Transmission and control of SARS-CoV-2 on ground public transport: A rapid review of the literature to date.

Authors:
Nicola Gartland[a], David Fishwick[a], Anna Coleman[a], Karen Davies[a], Angelique Hartwig[b], Sheena Johnson[b], Martie van Tongeren[a]

Affiliations:
[a]School of Health Sciences, University of Manchester, Manchester, United Kingdom
[b]Alliance Manchester Business School, University of Manchester, Manchester, United Kingdom

Corresponding Author:
Dr. Nicola Gartland
Email: nicola.gartland@manchester.ac.uk
Postal Address: Division of Population Health, Health Services Research and Primary Care
School of Health Sciences, University of Manchester, Manchester, M13 9PL

Contributions of authors:

All authors contributed to the conceptualisation of the review, development of the methodology, and visualisation. NG conducted the investigation. NG and DF performed the formal analysis and writing of the original draft. All authors contributed to the review and editing of the manuscript.

Key evidence statements:

1) Transmission of Covid-19 can occur on public transport, however the relative importance of route of transmission is unknown.
2) Masks, ventilation, and social distancing will reduce risk of transmission on public transport.
3) The relative risk of infection on public transport compared to other activities is unknown.
4) Current evidence and knowledge gaps need to be addressed in order to improve risk assessment and support decision making to balance keeping public transport operationally effective, whilst protecting those working on and using public transport.
5) Current studies are underway in the UK to address some of these evidence gaps.

Abstract

During a pandemic, public transport is strategically important for keeping the country going and getting people where they need to be. The essential nature of public transport puts into focus the risk of transmission of SARS-CoV-2 in this sector; rapid and diverse work has been done to attempt to understand how transmission happens in this context and what factors influence risk.

This review aimed to provide an overview of the literature assessing transmission, or potential for transmission, of SARS-CoV-2 on ground-based public transport, as well as studies assessing the effectiveness of control measures on public transport.

An electronic search was conducted using Web of Science, Ovid, the Cochrane Library, ProQuest, Pubmed, and the WHO global COVID database.

The search strategy identified 28 papers for inclusion in the review; 10 papers assessed transmission of SARS-CoV-2, 11 assessed control measures, and seven assessed levels of contamination. Eleven papers were based on modelling approaches; 17 studies were original studies reporting empirical COVID-19 data.

The literature is heterogeneous, and there are challenges for measurement of transmission in this setting. There is evidence for transmission in certain cases, and mixed evidence for the presence of viral RNA in transport settings; there is also evidence for some reduction of risk through mitigation. However, the routes of transmission and key factors contributing to transmission of SARS-CoV-2 on public transport are not yet clear. Research gaps are identified and discussed and six key questions still to be answered are highlighted. Further exploration of transmission factors and effectiveness of mitigation strategies is required in order to support decision making in the future.

Keywords:

COVID-19, coronavirus, public transport, transmission, review

Funding

This work was supported by funding from the PROTECT COVID-19 National Core Study on transmission and environment, managed by the Health and Safety Executive on behalf of HM Government. The contents of this publication, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy.

Declarations of interest

DF is the Chief Medical Adviser for the Health and Safety Executive, GB and also HSE NI. The contents of this publication reflect the opinions of the authors, and not necessarily those of HSE policy or policy makers.

1. Introduction

Coronavirus disease 2019 (COVID-19) is an infectious respiratory disease, caused specifically by the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2; Gorbalenya et al., 2020). This paper presents a rapid review of research studies of COVID-19 and transmission associated with ground public transport. Globally, public transport was quickly identified as a potential high risk environment for SARS-CoV-2 transmission due to (a) confinement of passengers in a limited space with limited ventilation, (b) inability to identify potentially infected individuals, and (c) the presence of multiple potentially contaminated surfaces (Union Internationale des Transports Publics, 2020). In the UK, the public were initially advised to avoid public transport unless travel was essential, whereas more recently, advice has been to adhere to guidance aimed at reducing risk of transmission. It is anticipated that passenger numbers will continue to increase from the very low rates observed during the initial lockdowns, which means understanding of risk is increasingly important. However, to date, relatively little is understood about the risk of transmission and the effectiveness of measures aimed at reducing this. This review aims to present current insight into transmission risk, and the effectiveness of control measures designed to reduce risk to individuals using, or working in, public transport.

Understanding the modes of SARS-CoV-2 transmission, and their relative importance, is crucial for the development and implementation of control measures to reduce the risk of viral transmission. The virus is known to be transmitted from person to person through three routes:

(1) via droplets expelled from the nose or mouth of an infected person to another person who is in close proximity;

(2) via contact with surfaces that have been contaminated with the virus (e.g., as an infected person has touched the surface or droplets/aerosols containing virus have deposited on the surface) followed by hand to mouth, nose or eye contact; and

(3) via airborne transmission through aerosols containing virus emitted from an infected person and which can remain persistently airborne (Morawska & Cao, 2020).

It is known that the virus can survive outside a host for variable durations depending on the type of surface and environmental conditions. For example, it can survive for over 3 hours in the air, on copper surfaces for up to 4 hours, on cardboard for up to 24 hours, and on plastic and stainless steel for up to 72 hours (van Doremalen et al., 2020). Fragments of the virus have been detected in community settings for up to seven days, but as these studies do not distinguish between live virus, dead virus and viral fragments, it is unknown if the virus detected remained infectious (Onakpoya et al., 2021; National Collaborating Centre for Methods and Tools, 2021), and conclusions about the infectiousness of such samples cannot yet be drawn (Heneghan et al., 2021).

The risk of viral transmission on public transport was initially highlighted by studies investigating risk of infection by occupation. One early observational study utilised governmental investigation reports in Hong Kong, Japan, Singapore, Taiwan, Thailand, and Vietnam (Lan, Wei, Hsu, Christiani, & Kales, 2020). Drivers and transport workers were included in the five occupational groups with the highest number of cases [healthcare workers (22%), drivers and transport workers (18%), services and sales workers (18%), cleaning and domestic workers (9%) and public safety workers (7%)]. Drivers and transport workers included car, taxi and van drivers, locomotive engine drivers and related workers and bus/tram drivers; car, taxi and van drivers had the highest rates of COVID-19 within these subgroups. In a study carried out in Norway, after nurses, physicians and dentists, bus and tram drivers were found to have the next highest risk (of COVID-19 during the first wave of infection (Magnusson, Nygård, Vold, & Telle, 2020). The relative risk for bus and tram drivers reduced in the second wave of infections in Norway, but taxi drivers, transport conductors and bus and tram drivers were still among the occupations with highest risks.

In the UK, the Office for National Statistics (ONS) reported that road transport drivers had higher mortality rates related to COVID-19 among men; overall working age men had a mortality rate of 31.4 deaths (per 100,000), while taxi drivers and chauffeurs had a rate of 101.4 and bus and coach drivers of 70.3 (Office for National Statistics, 2021). Multiple factors could have contributed to this observation, including occupational risk of exposure (UCL Institute of Health Equity, 2020). The heightened risk of public transport workers suggests the need to identify the routes of transmission and risks to health and safety specific to public transport.

A range of control measures have already been identified and implemented, directed at reducing transmission. These include face mask or covering usage on public transport, improved facilities for handwashing and sanitisation, increased cleaning and disinfection of vehicles, maintenance of social distancing, increased ventilation, and health messaging (Pardo et al., 2021; Shen, Kong, Dong, Birnkrant, & Zhang, 2021; Tirachini & Cats, 2020). Transmission can occur through the 3 routes described above; the fomite route may be possible to detect as traces of the virus can remain on surfaces, and airborne virus could be identified through sampling by air filters. It may be harder to detect infection via droplets as this could occur more directly from person-to-person. An early rapid review conducted by Public Health England identified only four studies (Public Health England, 2020) reporting transmission patterns. The current review assimilates and reports on the growing evidence base informing on the transmission patterns of SARS-CoV-2, particularly relating to ground public transport (e.g. bus, train, taxi). There are of course challenges to collecting data to link a transmission event to a particular journey; people can use multiple forms of transport, at variable times in a day, for variable amounts of time and with a random and changing group of other people. At present, reliable contact tracing for journeys via public transport in the UK has not been possible, unless the person testing positive knows the co-passenger personally (Leith & Farrell, 2020).

Population based studies (Burns et al., 2020; Carteni, Di Francesco, & Martino, 2020; Francetic & Munford, 2021; Zhang, Zhang, & Wang, 2020) have assessed the effect of the use of public transportation on rates of SARS-CoV-2 transmission in the population, in particular the effects of movement restrictions on national infection rates. These studies have demonstrated that public transportation links are associated with increased spread of the virus; one study reported that trips on public transport in Italy were linked to increased infection rates three weeks later (Carteni et al., 2020). However, in these papers, no characteristics of public transport were measured or assessed for their effect on transmission rates. While these studies suggest that public transport may play a role in the spread of the virus, it cannot be determined whether transmission occurred on public transport. Therefore, these papers have not been included in the current review.

Research has also been published in relation to air travel and transmission aboard cruise ships (Batista, Dickenson, Gurski, Kebe, & Rankin, 2020). However, these forms of transport are distinct from the more transient engagement with ground public transport which is the focus of this review; on planes air circulation is highly controlled, and the studies on cruise ships have largely focussed on transmission of SARS-CoV-2 between passengers onboard vessels who were quarantined for multiple weeks. Additionally, air and cruise travel environments require stricter testing regimes pre- and post-travel, and higher levels of control over passenger admission and identification. For these reasons, these papers have been excluded from the current review.

