
Other updated Sectors	675.3	841.5	*24.7%*
Total	**6,752.6**	**13,622.2**	***102%***

Source: London Economics analysis

7.2 Economic loss

The economic loss of losing GNSS for seven days has been estimated at **£7,644.5m**. A separate analysis of a 24-hour outage identified as estimated loss of **£1,424.4m during a 24-hour outage**.

Figure 19 Share of 7-day economic loss, by sector



Source: London Economics

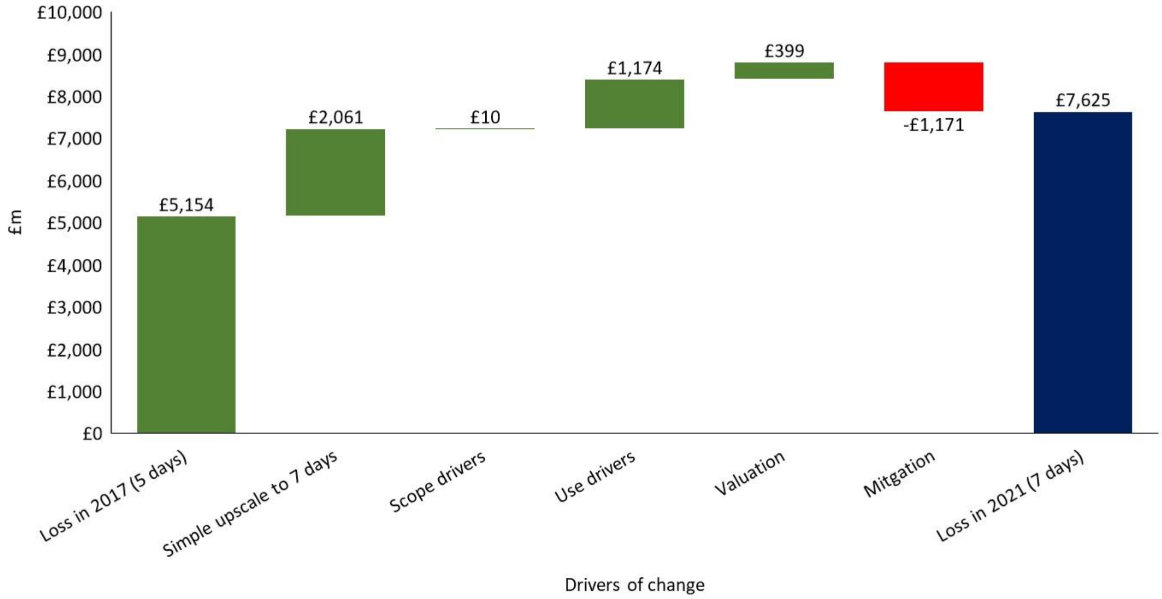
Applications in emergency services, maritime, and road together account for 87.6% of the total economic loss.

This report assumes a Reasonable Worst Case Scenario (RWCS) of a full outage of GNSS of 7-days, as opposed to the 5-days assumed for the 2017 study. This means that the 2017 and new 2021 loss estimates cannot be directly compared, even when adjusted to give an 'average loss per day' estimate. This is because: 1) loss per day accrues non-linearly as the holdover of applications may be sufficient for the early days before it fails. Similarly, the impact of loss may reduce over time as the population realises the event is on-going and shifts its behavioural patterns, and 2) a 7-day outage incorporates weekend activity where the profile of losses are very different than on the weekday.

Nevertheless, Figure 20 provides a simplified explanation on the difference between 2017 and 2021 estimates. The economic loss over 5-days was estimated at £5,153.5m. Applying a simple upscale of 40% to allow for some naïve comparison between the 2017 and 2021 loss estimates increases the economic loss by £2,061.4m.[238] Note that economic losses are considered against a baseline where GNSS is fully functional; mitigating efforts through 'traditional' means (e.g. by using paper maps) will be considered but may be limited owing to the immediacy and brevity of the disruption. These losses may diverge from monetised benefits of an application as they are measured against a different baseline to the marginal improvement considered when monetising benefits.

New applications identified and monetised in this report (scope drivers) increase the economic loss by £10.0m. The change in GNSS penetration and volume of users (use drivers) further increases the economic loss by £1,173.9m. The parameters which are used to monetise impacts have also increased (valuation), increasing the economic loss by £398.6m. Improvement in holdover and resilience since 2017 (mitigation) reduces the economic impact of GNSS loss, decreasing the economic loss by £1,171.1m. All these drivers of change combined bring the figure of £5,153.5m in the 2017 report to the figure of £7,625.3m in the 2021 report.

Figure 20 Drivers behind difference between 2017 and 2021 loss estimates



Note: 'Simple upscale' = a change in the RWCS i.e. 5 days to 7 days, or 40% increase. 'Scope drivers' = new applications identified and applications that were not modelled in the 2017 report but are in the 2021 report. 'Use drivers' = change in GNSS penetration and change in volume of users. 'Valuation' = a change in the parameters used to assess economic impact. 'Mitigation' = change in holdover and resilience.

