Modal Emissions Analysis For Domestic Aviation Routes in Scotland

Final Report for Transport Scotland

25th March 2021

elementenergy

Element Energy Limited, Suite 1, Bishop Bateman Court, Thompson's Lane, Cambridge, CB5 8AQ UK

Tel: +44 (0)1223 852499

Executive Summary

Introduction

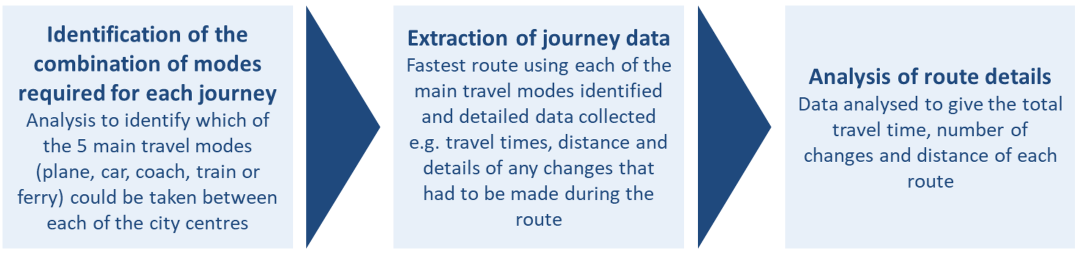
The Scottish Government has ambitious climate targets of achieving net-zero greenhouse gas emissions by 2045 (Climate Change (Emissions Reduction Targets) (Scotland) Act 2019), five years ahead of the rest of the UK. The decarbonisation of the transport sector in Scotland will play a key role in achieving the government's net-zero targets.

The objective of this study is to understand the emissions and convenience of different modes of transport. The study considered 16 journeys between 5 different origin cities within Scotland and 12 end cities across the UK. Routes using one of five main transport options (plane, car, coach, train or ferry) were analysed for each journey, and were compared on time, complication (number of legs) and CO_2 emissions (on per vehicle and per passenger bases).

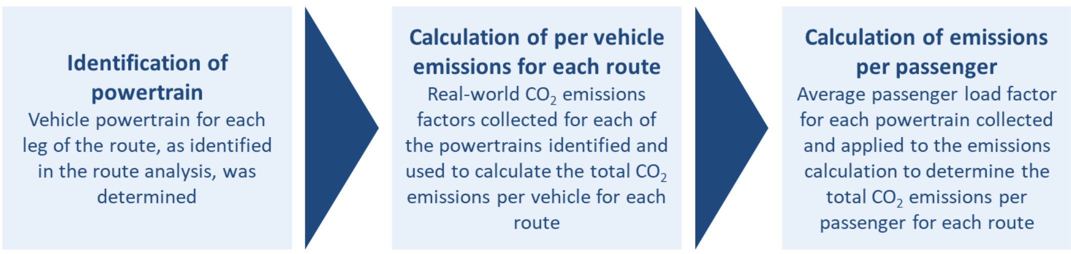
Method

The study involved a route analysis, followed by an emissions analysis.

The **route analysis** aimed to build a database of routes for each of the 16 journeys, to understand the most convenient options in terms of time and route complication. Three key steps were taken to carry out the route analysis:



The **emissions analysis** used the data collected during the route analysis and real-world emissions factors to calculate the CO_2 emissions per vehicle and CO_2 emissions per passenger for each of the analysed routes. Three key steps were taken to carry out the emissions analysis:



A **passenger load factor sensitivity** was additionally carried out, which repeated Step 3 of the emissions analysis with high and low passenger load factors for each of the main transport modes.

Results and Impacts

As shown by Figure 1, the study found that routes between city centres by train or coach are consistently the options with the lowest per passenger CO_2 emissions. When the train route between city centres is electrified, the per passenger CO_2 emissions of the journey are considerably lower than those of all other transport modes. Travelling mainly by plane is generally the option with the highest CO_2 emissions on a per passenger basis. This becomes more considerable for longer routes that use larger, more fuel intensive planes. Routes using land transport modes for shorter journeys across challenging terrain (e.g. Wick to Aberdeen or Edinburgh to Belfast) have comparatively high per passenger CO_2 emissions for that mode.