This review aims to provide an overview of the literature that assesses the transmission, or potential for transmission, of SARS-CoV-2 on ground based public transport, as well as studies assessing the effectiveness of mitigating control measures. Specifically, the following research questions were focussed on:

1. What is the evidence for the presence of SARS-CoV-2 in air and on surfaces in ground public transport?
2. What do empirical studies of SARS-CoV-2 transmission on public transport show?
3. What evidence is there for the effectiveness of control measures in public transport?
4. What does risk modelling for SARS-CoV-2 transmission rates on ground public transport show?

2. Methods

A search was conducted using Web of Science, Ovid, the Cochrane Library, ProQuest, Pubmed, and the WHO global COVID database (initial search December 7th, 2020; updated March 2nd and May 10th, 2021), with the following search terms: Covid, SARS-CoV-2, coronavirus, public transport, transit, train, rail, bus, taxi, passenger, transmission, infection, risk, control. Grey literature and review articles were also searched, and forwards and backwards searches of identified studies were performed.

The inclusion criteria were; (a) studies that assessed effectiveness of control measures on transmission in any ground public transport in any country; (b) studies that looked at levels of transmission linked to characteristics of public transport (i.e., duration of journey, proximity with other passengers, type of transport) in any country; (c) studies that looked at transmission of SARS-CoV-2 in any country. Exclusion criteria were (a) commentaries, (b) studies that only reported on the effects of travel restrictions (lockdowns/stopping air travel/reduced mobility), (c) studies that reported on the effects of COVID-19 on transport habits or industry, (d) population-based studies using transport as a proxy for mobility, (e) air and cruise ship travel and (f) studies not accessible in English.

3. Results

The initial search identified 734 papers for consideration (duplicates removed). Following application of the inclusion and exclusion criteria, 28 papers were included in this review, shown in Table 1. Eleven were based on modelling approaches, which used existing datasets to estimate transmission rates and disease spread; the remaining 17 studies were original studies reporting empirical data. Two were conducted in the UK, six in the USA, four in China, three in India, the remaining in a variety of locations including Australia, Brazil, Ethiopia, Germany, Ghana, Iran, Ireland, Italy, Singapore, Spain, and Thailand. Seventeen of the studies were peer-reviewed, while the others were pre-prints, reports, or conference publications. Seven studies assessed levels of contamination, ten studies assessed transmission of SARS-CoV-2, and eleven studies assessed control measures. Most of the studies focussed on bus or train transport (22 studies), but other modes included subways, light rail, trolley bus and cars/taxis, and some studies focussed on all public transport.

	Authors	Year	Peer reviewed?	Location of study	Transport Mode	Data Collected	Sample Size	Factors Investigated
Detecting Contamination by SARS-CoV-2								
1	Abrahão et al.	2021	yes	Brazil	bus stations	yes	64 samples (bus)	Measuring viral contamination on distinct material surfaces
2	Brazell et al.	2021	pre-print	USA	bus and light rail	yes	167 samples (in PT)	Measuring viral contamination on bus and light rail high-touch points
3	Di Carlo et al.	2020	pre-print	Chieti, Italy	bus	yes	104	Measuring viral contamination on a bus
4	Hadei et al.	2021	yes	Iran	subway trains and bus	yes	10 samples (in PT)	Measuring viral contamination of air samples in public places
5	Lednicky et al.	2021	pre-print	USA	car	yes	NA	Testing for air contamination in a car
6	Moreno et al.	2021	yes	Spain	subway trains and bus	yes	58 surface samples 24 air samples	Measuring viral contamination on surfaces and in air
7	Passos et al.	2021	yes	Brazil	bus stations	yes	5 samples (bus stations)	Measuring viral contamination in air
Transmission of SARS-CoV-2								
8	Dai & Zhao	2020	pre-print	China	bus	modelling	NA	Modelling transmission risk on bus with and without mask
9	Hu et al.	2020	yes	China	train	yes	2334 index patients 72093 contacts	Measuring spatial distance, co-travel time
10	Krishnamurthy et al.	2020	yes	Chennai, India	bus and train	modelling	NA	Modelling number of passengers and exposure time
11	Luo et al.	2020	yes	Hunan Province, China	coach and minibus	yes	1 index patient 243 contacts	Seating, duration, ventilation
12	Mesgarpour et al.	2021	yes	Thailand	bus	modelling	NA	Modelling droplet spread
13	Mo et al.	2021	yes	Singapore	bus	modelling	NA	Modelling effects of operational mitigations on viral spread in network
14	RSSB	2020	yes (by CSA's team at DfT)	UK	train	modelling	NA	Risk for person-to-person contact, number of person contacts, mitigation factors

15	Shen J et al.	2021	pre-print	USA	all public transport	modelling	NA	Modelling probability of infection, and estimating effectiveness of IAQ strategies
16	Shen Y et al.	2020	yes	Zhejiang province, China	bus	yes	1 index patient 172 contacts	Modelling high risk vs low risk zones on bus
17	Shoghri et al.	2020	Conference publication	Sydney, Australia	bus	modelling	NA	Modelling movements, distance travelled, and number of encounters
Control of SARS-CoV-2								
18	Bonful et al.	2020	yes	Ghana	taxi and bus	yes	45 stations	Observational study of compliance with guidelines
19	Defar et al.	2020	yes	Addis Ababa, Ethiopia	public transport drivers	yes	6007	Measuring knowledge, and practices that control COVID-19
20	Dzisi & Dei	2020	yes	Ghana	bus	yes	859 face masks observations 909 distancing observations	Observational study of compliance with guidelines
21	Edwards et al.	2021	pre-print	USA	bus	yes	NA	Characterising cough aerosol dispersion, operational controls, masks
22	Heald et al.	2020	yes	UK	all public transport	modelling	NA	Modelling the effect of face masks on transmission
23	Mathai et al.	2020	pre-print	USA	taxi	modelling	NA	Modelling spread of pathogens within a car with air flow from windows
24	Mitze et al.	2020	no	Germany	all public transport	yes with modelling	NA	Measuring the effect of compulsory face masks on infection rates
25	Natnael et al.	2021	yes	Ethiopia	taxi	yes	417 drivers	Measuring facemask wearing and associated factors
26	Pavansai et al.	2021	Conference publication	India	bus	modelling	NA	Modelling droplet dispersion with vehicle velocity and cough velocity
27	Talekar et al.	2020	pre-print	India	train	modelling	NA	Modelling the effects of cohorting workers
28	Zhang et al.	2021	yes	USA	bus	yes	NA	Measuring droplet spread, ventilation, masks

PT public transport; IAQ indoor air quality

Table 1. Characteristics of the papers included in the review.

3.1 What is the evidence for the presence of SARS-CoV-2 in air and on surfaces in ground public transport?

Seven studies were found to address this question. A study in the Abruzzo region of Italy took samples from the air and frequently touched surfaces of a trolleybus in routine operation, in May 2020 (Di Carlo et al., 2020). The service ran for 20km with 50 passenger stops. Samples were collected every weekday for two weeks; air samples were taken with gelatine membrane filters (one installed near ticket machine, one at the rear of bus), surface samples from five frequently touched points, before and after the bus shift, prior to cleaning. Transmission mitigation strategies were in place, including increased cleaning and behavioural control measures (face masks, social distancing and hand hygiene). All samples were tested using specific real-time reverse transcriptase-polymerase chain reaction (RT-PCR) targeting ribonucleic acid (RNA)-dependent RNA polymerase. During the two-week period, 1100 passengers travelled on the trolleybus, with an average of 123 passengers per measurement shift. All samples were negative for SARS-CoV-2. It was estimated that about 37 infected and asymptomatic people could have travelled on the trolleybus each day. The authors argued that cleaning procedures, ventilation recommendations, and passenger guidance for handwashing/sanitizing, social distancing and wearing face masks were effective in controlling the spread of the virus.

Three additional studies investigated viral RNA in the air. In Brazil, Passos and colleagues (2021) assessed the presence of viral RNA in a variety of aerosol samples, primarily taken in health care environments, but five air samples taken from a busy ("intense movement of people") bus station were negative for viral RNA. This bus station was monitored by security staff to ensure mask wearing compliance. Hadei and colleagues (2021) investigated the presence of SARS-CoV-2 in the air sampled using glass fibre filters from a variety of public spaces in Iran, including an airport, subways, and buses. Eight transport locations were studied. Sampling duration was 1-1.5 hours. The presence of viral RNA was measured using a coronavirus nucleic acid diagnostic real time PCR technique. In 67% of samples taken from transportation sites, SARS-CoV-2 RNA was detected. The number of people present, and the air volume sampled were both positively associated with presence of viral RNA, whereas the percentage of people with masks and air temperature were negatively related to viral presence. None of the associations, however, were statistically significant, and RNA presence does not confirm live virus, or sufficient virus to enable transmission. Indeed, RNA is much more persistent than infectious virus in the environment (Transmission in the Wider Environment Group, 2020). Only one study was identified that attempted to determine if detected virus was viable. Air sampled from the sun-visor on the passenger side of a car driven by a patient with COVID-19 for 15 minutes was shown to contain SARS-CoV-2 using a PCR technique (Lednicky et al., 2021). SARS-CoV-2 RNA was detected on four filters, ranging from 0.25μm to 10μm, but the greatest number of particles were obtained in the 0.25 to 0.50μm diameter range. Cells inoculated with viral material in this diameter range demonstrated viral infection, indicating that viral material of this diameter was viable. Cells inoculated with viral material from other filters did not demonstrate infection. Whilst inherently limited, this finding has wider relevance for all forms of public transport.