Source: London Economics

Table 28 presents the 2017 and 2021 loss estimates by sector. Again, the two sets of estimates cannot be directly compared, but are presented together here for simple illustration.

[238] As noted above, bear in mind that while this is too simplistic to derive meaningful insights, it does make the time period of the outage more comparable.

Table 28 Economic loss estimated in 2017 and 2021 (current) report

Sector	Loss in 2017 (5 days, £m)	Loss in 2021 (7 days, £m)	Change
Agriculture	155.8	223.6	*44%*
Aviation	0.3	4.0	*1,190%*
Emergency Services	1,531.5	3,533.9	*131%*
Finance	-	-	*0%*
Maritime	1,064.6	1,500.2	*41%*
Rail	110.4	139.9	*27%*
Road	1,920.2	1,659.9	*-14%*
Other updated	387.8	583.0	*52%*
Total	**5,170.6**	**7,644.5**	***48%***

Source: London Economics analysis

Index of Tables, Figures and Boxes

Tables

Figures

ANNEXES

Annex 1 List of sources

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Annex 2 List of Acronyms

ADS-B	Automatic Dependent Surveillance – Broadcast
AIS	Automatic Identification System
AR	Augmented Reality
ATM	Automated Teller Machine
bCall	Breakdown call
BEIS	Department for Business, Energy and Industrial Strategy
BT	British Telecom
C/A	Coarse Acquisition
CAGR	Compound Annual Growth Rate
C-DAS	Connected Driver Advisory System

CFIT	Controlled Flight Into Terrain
C-ITS	Cooperative Intelligent Transport System
CME	Coronal Mass Ejection
CNI	Critical National Infrastructure
CODA	Central Office for Delay Analysis
COMPASS	BeiDou second generation, now known as BeiDou-2
DAS	Driver Advisory System
eCall	Emergency call
EE	Everything Everywhere (British mobile network operator)
EGNOS	European Geostationary Navigation Overlay Service
ELT	Emergency Locator Transmitter
EPIRB	Emergency Position-Indicating RadioBeacons
ERP	Effective Radiated Power
ESA	European Space Agency
EU	European Union
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
EUSPA	EU Agency for the Space Programme (formerly 'GSA')
EWAs	EGNOS Working Agreements
FCC	Federal Communications Commission
FMC	Fisheries Monitoring Centre
FTE	Full Time Equivalent
GAGAN	GPS Aided Geo Augmented Navigation system
GDP	Gross Domestic Product
GLONASS	Globalnaya Navigazionnaya Sputnikovaya Sistema
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GVA	Gross Value Added

HFT	High Frequency Traders
HMRC	Her Majesty's Revenue and Customs
IALA	International Institute of Lighthouse Authorities
ILS	Instrument Landing System
IMU	Inertial Measurement Units
IOAT	Input Output Analytical Table
ISA	Intelligent Speed Assistance
ISES	International Space Environment Service
LBS	Location-Based Services
LEO	Low Earth Orbit
LiDAR	Light Detection and Ranging
LoLo	Lift-on Lift-off
LPV	Localizer Performance with Vertical guidance
M25	A major motorway encircling London, UK.
MarRINav	Maritime Resilience and Integrity of Navigation
MEO	Medium Earth Orbit
MMO	Marine Management Organisation
MSAS	Multifunctional transport satellites Satellite Augmentation System
NAVIC	Navigation Indian Constellation (formerly IRNSS)
NHS	National Health Service
NPL	National Physics Laboratory
NTP	Network Time Protocol
ONS	Office for National Statistics
OSNMA	Open Service – Navigation Message Authentication
PCS	Personal Communication Services
PLB	Personal Locator Beacons
PLPR	Plain Line Pattern Recognition

PNT	Position Navigation Timing
PPP	Precise Point Positioning
PSAP	Public-Safety Answer Point
PTP	Precision Time Protocol
QZSS	Quasi-Zenith Satellite System
RFID	Radio-Frequency Identification
RNSS	Regional Navigation Satellite System
RoRo	Roll-on Roll-off
RPAS	Remotely Piloted Aerial Systems
RTK	Real Time Kinematic
RWCS	Reasonable Worst Case Scenario
SAR	Search and Rescue
SBAS	Satellite Based Augmentation System
SCC	Social Cost of Carbon
SNR	Signal to Noise Ratio
SOLAS	Safety Of Life At Sea
SST	Space Surveillance and Tracking
STL	Satellite Time and Location
TETRA	Terrestrial Trunked Radio
U.S.	United States
UAV	Unmanned Air Vehicle
UK	United Kingdom
UKMCC	UK Mission Control Centre
UTC	Coordinated Universal Time
UWB	Ultra Wideband
V2X	Vehicle to Everything
VDES-R	Very high frequency Data Exchange System – Ranging mode

VMS	Vessel Monitoring System
VRA	Variable Rate Application
VTS	Vehicle Traffic Services
WAAS	Wide Area Augmentation System

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