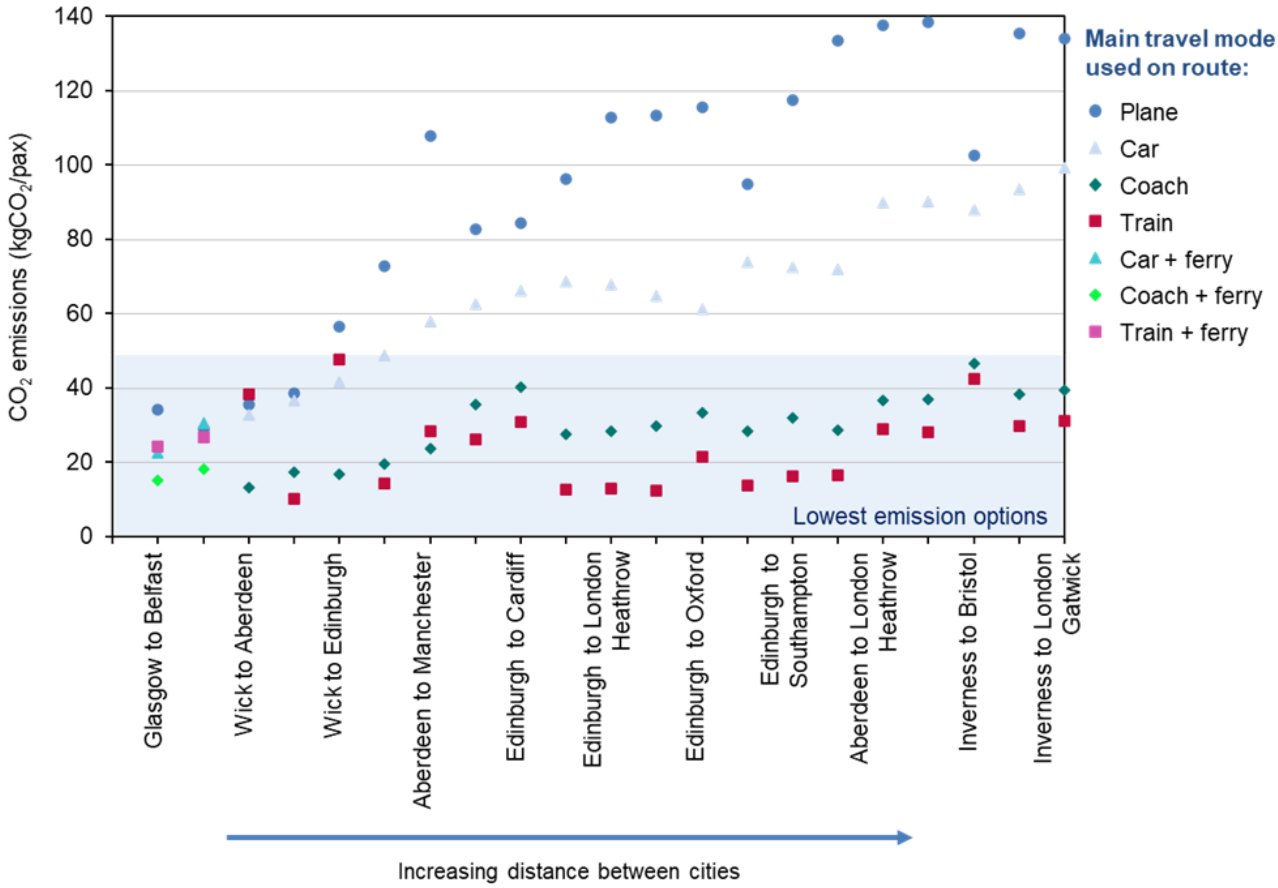


Figure 1: CO_2 emissions per passenger ($kgCO_2$/pax) across routes for each journey and main mode of transport. Note: the emissions shown are the total per passenger emissions from the entire route. Includes emissions from main transport mode and additional modes of transport used during the route.

These findings remain generally consistent across the low and high passenger load factors used during the passenger load factor sensitivity.

Exceptions were found for particular cases, such as routes that use particularly emissions intense alternative transport modes to planes (e.g. ferries).

Passenger load factors for the transport modes analysed are highly uncertain and likely to vary on a regular basis. Although the passenger load factor sensitivity leads to a large range in the overall per passenger CO_2 emissions of the routes analysed, the results of the lowest emissions transport options are generally robust across passenger load factors with trains or coaches remaining the lowest emission mode per passenger independent of passenger load factor.

Travelling by plane is the fastest transport option for all domestic journeys analysed. While train and coach are often the lowest emission mode there is a concern that these modes may not always be a practical alternative to planes given the long journey times required. To better understand this Figure 2 shows the lowest emission mode for each route, excluding modes that take greater than 2 hours more than plane. For many routes this excludes all other modes but planes.