Three additional studies sampled public transport surfaces for the virus. Abrahão and colleagues investigated the presence of SARS-CoV-2 on various surfaces in public spaces in Brazil, between April and June 2020 (Abrahão et al., 2021). RT-qPCR was used to assess the presence of viral genome in the collected samples. Across six bus stations, 14.3% of the samples were positive for SARS-CoV-2 RNA; compared to 40.8% of samples from health care units, 34.7% of samples from public squares, 8.1% of samples in other public places and 2.1% of public markets. Most of the positive samples were detected on metal and concrete surfaces. The authors argued that the presence of the virus in busy transport locations like bus stations highlights the need for interventions to reduce transmission.

Moreno and colleagues (2021) collected samples taken from buses and subway trains in Barcelona, Spain, during early summer 2020. Eighty-two (58 surface swabs, 9 air conditioning (a/c) filters, 3 a/c dust, 12 ambient air) were analysed using an RT-PCR technique for SARS-CoV-2. Thirty samples (36%) had evidence for at least one of the three tested viral RNA targets. Positive results were more common from vehicle support bars than ambient air inside vehicles. In addition, there were higher concentrations of viral RNA in buses compared to trains. Three a/c train samples were viral RNA free, whereas 4 of the 9 bus samples (a/c filter and dust samples) showed RNA presence. After cleaning, fewer positive samples were obtained in buses, although four samples still showed evidence of viral RNA presence. The authors suggested that their data supported close attention to ventilation systems and regular vehicle disinfection.

A North Carolina based transport study (Brazell et al., 2021) investigated the presence of viral RNA on high-touch surfaces on buses, light rail trains, and paratransit vehicles (with wheelchair access), at three time points during the pandemic. During phase two (July 2020), none of the 51 samples tested positive. In phase three (November 2020), three of 116 samples tested positive. Samples that tested positive were from the stop request line on a bus (pre-sanitisation), and grab rings and poles on trains (post-sanitisation). It was confirmed that an asymptomatic infected individual had been working in vehicle maintenance on the day samples were collected, providing an explanation for the post-sanitisation positive tests. The contamination of high touch surfaces by maintenance staff suggests that the recency of the exposure is a likely factor in the positive detection of viral RNA. The authors concluded that the lack of detectable SARS-CoV-2 on surfaces even before sanitisation suggests that current practices are adequate to minimise contact on public transport.

3.2 What do empirical studies of SARS-CoV-2 transmission on public transport show?

Three Chinese cohort studies have assessed factors related to transmission in transport outbreak settings. One study investigated an outbreak that originated from a single infected individual on a 100-minute round bus trip to attend a 150-minute event in Zhejiang province, China. The trip was taken by 128 individuals on two buses (Shen et al., 2020). This observational cohort study allowed for the analysis of transmission rates aboard the bus with no infected passengers (bus 1) in comparison to the bus carrying the infected individual (bus 2). On bus 2, 24 out of 68 passengers tested positive for SARS-CoV-2 after the event (attack rate 34.3%; 95% CI, 24.1-46.3%), compared to none on bus 1. The event attended was held largely outdoors, and of the other 172 attendees of the event (not travelling on the 2 buses), 7 (4.1%) subsequently tested positive for SARS-CoV-2; all these individuals reported being in close contact with the index patient during the event. Aboard both buses, central air conditioners were set to heating and indoor recirculation. Those closer to the patient (within 2 meters or 2 rows) had a moderately but not significantly increased risk of contracting COVID-19; the authors used this finding to argue for a central role for airborne transmission. Importantly, only those fulfilling clinical and epidemiologic criteria as a ‘suspected case’ were tested to confirm infection; therefore, levels of asymptomatic transmission were not accounted for except when identified through contact tracing from subsequent confirmed COVID-19 cases. It was not possible to exclude fomite transmission as surfaces were not sampled.

Another cohort study investigated an outbreak event that was linked to two journeys (a 2.5-hour coach trip and a 1-hour minibus trip) made by an infected individual in Hunan Province, China (Luo et al., 2020). The primary case was pre-symptomatic and travelled without a facemask. This study differed from the Shen study in that all 243 people epidemiologically linked to the coach and minibus trips were quarantined for 14 days and tested for SARS-CoV-2, thus allowing for the identification of asymptomatic infections. Of these individuals, 11 tested positive for SARS-CoV-2 during the quarantine period. From the coach trip with 49 passengers, 7 individuals subsequently tested positive; 6 were symptomatic and 1 was asymptomatic. In addition, one further case became infected when the bus made its return journey (with the index patient no longer aboard; total of 49 passengers); this patient sat in close proximity to the seat vacated by the index patient. In accord with Shen and colleagues (2020), secondary cases were distributed throughout the bus. One secondary case boarded and alighted the bus through different doors to that of the index patient and had no direct contact with the index patient, thus providing support for the airborne transmission route. From the minibus trip with 12 passengers, two people were subsequently diagnosed with COVID-19; one seated one row away (about 1.5m) from the index patient, and one seated three rows away (about 4.5m). The windows on the buses were closed and ventilation systems were running. Two further tertiary cases were identified; both were co-inhabitants of secondary cases. The authors estimated the attack rate during an exposure period of up to 2.5-hours on a bus to be 15% (95% CI, 6-24%). These two studies of outbreaks in public transport settings help to identify potential risk factors, but represented single occasions of infection which may not be representative of transmission within public transport as a whole.

The final empirical study assessing transmission within public transport looked at patterns of transmission associated with a large number of index cases. Risk of transmission on high-speed trains in China was investigated, using data from 2334 index patients and 72,093 co-travellers collected between 19 December 2019 and 6 March 2020 (Hu et al., 2020). This study provided important information about the relationships of seat location, spatial distance and co-travel time with transmission. A total of 2568 confirmed cases reported travelling by train within the preceding 14 days before illness onset; 2335 were included as index patients, and 234 were confirmed as secondary cases. A total of 72,093 close contacts of index patients were identified (defined as a person seated within a 3-rows). The overall attack rate of COVID-19 in train passengers with close contact with index patients was 0.32% (95% CI, 0.29-0.37%). However, this rate varied with distance; for passengers in the same row as an index patient the attack rate was 1.5% (95% CI, 1.3-1.8%), approximately 10 times higher than for those one or two rows from the index patient. Passengers sitting adjacent to an index patient had the highest attack rate (3.5%, 95% CI, 2.9-4.3%). The duration of co-travel time also affected attack rate. For all seats, the correlation between COVID-19 attack rate and the duration of co-travelling with an index patient followed a quadratic relationship, with the average attack rate increasing by 0.15% per hour of co-travel, but with a greater slope when the co-travel time extended beyond four hours. For seats adjacent to an index patient, the relationship was linear, with an increase in attack rate of 1.26% per additional hour of co-travel. Finally, the attack rate among passengers who immediately used the seat previously occupied by index patients did not differ significantly from the attack rate of passengers who immediately used seats within 3 rows and 5 columns of the seat previously occupied by index patients. The risk of infection was much higher within the same row as the index patient compared to other rows.

The authors suggested that this could be because family members or friends may be travelling together and have a greater amount of close contact, or because when people move around the train they had to pass others in the same row which could have increased close face-to-face contact. The authors also pointed out that although care was taken to determine that individuals that had confirmed cases of COVID-19 had travelled on the relevant public transport within a plausible window for infection, passengers infected either before or after their journey by alternative sources would have resulted in an overestimate of attack rates. This is particularly relevant where household groups travel together, and sit next to each other on public transport, as this may artificially inflate the risk of sitting in seats adjacent to index patients. Therefore, the attack rates presented should be considered as upper estimates.

3.3 *What evidence is there for the effectiveness of control measures in Public Transport?*

3.3.1 *Ventilation*

Air flow inside passenger cars has been modelled in relation to transmission of SARS-CoV-2, relevant for transport in taxis (Mathai, Das, Bailey, & Breuer, 2020). The authors argued that the installation of barrier shields was important to reduce direct exposure to droplets, but that this does not protect against aerosol transmission. This study ran simulations of ventilation, and its effect on the transport of a contaminant, from a passenger to the driver, and vice versa (assuming just two people were in the car, a left-hand drive vehicle with a passenger in rear right seat to maximise distance to about 1.5m). The reference configuration used was; all windows closed, non-recirculating air-conditioner flow turned on. Transmission of pathogen was simulated by computing the concentration field of a passive tracer released from each occupant. The reference configuration resulted in 11% of the tracer released by the driver reaching the passenger, and 8% of the tracer released by the passenger reaching the driver. When all the windows were open, these rates dropped to 0.2% and 2%, respectively. If just two windows were opened, the windows non-adjacent to the driver and passenger were most effective in reducing the transport of airborne pathogens from the driver to the passenger. This was *not* true for transport of airborne pathogens from the passenger to the driver, where opening the adjacent window to the passenger resulted in the flushing out of the tracer and the reduction of the amount reaching the driver.

Edwards and colleagues (2021) also identified that, when studying aerosol dispersion and its control in a real world bus environment, natural ventilation from window opening and the use of vehicle heating, ventilation, and air conditioning (HVAC) systems maintained airflow and reduced the counts of aerosol particles. In another recent study, Pavansai and colleagues (2021) simulated airborne droplet dispersion on a bus; using computational fluid dynamics, they modelled the effectiveness of social distancing and face masks, based on turbulent conditions influenced by air inlet velocity at different speeds (0, 20, 30, and 40 km/h). Cough velocity was modelled at different speeds (20, 30, and 40 m/s). The distance travelled by droplets was estimated within these parameters, and ranged between 0.5m and 7.5m; the distance travelled by droplets reduced as bus speed increased, while the distance travelled by droplets increased as cough velocity increased. Therefore, the greatest distances were calculated when the bus speed was 0 km/h.

However, the ventilation studies presented thus far did not incorporate estimates of viral load in droplets or the necessary level of exposure for infection in another passenger; therefore, they can only conclude that passengers are exposed to fewer droplets under certain conditions and not what reduction in risk of infection the change in exposure carries.

There were two studies which modelled the probability of infection along with exposure. Using both experimental and modelling analysis, Zhang and colleagues (2021) investigated potential transmission mechanisms on an urban bus. The bus was fitted with one aerosol generator, to mimic an infected passenger, and two sampling instruments to measure aerosol dispersion. They identified that the flow carrying aerosols was predominantly controlled by the bus ventilation systems (heating, ventilation, and air conditioning; HVAC), uniformly distributing aerosol throughout the bus, and diluting it with fresh ambient air. It was determined that during a 15-minute exposure, transmission rates varied by HVAC rate and location of the infected passenger. With an infected passenger at the front of the bus, there would be 3, 5, and 2 transmissions for HVAC rates of: maximum (100%), 50% of the maximum rate and 10% of the maximum rate, respectively. This finding appears counter-intuitive, as the lowest number of transmissions was associated with the lowest HVAC rate; however, this is because of the placement of the infected passenger, as high concentrations of aerosol were measured at the front of the bus where only the driver sits. Therefore, there was an increase in risk for the bus driver with reduced HVAC rates, but not for the rest of the passengers. If the infected individual stood in the middle of the bus, the number of transmissions were 0, 3, and 26 respectively. It was also concluded that opening doors and windows reduced the aerosol concentration by approximately one half, although recirculation of airflow caused by entrainment through windows was seen, suggesting that not all passengers would benefit from this intervention. Indeed, the driver could be at increased risk if an infected passenger was standing near the front of the bus while windows were open. Therefore, it was felt that ventilation did not uniformly reduce risk of transmission, and the implementation of ventilation systems and passenger arrangement within vehicles should be carefully considered in order to minimise transmission risks.

Similar findings were identified using a modelling approach to investigate the effectiveness of indoor air quality strategies; it was reported that the probability of infection could be reduced to below 0.1% for all ground public transport (including subways, buses, coaches, school buses and taxis) if available technologies (including double supply air, HEPA filters, displacement ventilation, personal ventilation (taxis only), use of partitions, and the use of face masks) were implemented (Shen et al., 2021). Modelling suggested that an acceptable level of infection risk could be achieved on public transport without the need for reduced occupancy and social distancing.

3.3.2 Face Masks

Only one study measured real time changes in infection rates associated with a particular control measure. The study analysed infection rate data related to the introduction of compulsory face mask guidance for public transport and shops in Germany (Mitze, Kosfeld, Rode, & Wälde, 2020). Face masks were made compulsory at different times in different regions, ranging from 6 April to 25 April 2020, with a lag-range of 2-18 days. Using synthetic control methods, COVID-19 rates in various regions were compared to their synthetic counterparts. Synthetic counterparts were constructed as a weighted average of control regions that were similar in terms of COVID-19 cases, demographic structure and local health care systems, but have not yet implemented compulsory face masks. The first region to implement compulsory face masks was Jena; analysis suggests that the early introduction of face masks resulted in a 25% reduction in the number of COVID-19 cases after 20 days (the reduction is greater than 50% in those 60 years old and over). Summarising data from all regions, it was reported that the daily growth rate of COVID-19 cases was reduced by 20% through the use of face masks. However, analysis showed that face masks on public transport and in shops may have been particularly effective in reducing COVID-19 rates in larger cities (reduction of growth rate of infections by 40%). This was because of the higher population density and higher levels of social interaction.

A similar study assessed the effectiveness of face coverings for reducing transmission on public transport and in retail outlets in the UK, but through prospective modelling rather than observation of reported infection rates (Heald, Stedman, Tian, Wu, & Fryer, 2020). A stepped model estimated that 28 minutes/day were spent on public transport and that it carried an estimated relative risk of 5 out of 10 compared to other activities; providing an 'Infection Risk Score (IRS)'. This risk score decreased with the modelling of variable rates of estimated risk reduction by face coverings (20%, 1.9; 40%, 1.4; 60%, 0.9; 80%, 0.5). The reduction in transmission from wearing face masks on public transport and in the retail sector was then determined to provide between a 5% and 31% reduction in infections over a 3-month period, depending on the effectiveness of face coverings and the ongoing R-value. There was no analysis of the actual changes in infection rates after the introduction of the guidance for face masks to be worn on public transport and in retail outlets. The authors concluded that the impact of face masks on public transport and in retail was limited and suggested that workplace control measures may be more worthwhile.

These estimates were based on a number of assumptions. The estimated risk of infection was based on a 2014 Time Use Survey. The authors note that time use before the COVID pandemic may be different from current time use. This is true particularly in relation to the use of public transport (Abdullah, Dias, Muley, & Shahin, 2020). Furthermore, a published set of ranked risks (Texas Medical Association, 2020) were used to calculate the IRS. This list did not specifically rank public transport. The authors stated that the risk stratification was sense-checked using ONS data by assessing infection risk associated with working from home compared to working in other environments, although this process was not made clear.

Edwards and colleagues (2021) studied cough aerosol dispersion and control in a real world bus environment, using an exhalation simulator. The simulation of face mask wearing reduced the overall particle count released into the bus by 50% on average, and this reduction was also a function of mask quality. Specifically, the mask used had two outer layers of cotton with an inner woven layer (Delca Corp. 2020) and was anticipated to have a filtration efficiency of around 50 percent when compared to testing results of similar tight-weave cotton fabric (Zangmeister, Radney, Vicenzi, & Weaver, 2020). The authors also commented that these real-world observations of aerosol were fundamentally different from existing fluid dynamics simulations. Authors concluded that one intervention approach will not universally apply, given differences in many other factors including bus design, occupancy, weather conditions, school bus pickup and drop off procedures and length of bus routes.

The experimental and numerical analysis of expiratory aerosols on buses, carried out by Zhang and colleagues (2021), also investigated the effects of face masks on disease transmission. Well fitted surgical masks for passengers were determined to significantly reduce the transmission of virus. Modelling the wearing of no masks, surgical masks, or handmade masks estimated that during a 15-minute bus ride with 35 seated passengers, the number of infected passengers was 26, 0 and 10, respectively. Therefore, surgical masks worn by everyone were concluded to offer the best protection.

3.3.3 Behavioural Interventions: Knowledge and Compliance

A study in Addis Ababa, Ethiopia, measured factors associated with knowledge about transmission of SARS-CoV-2 as well as self-reported knowledge and practice of preventative actions against COVID-19.

A cross-sectional survey (n=6007) was conducted in April 2020, with 'high-risk groups' including members of the public at bus stations and public transport drivers (Defar et al., 2021). Public transport drivers were 18% less likely to be knowledgeable about the prevention of COVID-19 than other occupations, but conversely were found to be nearly twice as likely to implement precautionary COVID-19 actions. Another study measured self-reported compliance with face mask use amongst taxi drivers in Ethiopia (Natnael et al., 2021); a cross-sectional survey was carried out in July 2020, which revealed that 55% of taxi drivers reported wearing a face mask. However, it was not made clear if this was all or some of the time, or in which contexts the face masks were worn. Factors which were significantly associated with face mask wearing included being married, reporting fear of COVID-19, believing face masks were effective, and feeling the presence of government pressure to wear a face mask. Belief in the effectiveness of face masks was the largest predictor of face masks wearing (OR 7.82; 95% CI, 4.63-13.21). More than half of taxi drivers felt discomfort while wearing a face masks, but this did not predict face mask wearing.

We identified two observational studies which recorded compliance with recommendations for public transport; both conducted in Ghana (Bonful et al., 2020; Dzisi & Dei, 2020). Bonful and colleagues conducted a 1-hour observational audit during peak periods in 45 public transport stations (March 2020). The public transport system in the Greater Accra Region is managed privately by independent operator unions; intra-city commuters are transported using minibuses and taxis, while large capacity buses are used for inter-city transport. Crowding at stations is noted as being a particular issue for this transport network. Hand washing facilities were not available at all stations; 16% had no hand washing facility at all, 53% of stations had only one facility for hand washing, and 10% of the stations with some facility for hand washing did not provide soap. Alcohol-based hand sanitizer was only available in 7% of stations. Furthermore, hand washing facilities were used 'frequently' in only 5% of the stations where facilities were available. Only one station had infrastructural arrangements to facilitate social distancing, and only two stations provided communications to promote social distancing. Passengers were observed to be exercising physical distancing with other passengers in only one station. The wearing of face masks (non-mandated) by none or only a few people was observed in all but one station. Therefore, the availability of facilities, promotion of health messages, and supportive infrastructure were significant issues to address in Ghana.