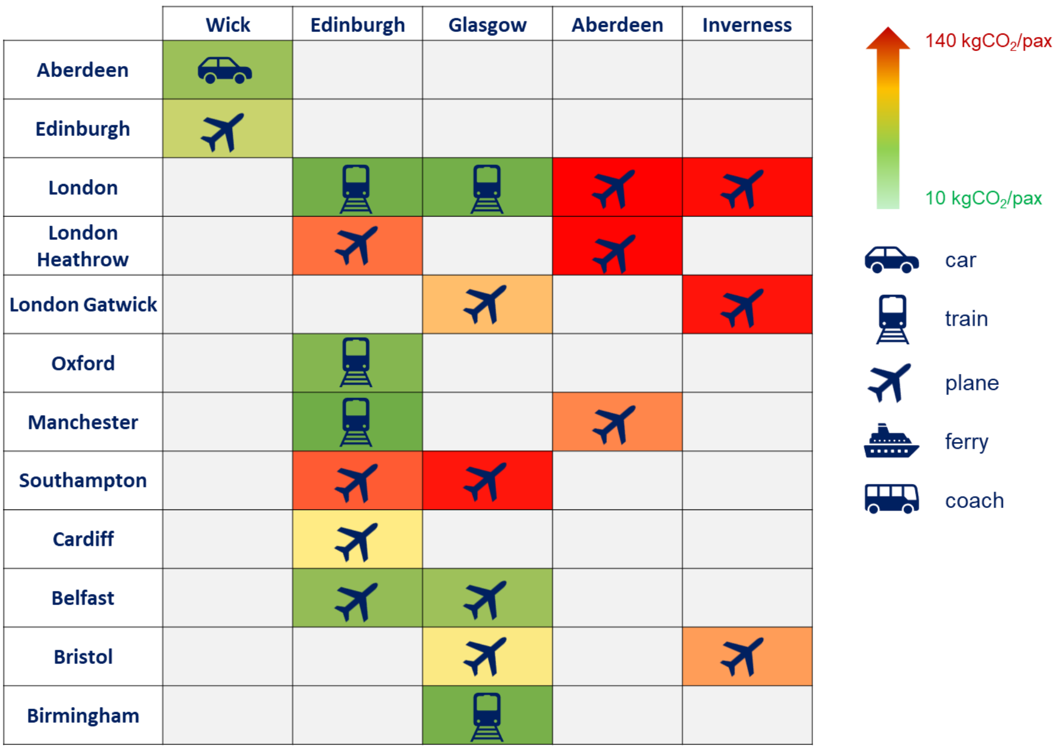


Figure 2: Transport options with the lowest per passenger CO_2 emissions between city centres, considering only transport options that take within 2 hours of the fastest option. Note: per passenger CO_2 emissions indicated by colour scheme.

Contents

Authors

Daisy Tyrer, Consultant

Reviewers

Richard Riley, Principal Consultant

Celine Cluzel, Director

For comments or queries please contact:

richard.riley@element-energy.co.uk

+44 (0)1223 855 245

Acronyms

API Application Programming Interface

CO_2 Carbon dioxide

EU European Union

GHG Greenhouse gases

IATA International Air Transport Association

ICAO International Civil Aviation Organisation

UIC International Union of Railways (Union Internationale des Chemins de Fer)

UK United Kingdom

1 Introduction

1.1 Context

The Scottish Government has ambitious climate targets of achieving net zero greenhouse gas emissions by 2045 (Climate Change (Emissions Reduction Targets) (Scotland) Act 2019), five years ahead of the rest of the UK. Currently, the transport sector has the highest greenhouse gas emissions in Scotland, responsible for over 1/3 (35.6%) of total Scottish emissions in 2018 (*Securing a green recovery on a path to net zero: climate change plan 2018 – 2032 – update*, Scottish Government (December 2020)). The decarbonisation of the transport sector in Scotland will play a key role in achieving the government's net zero targets.

Scotland's National Transport Strategy sets out the government's vision for a sustainable, inclusive, safe and accessible transport system (*National Transport Strategy (NTS2)*, Transport Scotland, (February 2020)). The strategy prioritises climate action, but also highlights the importance of reducing emissions in a way which tackles inequality and maximises economic and social opportunities.

1.2 Objectives and scope

The objective of the study is to understand the emissions and convenience of alternative modes to aviation for main Scottish domestic routes.

The study looked at 16 journeys between 5 different origin cities within Scotland and 12 end cities across the UK.