The second study from Ghana, carried out in May 2020 (Dzisi & Dei, 2020), used roadside observer surveys to assess compliance with COVID-19 guidelines at a major bus stop. Trained observers collected data on in-vehicle physical distancing and use of face masks. Complete compliance with use of face masks (compliance considered a maximum of 2 people without a mask) was low; an average of 12.6% buses were compliant, with the highest rates on Monday (18.9%). On average 4 people per vehicle were not wearing a mask. However, compliance with physical distancing was high with an average of 98% of buses showing adequate spacing of passengers (compliance considered max of 2 per row on smaller buses, 3 per row on larger buses). This could have been due to lower than usual passenger numbers, although not discussed. The authors concluded that the use of face masks in vehicles required stricter enforcement.

3.4 *What does risk modelling for SARS-CoV-2 transmission rates on ground public transport show?*

Eight studies used modelling to estimate the risks of viral transmission, under a range of circumstances. The UK Rail Safety and Standards Board (RSSB, 2020) devised a model of risk of infection during rail journeys. The model included risk per person-person contact (including defining a contact, contact distance, contact time, and risk per contact), number of person contacts (throughout journey - including platform, boarding, sitting on train, moving on train, and queueing at shop/toilet), and mitigation factors (face coverings and ventilation). The model was based on a community COVID-19 infection rate of 0.5%, and trains running at 50% capacity. They estimated the risk of COVID-19 infection at 1 per ~11,000 journeys *without* face coverings, and 1 per ~20,000 journeys *with* face coverings. This risk reduction was based on the direct application of the 0.56 value for relative infection risk for mask wearers compared to non-mask wearers in non-healthcare settings (Chu et al., 2020). This model did not account for transmission of infection through airborne or fomite routes, or for proximity to an infected individual.

Another study employed the Wells-Riley equation (Riley, Murphy, & Riley, 1978) to estimate the association between infection probability and ventilation rate in confined spaces, including buses (Dai & Zhao, 2020). Separate models were developed for the different spaces. In all models, it was assumed that one index case is present. As the quantum generation rate (q; rate at which an infector emits viral material) was not known for SARS-CoV-2, it was estimated using the R_0 for SARS-CoV-2 and the fitted association between q and R_0 from other airborne transmitted infectious diseases (TB, MERS, SARS, Influenza and Measles). The wearing of a mask was modelled by doubling the ventilation rate, as the wearing of an 'ordinary medical surgical mask' was argued to have a greater filtration effect and thus dilute the concentration of virus that other people inhale. The model identified that if people wear masks, then normal ventilation systems or natural ventilation was found to be sufficient to reduce the infection probability to 0.5% on buses, even at the top of the estimated range for quantum generation. However, if people did not wear face masks, then normal ventilation could only achieve 2.0% infection probability at the top of the estimated range for quantum generation. The authors argued that because risk of infection is relatively high for SARS-CoV-2, efforts should be made to prevent infectors (especially asymptomatic infectors) from entering public spaces, and that wearing ordinary medical surgical masks may be, based on the modelling approach, effective at reducing risk of viral transmission and should be worn in confined spaces, including buses.

A modelling study using data from Chennai, India demonstrated that the probability of infection varied as a function of both number of infected individuals travelling and travelling time (for bus, single train coach, and ladies compartment train coach; Krishnamurthy, Ambikapathy, Kumar, & De Britto, 2020). The quantum generation rate assumed in this study was based on that of influenza estimated from school-based data (Liao, Chang, & Liang, 2005). On a bus, with a travelling time of 2 hours and 3 infected passengers, the probability of infection was 47%. Operating at a reduced capacity of 50% reduced the probability of infection to 27%. The model also suggested that the probability of infection on public transport in the case of a single index case in the closed environment was lower in train travel running at 50% capacity compared to bus travel running at 50% capacity (7% vs 19%, respectively). It appears that the only differences in the modelling of the buses and train compartments were in the number of passengers contained in each and potentially in the volume of shared air space.

Shen and colleagues (2021) also used the Wells-Riley equation to estimate the baseline risk of infection by SARS-CoV-2 in different spaces, including transport settings, as well as the effectiveness of multi-scale indoor air quality (IAQ) control strategies within these spaces. In this model, quantum generation rate was based on recent work by Buonanno and colleagues (2020) which predicted this from viral load in sputum. This represented an improvement in quantum generation rate estimation, because it revealed important differences in quantum generation rate based on activity state. Baseline infection risk was calculated by assuming that at least one index case was present and taking into account: the area and height of the enclosed space, number of occupants, duration of journey, activity level of occupants, and ventilation rate. In relation to ground public transport, taxis were estimated to have the highest infection probability (3.2%), followed by coaches and school buses (2.9% and 2.2%, respectively), with the lowest infection probabilities in subway cabins and transit buses (both 0.6%). Comparing ground public transport to other spaces showed higher infection probabilities in nearly all other settings, including schools (7.1%), retail outlets (18.8%), and offices (15.0%).

An alternative passenger-centred approach to risk modelling on public transport was taken by Shoghri and colleagues (2020). They used citywide smart card bus travel data collected in Sydney, Australia, during the month of April, 2017, and classified passengers as (a) returners or explorers, (b) short distance travellers or long-distance travellers and (c) low number of encounters or high number of encounters. They then assessed the effect of each of the 8 different behaviour patterns on viral transmission. The most common movement behaviour type was highly connected (high number of encounters) returners who travel short distances (36.8% of the population); these were felt to be commuters, and had an average transmission rate per individual of 1.2. Highly connected explorers who travelled long distances had the greatest spreading power, with an average value of 1.7 transmissions per individual. Low connected explorers who travelled short distances had the least spreading power with an average value of 0.6 transmissions per individual. The authors pointed out that the group with the highest spreading power did not have the highest average number of encounters; therefore, it is important to consider these multiple factors in considering the probability of any one individual's risk of transmitting disease.

Modelling has also been applied to particle movement through a bus following a passenger sneeze (Mesgarpour et al., 2021). The authors employed an artificial intelligence-based modelling approach that predicted the evolution of droplet distribution. More specifically, they concluded that aerosols of 250 microns or less generated from a sneeze were largely responsible for dispersion as they remained in the air, and that these aerosols could travel a bus length within 10 seconds. However, the viral load of these aerosols was not modelled.

Agent based modelling techniques have also been used to assess the impact of cohorting travellers on the transmission of SARS-CoV-2 on a suburban Indian railway system (Talekar et al., 2020). Cohorting, or developing groups of passengers that always travel together, is a potential intervention to reduce disease transmission. It was concluded that cohorting travellers can assist with reducing viral transmission, while reducing the negative impact on traveller numbers or economic activities. Larger cohort sizes were generally deemed to be more effective at reducing disease transmission; however, implementation of cohorting interventions may not be practical for many public transport networks.

Certain models are incorporating transport along with other social behaviours. Using smart card data in Singapore, Mo and colleagues (2021) identified that whilst altering departure times and limiting maximum numbers of passengers of buses could slightly decelerate the viral spreading process, closing high-demand bus routes was more effective than the closure of low demand bus routes. They also reported that when reducing trip frequency, it was only after an 80% reduction in trips that the reduction in R_0 started to accelerate. Their view was that most effective strategy was to isolate infectious passengers early, to reduce onward transmission.

4. Discussion

This review provides a current overview of the evidence for transmission and the key factors affecting transmission risk for workers and passengers in the public transport setting (up to May 2021). This review of the emerging literature on the transmission of SARS-CoV-2 within public transport settings identified a number of knowledge gaps resulting in six key questions for future research.

Four are specific to public transport: (1) what is the relative importance of the routes of transmission for infection risk on public transport; (2) are there differences in the effectiveness of control strategies across different modes of transport (i.e. where a control measure is shown to be effective in one vehicle, can this be generalised to other vehicles); (3) what are the objective levels of compliance with behavioural control measures on public transport in the UK, and what factors predict compliance; (4) what is the risk of infection on public transport compared to other activities, such as (e.g. shopping, visiting hospitality, or car sharing)? The final two are wider questions about COVID-19: (5) are there particular conditions in which SARS-CoV-2 RNA on surface or in air samples pose an infection risk (e.g. a time window during which contamination can lead to infection); (6) what is the quantum generation rate for SARS-CoV-2?

A number of studies addressed air and surface contamination with SARS-CoV-2 RNA in public transport, and one study in a private car. The mixed results, noting both positive and negative viral presence in similar settings, report general differences in methodologies and contexts, and also different time periods between the potential for viral presence and deposition, and subsequent sampling (end of day sampling vs. exposure linked sampling). At present, there is little information available on quantification of transmission risk, limits of detection and method validation in the detection of the virus in the environment, which means the current data is difficult to interpret (Transmission in the Wider Environment Group, 2020). Further research is necessary to determine the reliability of these methods and findings, and where and when risk through these routes is highest, and how effective control measures (such as ventilation and cleaning regimes) are in mitigating this risk.

It will be particularly important to implement sensitive and effective testing methods as the number of people using public transport increases; it would be useful to measure the effects of reducing community infection rates and increasing passenger numbers on surface and air contamination. However, the presence of viral RNA does not imply presence necessarily of live virus that is able to infect passengers. One study demonstrated that the viral material collected through an air sampling filter was viable, and infected new cells (Lednicky et al., 2021). Therefore, while there is preliminary evidence that airborne viral material can cause onward infection, one key knowledge gap is the infectious dose of SARS-CoV-2 virions required to produce infection in people; without a better understanding of this, inferences from these findings are hard to make. While data from other settings (such as hospitals) could be used to inform our understanding of transmission via fomite and aerosol pathways (e.g. Lednicky et al., 2020), there is also evidence of a role for environmental factors such as temperature on the viability of viral material (Ben-Shmuel et al., 2020). Therefore, it is important that research is done within the relevant setting and climatic conditions in order to provide the most useful data (Goldman, 2020). Rates of vaccination will also influence the risk of infection in real-world settings and should be considered in future research. Further studies would assist here to reduce the variations in methodology and to focus on real-world data to develop our understanding of the risk of *transmission* via the fomite and airborne routes.

The evidence from the available empirical studies suggests that while transmission rates on public transport can be very high in certain, exceptional, cases with small sample sizes (Luo et al., 2020; Shen et al., 2020), large datasets report much lower transmission rates (Hu et al., 2020). Empirical studies, which collect infection data associated with public transport use, are valuable for identifying the factors that increase the likelihood of transmission. Spatial distance from an index case was identified as an important factor, highlighting the importance of social distancing on public transport. The variability between the attack rates reported by the empirical studies may suggest that the high attack rates reported in certain circumstances represent the extreme end of a distribution of attack rates in similar scenarios.

In addition, there is a need for more research into heterogeneity in quantum generation rates between individuals (e.g., super-spreaders), as it is possible that transmission heterogeneity is a factor that predicts attack rate. Large data sets will be required to determine the effects of variability in an individual's ability to spread the virus. The empirical data currently available was limited to three studies conducted in China. There are significant difficulties in collecting this type of data in the UK. While public transport passengers with the NHS Test and Trace App could be informed if they spent more than 15 minutes within 2m of an infected individual, co-passengers further than 2m away would not be contacted. It is important to consider that while outbreaks of COVID-19 in the UK have not been linked to public transport, this could be due to a lack of necessary data rather than demonstrating that such transmission is not occurring. Additionally, asymptomatic infection may have gone undetected resulting in an underestimate of attack rates. Most of these studies were performed at the beginning of the COVID-19 pandemic, and thus interventions to reduce the spread of the virus had not always been implemented yet.

Evidence for the effectiveness of control measures focussed predominantly on ventilation and the use of face masks. Experimental simulations of ventilation provided evidence for the reduction of circulating particles in most cases. A limited number of studies estimated the associated reductions in infection risk; measurements of the effects of HVAC systems in a bus demonstrated that the benefits of ventilation are not uniform across the vehicle space and can be dependent of the location of the infected passenger, therefore careful consideration is needed to minimise the risk of transmission. Research into the effectiveness of face masks has demonstrated promising findings for reducing aerosol dispersion of droplets on buses. The effectiveness of handmade masks was lower. This could indicate the need for quality standards for face masks to achieve their maximal benefits.

Work looking at the positive effects on regional infection rates associated with the introduction of compulsory face masks on public transport and in shops is indicative of the value of face masks for reducing transmission. However, it is impossible to determine what portion of this effect is associated with public transport use *per se*. Some of the effect will come from wearing face masks in shops, but the introduction of regulations will also increase concerns about the pandemic and could encourage more people to stay at home or specifically to avoid public transport and shops. Compliance with these measures was not taken into account in this study.

Compliance with guidelines aimed to reduce transmission are factors which influence the effectiveness of any behavioural mitigation strategies, and therefore are important to measure. Studies assessing understanding and compliance in the public transport sector were limited and were carried out at the start of the pandemic when knowledge levels were understandably low. Indeed, the infrastructure to facilitate the recommended behaviours would not yet have been in place in some instances. It would be valuable to see follow-up studies in the same sites to see if compliance has changed over time. Objective studies of compliance in the UK would also provide essential knowledge about status of structural facilitation for control measures, the effectiveness of the communication of public safety information and of the mitigation strategies themselves. There have been rapid knowledge gains by the public throughout the development of the pandemic, and research tracking both knowledge and behaviour longitudinally to observe developments in both would be valuable.

The modelling studies included here took a range of approaches to quantifying transmission. One estimated the risk of transmission given the population levels of COVID-19, while others modelled the risk of transmission given the presence of an index case. Both types of model were informative and valuable, the former useful in demonstrating that the chance of encountering an infectious individual while using public transport is quite small (though this will increase with increases in infection rate and public transport use), while the latter highlights what factors may be important reducing transmission (e.g., ventilation, capacity). The estimated transmission rates in the models with an index case present varied greatly; likely due to differences in the assumptions that are made to feed into the model. One piece of missing information was the quantum generation rate for index cases. Data on this rate will help to make these models more accurate.

Krishnamurthy and colleagues used influenza rates as an estimate to model the quantum generation rate, while Dai and Zhao used the known relationships between this value and R_0 for multiple infectious respiratory diseases and reported lower probabilities of infection. An alternative approach to the modelling of this rate was proposed by Buonanno and colleagues (2020), who predicted the SARS-CoV-2 quantum generation rate from the SARS-CoV-2 viral load in sputum. This was employed by Shen and colleagues (2021) to estimate the baseline risk of infection by SARS-CoV-2 in different spaces, including transport settings. The infection probabilities estimated using these methods were more similar to the estimates provided by Dai and Zhao, rather than the higher probabilities estimated by Krishnamurthy and colleagues. Nevertheless, having more data to quantify the quantum generation rate for SARS-CoV-2 will provide more accurate estimations in these models. However, the value of these models is not necessarily in the accurate quantifying of the transmission rates (at present), but in the relative rates of transmission as the impact of ventilation and capacity are modelled.

The estimated effects on transmission of mitigation strategies such as wearing face masks and improving ventilation were encouraging, as the models suggested these provided a significant reduction in transmission risk. However, the modelling of mitigation strategies was relatively crude in these studies. Mo and colleagues (2021) modelled the effects of operational interventions on transmission and reported that while changes such as spreading departure times and loading of buses had a slight effect, the control of viral spread only started to take effect when over 80% of travel was cancelled. Data modelling of droplet dispersion within different vehicles has started to be reported, and this will provide vital knowledge about transmission routes (Mesgarpour et al., 2021). As we gain more understanding about the routes of infection and the proportional risks of these routes, the effectiveness of different mitigations targeted at particular routes will be clearer. The accuracy of models will be improved with the collection of data relating to the myriad of factors involved in transmission of SARS-CoV-2 and the way in which people use public transport going forward.

The need to achieve and maintain social distance on public transport networks presents a range of challenges for the transport industry. Nevertheless, a diverse range of adaptations have been developed, including the use of new technologies to aid demand management (Hörcher, Singh, & Graham, 2021; Kamga & Eickemeyer, 2021).

Chin and Bouffanais (2020) have also modelled human movement networks, based on transport use in Singapore. Whilst these data may have less UK relevance, they suggested that their data-driven methodologies offered an effective way of devising targeted and localised preventive measures. Other authors have also used a variety of modelling techniques to assess emergency response (Wang, Liang, Sun, & Yang, 2020), staggered commuting (Wang, Guan, Wang, Peng, & Xue, 2021) and transport safety, policing and security issues (Liu & Huang, 2020). Although none of these assess features of public transport in relation to transmission risk, they have potential relevance for the development of mitigation strategies in transport network design.

5. Conclusion

In conclusion, similar to other settings where individuals come into proximity with others, public transport can represent a COVID-19 transmission risk. Standard mitigations such as the wearing of face masks, social distancing and ventilation will reduce this risk. However, there are certain features of public transport that are distinct, for instance the dynamics of ventilation at different speeds and the variability of proximity and duration to exposure to others depending on different modes, routes and duration of the journey. Evidence suggests that the crowding of vehicles and the length of journey also affect risk, and therefore this could be used to identify particularly high-risk services and potentially allow for targeted interventions. The review identified important knowledge gaps around risk, transmission route and mitigation measures that require further research. Two substantial research projects are currently being carried out in the UK, which will provide valuable insights to address some of these research gaps: TRACK (University of Leeds) and VIRAL (UCL). Results of these and other studies will improve knowledge and better inform decision-making of those balancing keeping public transport operationally effective and keeping those working on and using public transport safe.