Table 1: Summary of journeys analysed in this study.

Origin city	End city
Wick	Aberdeen
	Edinburgh
Aberdeen	London
	Manchester
Edinburgh	Southampton
	Manchester
	London
	Cardiff
	Belfast
Glasgow	London
	Bristol
	Birmingham
	Southampton
	Belfast
Inverness	London
	Bristol

For each journey, routes using one of five main transport options (plane, car, coach, train, or ferry) were analysed. The analysis compared each of the journeys' routes on time, complication, and CO_2 emissions (on per vehicle and per passenger bases).

Cost was not included in the analysis as ticket prices over the past 12 months have been highly affected by the COVID-19 pandemic and the subsequent lockdown restrictions. It is unclear how ticket prices will continue to be impacted in the near future. As a result, it was difficult to collect representative price data to carry out an analysis.

1.3 Structure of the report

Following this section, the report is structured as follows:

Section 2: Method sets out the steps taken to complete the route analysis followed by the emissions analysis.

Section 3: Results and impacts explores the results of the route and emissions analyses, to understand the convenience and CO_2 emissions impact of different travel options.

Section 4: Conclusions presents the key conclusions from the results presented in the previous section.

Section 5 is the **Appendix**

2 Method

This section presents the methodology used for this analysis. The methodology followed three key steps:

1) **Route analysis:** time, distance and route data was collected for each journey and travel mode, and used to analyse the most convenient transport option for each journey.
2) **Emissions analysis:** data collected during the route analysis was used alongside real-world CO_2 emissions factors and average per vehicle passenger load factors to calculate CO_2 emissions per vehicle and per passenger for each route.
3) **Passenger load factor sensitivity**: emissions analysis was repeated for each route with a high and a low passenger load factor, to understand the variation in emissions at peak and off-peak loading and to ensure robustness in results.

2.1 Route analysis

The route analysis aimed to build a database of routes and travel modes for each of the 16 journeys between city centres in Scotland and the rest of the UK. This database was used to analyse the details of the different travel options for each journey, with the aim of understanding the most convenient routes for passengers in terms of time and route complication.

To carry out the route analysis, the following steps were taken:

1. Identification of the combination of modes required to travel between city centres

Analysis was carried out to identify which of 5 main travel modes could be taken between each of the city centres. The main travel modes considered were plane, car, coach, train and ferry. Most routes analysed additionally used other travel modes (e.g. bus used to travel from Glasgow city centre to Glasgow airport), but the majority of each route used one of the main travel modes.

Table 2 summarises which of the main travel modes could be taken between each of the city centres.

Table 2: Table showing the main travel modes that could be taken between each of the city centres.

Origin city	End city	Plane	Car	Coach	Train	Ferry
Wick	Aberdeen	✓	✓	✓	✓	✗
	Edinburgh	✓	✓	✓	✓	✗
Aberdeen	London	✓	✓	✓	✓	✗
	Manchester	✓	✓	✓	✓	✗
Edinburgh	Southampton	✓	✓	✓	✓	✗
	Manchester	✓	✓	✓	✓	✗
	London	✓	✓	✓	✓	✗
	Cardiff	✓	✓	✓	✓	✗
	Belfast	✓	With ferry	With ferry	With ferry	With other modes
Glasgow	London	✓	✓	✓	✓	✗
	Bristol	✓	✓	✓	✓	✗
	Birmingham	✓	✓	✓	✓	✗
	Southampton	✓	✓	✓	✓	✗
	Belfast	✓	With ferry	With ferry	With ferry	With other modes
Inverness	London	✓	✓	✓	✓	✗
	Bristol	✓	✓	✓	✓	✗

All journeys were analysed assuming that the routes began at the city centre of the start location, as defined by Google Maps.

Journeys to London were analysed for two scenarios:

1. Route ends at the city centre
2. Route ends at a London airport (London Heathrow for journeys from Edinburgh and Aberdeen, London Gatwick for journeys from Glasgow and Inverness)

Additionally, a journey that began in Edinburgh and ended at Oxford (via London Heathrow airport for the aviation route) was analysed in order to consider a scenario where passengers travel onwards to a town or city near a London airport.

For all other journeys, it was assumed that the routes ended at the centre of the city, as defined by Google Maps.