References

Abdullah, M., Dias, C., Muley, D., & Shahin, M. (2020). Exploring the Impacts of COVID-19 on Travel Behavior and Mode Preferences. *Transportation Research Interdisciplinary Perspectives*, 100255-100255. doi:10.1016/j.trip.2020.100255

Abrahão, J. S., Sacchetto, L., Rezende, I. M., Rodrigues, R. A. L., Crispim, A. P. C., Moura, C., . . . Drumond, B. P. (2021). Detection of SARS-CoV-2 RNA on public surfaces in a densely populated urban area of Brazil: A potential tool for monitoring the circulation of infected patients. *The Science of the total environment, 766*, 142645-142645. doi:10.1016/j.scitotenv.2020.142645

Batista, B., Dickenson, D., Gurski, K., Kebe, M., & Rankin, N. (2020). Minimizing disease spread on a quarantined cruise ship: A model of COVID-19 with asymptomatic infections. *Mathematical Biosciences, 329 (no pagination)*. doi:10.1016/j.mbs.2020.108442

Ben-Shmuel, A., Brosh-Nissimov, T., Glinert, I., Bar-David, E., Sittner, A., Poni, R., . . . Weiss, S. (2020). Detection and infectivity potential of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) environmental contamination in isolation units and quarantine facilities. *Clinical Microbiology and Infection, 26*(12), 1658-1662. doi:10.1016/j.cmi.2020.09.004

Bonful, H. A., Addo-Lartey, A., Aheto, J. M. K., Ganle, J. K., Sarfo, B., & Aryeetey, R. (2020). Limiting spread of COVID-19 in Ghana: Compliance audit of selected transportation stations in the Greater Accra region of Ghana. *PLoS One, 15*(9), e0238971-e0238971. doi:10.1371/journal.pone.0238971

Brazell, L. R., Stetz, S., Hipp, A., Taylor, S., Stark, N., Jensen, K., . . . Gibas, C. (2021). Environmental Screening for Surface SARS-CoV-2 Contamination in Urban High-Touch Areas. *medRxiv* doi:10.1101/2021.05.04.21256107

Buonanno, G., Stabile, L., & Morawska, L. (2020). Estimation of airborne viral emission: Quanta emission rate of SARS-CoV-2 for infection risk assessment. *Environment international, 141*, 105794. doi:10.1016/j.envint.2020.105794

Burns, J., Movsisyan, A., Stratil, J. M., Coenen, M., Emmert-Fees, K. M. F., Geffert, K., . . . Rehfuess, E. (2020). Travel-related control measures to contain the COVID-19 pandemic: a rapid review. *Cochrane Database of Systematic Reviews*(9). doi:10.1002/14651858.Cd013717

Carteni, A., Di Francesco, L., & Martino, M. (2020). How mobility habits influenced the spread of the COVID-19 pandemic: Results from the Italian case study. *Science of the Total Environment, 741*. doi:10.1016/j.scitotenv.2020.140489

Chin, W. C. B., & Bouffanais, R. (2020). Spatial super-spreaders and super-susceptibles in human movement networks. *Scientific Reports, 10*(1), 18642. doi:10.1038/s41598-020-75697-z

Chu, D. K., Akl, E. A., Duda, S., Solo, K., Yaacoub, S., Schunemann, H. J., & Review, C.-S. U. (2020). Physical distancing, face masks, and eye protection to prevent person-to-person transmission of SARS-CoV-2 and COVID-19: a systematic review and meta-analysis. *Lancet, 395*(10242), 1973-1987. doi:10.1016/s0140-6736(20)31142-9

Dai, H., & Zhao, B. (2020). Association of infected probability of COVID-19 with ventilation rates in confined spaces: a Wells-Riley equation based investigation. *medRxiv*, 2020.2004.2021.20072397. doi:10.1101/2020.04.21.20072397

Defar, A., Molla, G., Abdella, S., Tessema, M., Ahmed, M., Tadele, A., . . . Tollera, G. (2021). Knowledge, practice and associated factors towards the prevention of COVID-19 among high-risk groups: A cross-sectional study in Addis Ababa, Ethiopia. *Plos One, 16*(3). doi:10.1371/journal.pone.0248420

Di Carlo, P., Chiacchiaretta, P., Sinjari, B., Aruffo, E., Stuppia, L., De Laurenzi, V., . . . Ucciferri, C. (2020). Air and surface measurements of SARS-CoV-2 inside a bus during normal operation. *PLoS One, 15*(11), e0235943-e0235943. doi:10.1371/journal.pone.0235943

Dzisi, E. K. J., & Dei, O. A. (2020). Adherence to social distancing and wearing of masks within public transportation during the COVID 19 pandemic. *Transp. Res. Interdiscip. Perspect.*(7). doi:10.1016/j.trip.2020.100191

Edwards, N. J., Widrick, R., Wilmes, J., Breisch, B., Gerschefske, M., Sullivan, J., . . . Espinoza-Calvio, A. (2021). Reducing COVID-19 Airborne Transmission Risks on Public Transportation Buses: An Empirical Study on Aerosol Dispersion and Control. *medRxiv*. doi:10.1101/2021.02.25.21252220

Francetic, I., & Munford, L. (2021). Corona and Coffee on your commute: A spatial analysis of COVID-19 mortality and commuting flows in England in 2020. *European Journal of Public Health*. doi:10.1093/eurpub/ckab072

Goldman, E. (2020). Exaggerated risk of transmission of COVID-19 by fomites. *The Lancet Infectious Diseases, 20*(8), 892-893. doi:10.1016/S1473-3099(20)30561-2

Gorbalenya, A. E., Baker, S. C., Baric, R. S., de Groot, R. J., Drosten, C., Gulyaeva, A. A., . . . Coronaviridae Study, G. (2020). The species Severe acute respiratory syndrome-related coronavirus: classifying 2019-nCoV and naming it SARS-CoV-2. *Nature Microbiology, 5*(4), 536-544. doi:10.1038/s41564-020-0695-z

Hadei, M., Mohebbi, S. R., Hopke, P. K., Shahsavani, A., Bazzazpour, S., Alipour, M., . . . Chobineh, H. (2021). Presence of SARS-CoV-2 in the air of public places and transportation. *Atmospheric pollution research*. doi:10.1016/j.apr.2020.12.016

Heald, A. H., Stedman, M., Tian, Z., Wu, P., & Fryer, A. A. (2020). Modelling the impact of the mandatory use of face coverings on public transport and in retail outlets in the UK on COVID-19-related infections, hospital admissions and mortality. *International journal of clinical practice, 75*(3), e13768. doi:10.1111/ijcp.13768

Heneghan, C., Spencer, E., Brassey, J., Pl¸ddemann, A., Onakpoya, I., Evans, D., . . . Jefferson, T. (2021). SARS-CoV-2 and the role of airborne transmission: a systematic review [version 1; peer review: awaiting peer review]. *F1000Research, 10*(232). doi:10.12688/f1000research.52091.1

Hörcher, D., Singh, R., & Graham, D. J. (2021). Social distancing in public transport: mobilising new technologies for demand management under the Covid-19 crisis. *Transportation*, 1-30. doi:10.1007/s11116-021-10192-6

Hu, M., Lin, H., Wang, J., Xu, C., Tatem, A. J., Meng, B., . . . Lai, S. (2020). Risk of Coronavirus Disease 2019 transmission in train passengers: an epidemiological and modelling study. *Clin. infect. dis, 72*(4), 604-610. doi:10.1093/cid/ciaa1057

Kamga, C., & Eickemeyer, P. (2021). Slowing the spread of COVID-19: Review of "Social distancing" interventions deployed by public transit in the United States and Canada. *Transp Policy (Oxf), 106*, 25-36. doi:10.1016/j.tranpol.2021.03.014

Krishnamurthy, K., Ambikapathy, B., Kumar, A., & De Britto, L. (2020). Prediction of the Transition From Subexponential to the Exponential Transmission of SARS-CoV-2 in Chennai, India: Epidemic Nowcasting. *JMIR public health and surveillance, 6*(3), 449-460. doi:10.2196/21152

Lan, F. Y., Wei, C. F., Hsu, Y. T., Christiani, D. C., & Kales, S. N. (2020). Work-related COVID-19 transmission in six Asian countries/areas: A follow-up study. *PLoS One, 15*(5), e0233588. doi:10.1371/journal.pone.0233588

Lednicky, J. A., Lauzardo, M., Alam, M. M., Elbadry, M. A., Stephenson, C. J., Gibson, J. C., & Morris, J. G. (2021). Isolation of SARS-CoV-2 from the air in a car driven by a COVID patient with mild illness. *International Journal of Infectious Diseases*. doi:10.1016/j.ijid.2021.04.063

Lednicky, J. A., Lauzardo, M., Fan, Z. H., Jutla, A., Tilly, T. B., Gangwar, M., . . . Wu, C.-Y. (2020). Viable SARS-CoV-2 in the air of a hospital room with COVID-19 patients. *International Journal of Infectious Diseases, 100*, 476-482. doi:10.1016/j.ijid.2020.09.025

Leith, D. J., & Farrell, S. (2020). Measurement-based evaluation of Google/Apple Exposure Notification API for proximity detection in a light-rail tram. *PloS one, 15*(9), e0239943-e0239943. doi:10.1371/journal.pone.0239943

Liao, C. M., Chang, C. F., & Liang, H. M. (2005). A probabilistic transmission dynamic model to assess indoor airborne infection risks. *Risk Analysis, 25*(5), 1097-1107. doi:10.1111/j.1539-6924.2005.00663.x

Liu, Q., & Huang, Z. Z. (2020). Research on intelligent prevention and control of COVID-19 in China's urban rail transit based on artificial intelligence and big data. *Journal of Intelligent & Fuzzy Systems, 39*(6), 9085-9090. doi:10.3233/jifs-189307

Luo, K., Lei, Z., Hai, Z., Xiao, S., Rui, J., Yang, H., . . . Chen, T. (2020). Transmission of SARS-CoV-2 in Public Transportation Vehicles: A Case Study in Hunan Province, China. *Open Forum Infectious Diseases, 7*(10), 1. doi:http://dx.doi.org/10.1093/ofid/ofaa430

Magnusson, K., Nygård, K., Vold, L., & Telle, K. (2020). Occupational risk of COVID-19 in the 1st vs 2nd wave of infection. *medRxiv*. doi:10.1101/2020.10.29.20220426

Mathai, V., Das, A., Bailey, J. A., & Breuer, K. (2020). Airflows inside passenger cars and implications for airborne disease transmission. *Sci Adv*. doi:10.1126/sciadv.abe0166

Mesgarpour, M., Abad, J. M. N., Alizadeh, R., Wongwises, S., Doranehgard, M. H., Ghaderi, S., & Karimi, N. (2021). Prediction of the spread of Corona-virus carrying droplets in a bus - A computational based artificial intelligence approach. *Journal of Hazardous Materials, 413*, 125358. doi:10.1016/j.jhazmat.2021.125358

Mitze, T., Kosfeld, R., Rode, J., & Wälde, K. (2020). Face Masks Considerably Reduce COVID-19 Cases in Germany: A Synthetic Control Method Approach. *IZA Institute of Labor Economics Discussion Paper Series*(12/01/2021).

Mo, B., Feng, K., Shen, Y., Tam, C., Li, D., Yin, Y., & Zhao, J. (2021). Modeling epidemic spreading through public transit using time-varying encounter network. *Transportation Research Part C, Emerging Technologies, 122*, 102893. doi:10.1016/j.trc.2020.102893

Morawska, L., & Cao, J. (2020). Airborne transmission of SARS-CoV-2: The world should face the reality. *Environment international, 139*, 105730. doi:10.1016/j.envint.2020.105730

Moreno, T., Pinto, R. M., Bosch, A., Moreno, N., Alastuey, A., Minguillon, M. C., . . . Querol, X. (2021). Tracing surface and airborne SARS-CoV-2 RNA inside public buses and subway trains. *Environment International, 147*, 106326. doi:10.1016/j.envint.2020.106326

National Collaborating Centre for Methods and Tools. (2021, March 5, 2021). Rapid Review Update 1: What is known about how long the virus can survive with potential for infection on surfaces found in community settings? Retrieved from https://www.nccmt.ca/knowledge-repositories/covid-19-rapid-evidence-service. Accessed March 30, 2021.

Natnael, T., Alemnew, Y., Berihun, G., Abebe, M., Andualem, A., Ademe, S., . . . Adane, M. (2021). Facemask wearing to prevent COVID-19 transmission and associated factors among taxi drivers in Dessie City and Kombolcha Town, Ethiopia. *Plos One, 16*(3), e0247954. doi:10.1371/journal.pone.0247954

Office for National Statistics. (2021). Coronavirus (COVID-19) related deaths by occupation, England and Wales: deaths registered between 9 March and 28 December 2020. Retrieved from https://www.ons.gov.uk/peoplepopulationandcommunity/healthandsocialcare/causesofdeath/bulletins/coronaviruscovid19relateddeathsbyoccupationenglandandwales/deathsregisteredbetween9marchand28december2020. Accessed 08/06/2021.

Onakpoya, I., Heneghan, C., Spencer, E., Brassey, J., Pl¸ddemann, A., Evans, D., . . . Jefferson, T. (2021). SARS-CoV-2 and the role of fomite transmission: a systematic review [version 1; peer review: awaiting peer review]. *F1000Research, 10*(233). doi:10.12688/f1000research.51590.1

Pardo, C. F., Zapata-Bedoya, S., Ramirez-Varela, A., Ramirez-Corrales, D., Espinosa-Oviedo, J.-J., Hidalgo, D., . . . Cucunubá, Z. M. (2021). COVID-19 and public transport: an overview and recommendations applicable to Latin America. *Infectio, 25*(3), 182-187. doi:10.22354/in.v25i3.944

Passos, R. G., Silveira, M. B., & Abrahao, J. S. (2021). Exploratory assessment of the occurrence of SARS-CoV-2 in aerosols in hospital facilities and public spaces of a metropolitan center in Brazil. *Environmental Research, 195*, 110808. doi:10.1016/j.envres.2021.110808

Pavansai, A., Deepak, P., Hari, S. R. H. R., & Kumar, M. B. S. (2021). Analyzing social distancing policy effectiveness using Computational Fluid Dynamics inside a bus to prevent COVID-19 airborne transmission. *IOP Conference Series. Materials Science and Engineering, 1128*(1).

Public Health England. (2020). Transmission of COVID-19 on Public Transport: A rapid review. Retrieved from https://phe.koha-ptfs.co.uk/cgi-bin/koha/opac-retrieve-file.pl?id=4f5a9a2ad2c495ff4e6312b2569869bc. Accessed 13/01/2021.

Riley, E. C., Murphy, G., & Riley, R. L. (1978). Airborne spread of measles in a suburban elementary school. *American journal of epidemiology, 107*(5), 421-432. doi:10.1093/oxfordjournals.aje.a112560

RSSB. (2020). Covid-19 Transmission Rates on Rail. Retrieved from https://www.rssb.co.uk/en/what-we-do/the-coronavirus-pandemic-how-we-can-help-you/infection-risks. Accessed 20/04/2021.

Shen, J., Kong, M., Dong, B., Birnkrant, M. J., & Zhang, J. (2021). A systematic approach to estimating the effectiveness of multi-scale IAQ strategies for reducing the risk of airborne infection of SARS-CoV-2. *Building and environment, 200*, 107926. doi:10.1016/j.buildenv.2021.107926

Shen, Y., Li, C., Dong, H., Wang, Z., Martinez, L., Sun, Z., . . . Xu, G. (2020). Community Outbreak Investigation of SARS-CoV-2 Transmission Among Bus Riders in Eastern China. *JAMA internal medicine, 180*(12), 1665-1671. doi:10.1001/jamainternmed.2020.5225

Shoghri, A. E., Liebig, J., Jurdak, R., Gardner, L., & Kanhere, S. S. (2020). Identifying Highly Influential Travellers for Spreading Disease on a Public Transport System. *21st IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks, WoWMoM*, 30-39. doi:10.1109/WoWMoM49955.2020.00020

Talekar, A., Shriram, S., Vaidhiyan, N., Aggarwal, G., Chen, J., Venkatramanan, S., . . . Tambe, M. (2020). Cohorting to isolate asymptomatic spreaders: An agent-based simulation study on the Mumbai Suburban Railway. *ArXiv*. doi:arXiv:2012.12839v2

Texas Medical Association. (2020). Know your risk during COVID-19. Retrieved from https://www.texmed.org/uploadedFiles/Current/2016_Public_Health/Infectious_Diseases/309193%20Risk%20Assessment%20Chart%20V2_FINAL.pdf. Accessed 12/01/2021.

Tirachini, A., & Cats, O. (2020). COVID-19 and Public Transportation: Current Assessment, Prospects, and Research Needs. *Journal of Public Transportation, 22*(1), 1-21. doi:10.5038/2375-091.22.1.1

Transmission in the Wider Environment Group. (2020). Monitoring the presence and infection risk of SARS-CoV-2 in the environment: approaches, limitations and interpretation. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/945838/S0942_Environmental_Monitoring_of_Viral_Presence_final.pdf. Accessed 08/06/2021.

UCL Institute of Health Equity. (2020). Initial Assessment of London Bus Driver Mortality from COVID-19. Retrieved from http://content.tfl.gov.uk/initial-assessment-of-london-bus-driver-mortality-from-covid-19.pdf. Accessed 05/01/2020.

Union Internationale des Transports Publics. (2020). Management of COVID-19: Guidelines for public transport operators. Retrieved from https://www.uitp.org/publications/management-of-covid-19-guidelines-for-public-transport-operators/. Accessed March 30, 2021.

van Doremalen, N., Bushmaker, T., Morris, D. H., Holbrook, M. G., Gamble, A., Williamson, B. N., . . . Munster, V. J. (2020). Aerosol and Surface Stability of SARS-CoV-2 as Compared with SARS-CoV-1. *New England Journal of Medicine, 382*(16), 1564-1567. doi:10.1056/NEJMc2004973

Wang, A. G., Guan, H. Z., Wang, P. F., Peng, L. Q., & Xue, Y. Q. (2021). Cross-Regional Customized Bus Route Planning Considering Staggered Commuting During the COVID-19. *Ieee Access, 9*, 20208-20222. doi:10.1109/access.2021.3053351

Wang, Y., Liang, Y., Sun, H., & Yang, Y. (2020). Emergency Response for COVID-19 Prevention and Control in Urban Rail Transit Based on Case-Based Reasoning Method. *Discrete Dynamics in Nature and Society, 2020*, 6689089. doi:10.1155/2020/6689089

Zangmeister, C. D., Radney, J. G., Vicenzi, E. P., & Weaver, J. L. (2020). Filtration Efficiencies of Nanoscale Aerosol by Cloth Mask Materials Used to Slow the Spread of SARS-CoV-2. *ACS Nano, 14*(7), 9188-9200. doi:10.1021/acsnano.0c05025

Zhang, Y. H., Zhang, A. M., & Wang, J. E. (2020). Exploring the roles of high-speed train, air and coach services in the spread of COVID-19 in China. *Transport Policy, 94*, 34-42. doi:10.1016/j.tranpol.2020.05.012

Zhang, Z., Han, T., Yoo, K. H., Capecelatro, J., Boehman, A. L., & Maki, K. (2021). Disease transmission through expiratory aerosols on an urban bus. *Physics of Fluids, 33*(1). doi:10.1063/5.00374