2. Extraction of journey data

The exact route taken, with details of changes and other modes of transport used alongside the main travel mode, was identified. The fastest route identified was selected for analysis. Each route was separated into sections or legs according to changes between different travel modes. Certain legs, such as travelling from the city centre to a train station, involved short distances (less than 1.5km) and it was assumed that these were walked. For longer legs that did not involve the main travel mode, it was assumed that the fastest public transport mode was taken. The sources used to identify the fastest route for each main travel mode are summarised in Appendix 5.1.

Once the fastest route had been identified, route data was collected. For coach and car routes, this data was collected for two cases - peak and off-peak times. The route was separated into legs according to any changes that had to be taken. Data collected for each leg included:

1. Mode of transport
2. Travelling time
3. Scheduled waiting times (e.g. at a train station between different trains)
4. Distance travelled

Data sources are summarised in Appendix 5.1.

For coach and car routes a rest time was added to the total travelling time to account for breaks taken by the driver. Coach routes were assigned a 45-minute break for every 4.5 hour driving time, as per EU regulations (Regulation (EC) No 561/2006). Car route times included a 15-minute break for every 2.5 hours of driving, as recommended by the UK government (UK government's *Think!* Campaign).

Scheduled waiting times between route legs were collected, however, the analysis also considered a standard waiting time (e.g. 10 minutes) during the analysis of total travelling time. This replicates the effect of more regular service scheduling on these routes. The option of the standard waiting time is not applied to the waiting time at airports before a flight, which is based on the Department for Transport's Aviation Modelling Framework (*Rules and Modelling: A Users' Guide to the DfT Aviation Modelling Framework* (April 2012)), or at the terminal before boarding a ferry (as advised by Stena Line, all routes assume that the passenger arrives at the ferry terminal 60 minutes before the ferry leaves).

3. Analysis of route details

Data from route legs was analysed and summed to give total time and distance of routes using each main travel mode for each journey. The number of route legs, and therefore complication of the route, was also analysed. For car and coach routes, only data taken at off-peak times were included in the final analysis, on the basis that these were the fastest routes and the difference in travel times between peak and off-peak was minimal for such long routes.

The total travel time, distance and complication for each route could then be compared and ranked, to give an understanding of the most and least convenient main transport modes for passengers travelling between particular city centres.

2.2 Emissions analysis

The emissions analysis used the data collected during the route analysis and real-world CO_2 emissions factors to calculate the CO_2 emissions per vehicle and CO_2 emissions per passenger for each of the identified routes.

The emissions analysis was carried out using the following steps:

1. Identification of powertrain

The vehicle type and powertrain for each leg of each route, as identified in the route analysis, was determined. The method varied between each of the main travel modes:

1. **Plane:** most common aircraft type flown on each route was collected
2. **Car:** characteristics of an average car in age, size and fuel consumption for the UK fleet were determined
3. **Coach:** average size, diesel coach was assumed for all routes
4. **Train:** percentage of electrified track used on each route was analysed; trains categorised as either regional or long-distance, electric or diesel
5. **Ferry:** operator specifications were used to understand size and capacity of the vessel

Data sources for vehicle types and powertrains are summarised in Appendix 5.2.

2. Calculation of per vehicle emissions for each route

For each of the vehicle types and powertrains identified in the previous step, real-world CO_2 emissions factors were collected.

Emission factors were made as route specific as possible. For example, when a specific aircraft type is used on a route, the fuel consumption for that aircraft and flight distance was used to determine the CO_2 emissions factor. Similarly, for road vehicles, the proportion of each route driven on different road types was collected. This was used to correct the overall emissions factor, therefore accounting for the average speed of the route (speed assignments of road types specified in Appendix 5.2.1). CO_2 emissions factors were also collected for local travel modes used in addition to the main travel mode, such as a local bus or the London Underground.

Emissions factor data sources are summarised in the Appendix 5.2.

The emissions factors were used to calculate the CO_2 emissions per vehicle (total CO_2 emissions as a result of the journey) for each route. This includes emissions due to all legs of the route (main transport mode and additional, local transport modes).

3. Calculation of emissions per passenger

An average passenger load factor (number of passengers per vehicle) for each vehicle type and powertrain was collected. Load factor data sources are summarised in Appendix 5.2. The average passenger load factors were used to calculate the overall CO_2 emissions per passenger for each journey and main transport mode. The CO_2 emissions intensity for each of the travel options between the city centres could then be compared. This includes emissions due to all legs of the route (main mode and additional, local modes).

2.3 Passenger load factor sensitivity

To highlight the high impact of passenger load factor on the results and the variability between trips taken at different times of day/year, a passenger load factor sensitivity was carried out. The per passenger CO_2 emissions for each route was calculated assuming both a high and a low passenger load factor, in addition to the average passenger load factor. The high and low passenger load factors were applied only to the main travel modes (plane, car, coach, train and ferry), not local transport modes.

The passenger load factor sensitivity was carried out to understand the extent to which certain modes see a significant variation in emissions intensity depending on if the passenger load factor is taken at peak or off-peak times or seasons. The sensitivity was also used to ensure robustness of the results around the lowest emission transport options for each journey, and that they remain consistent across a range of passenger load factors.

The high and low passenger load factors for each main transport mode were chosen to represent moderate, regularly observed peak and off-peak occupancies, rather than rare maximum and minimum values.

Common peak and off-peak occupancies of planes and cars were collected. The high, average and low occupancy rates (number of passengers as a percentage of maximum capacity) used in the analysis, and their sources are summarised in Table 3.

Limited data was found for high and low train passenger load factors. The occupancy of services at peak times in England could be calculated as ca. 80% using data from the Department for Transport (Table RAI0212, Department for Transport (2019)). This figure could be used alongside the average passenger load factor to give a rough estimate of occupancy at off-peak times. This was found to be approximately 20%.

As very little data could be found on peak and off-peak occupancy rates for coaches and ferries, it was decided that the passenger load factor sensitivity would apply a range similar to that of trains (± ca. 30% from the average occupancy rate) to these transport modes.

Table 3: Low, average and high occupancy rates of planes and cars

Vehicle	Occupancy rate (%)			Source (low and high passenger load factors)
	Low	Average	High	
Plane	60	83	90	Minimum off-peak season (January) and maximum peak season (August) occupancy rates as recorded by IATA (IATA Air Passenger Market Analysis reports (2019))
Car	20	30	80	Scottish Household Survey: Travel Diary 2019 (High passenger load factor taken as the 96th percentile of car occupancies. Low passenger load factor taken as lowest possible (66th percentile))

Vehicle	Occupancy rate (%)			Source (low and high passenger load factors)
	Low	Average	High	
Train (long-distance)	20	47	80	Calculated based on data from Peak rail capacity, standard class critical loads and crowding on a typical autumn weekday by city: 2019, Table RAI0212, Department for Transport (2019)
Coach	30	60	90	Based on percentage range as calculated for trains
Ferry	20	47	80	Based on percentage range as calculated for trains

3 Results and impacts

This section presents the results of the analysis and discusses the implications of these results. The results are grouped into three key themes:

1) **Emissions impact of journey routes:** the CO_2 emissions impacts on a per vehicle and per passenger basis of different routes between city centres are explored, and the lowest per passenger CO_2 emissions transport option is identified for each journey.
2) **Convenience for consumers:** the impact of passengers travelling by the fastest or least complicated route is presented, and the acceptable inconvenience to passengers of low emissions transport options is discussed.
3) **Passenger load factor sensitivity**: the impact of high and low passenger load factors on the per passenger CO_2 emissions of routes between city centres is presented.

The results of the analysis show that travelling by train or by coach is generally the transport option with the lowest per passenger CO_2 emissions across the domestic routes considered. This broadly remains the case across the high and low passenger load factors analysed. The lowest emissions transport modes are inconvenient to passengers except for certain routes that have well-developed low emissions options, such as the direct, electrified, long-distance trains between Edinburgh and London.

3.1 Emissions impact of journey routes

3.1.1 Emissions per vehicle

Figure 3 shows the total per vehicle CO_2 emissions of routes for each journey and main mode of transport, across all passengers carried in each vehicle and total distance travelled.

The variation in total journey CO_2 emissions across transport modes generally increases with distance between the cities, largely due to high total aviation emissions for long journeys. This is a result of the use of bigger planes with high fuel consumption on longer flight paths and the longer distances covered.

Ferries are only considered as a transport option on routes to Belfast. These routes use ferries alongside coach, rail, and car. The additional use of the ferry leads to noticeably higher total route CO_2 emissions than for routes of a similar distance using only land transport modes. This is a result of the high emissions factor of the large RoPax ferries used.

At medium to high route distances, plane routes have considerably higher total CO_2 emissions than all other modes of transport. However, for routes with short flightpaths that use small aircrafts and transport a low number of passengers, travelling by plane does not result in the highest total CO_2 emissions. For travelling to Belfast, a plane offers the lowest per vehicle CO_2 emissions. However, this is also due to the high emissions of the ferry used alongside all other transport modes, and the fact that the plane route follows a more direct path between the city centres than other transport modes.

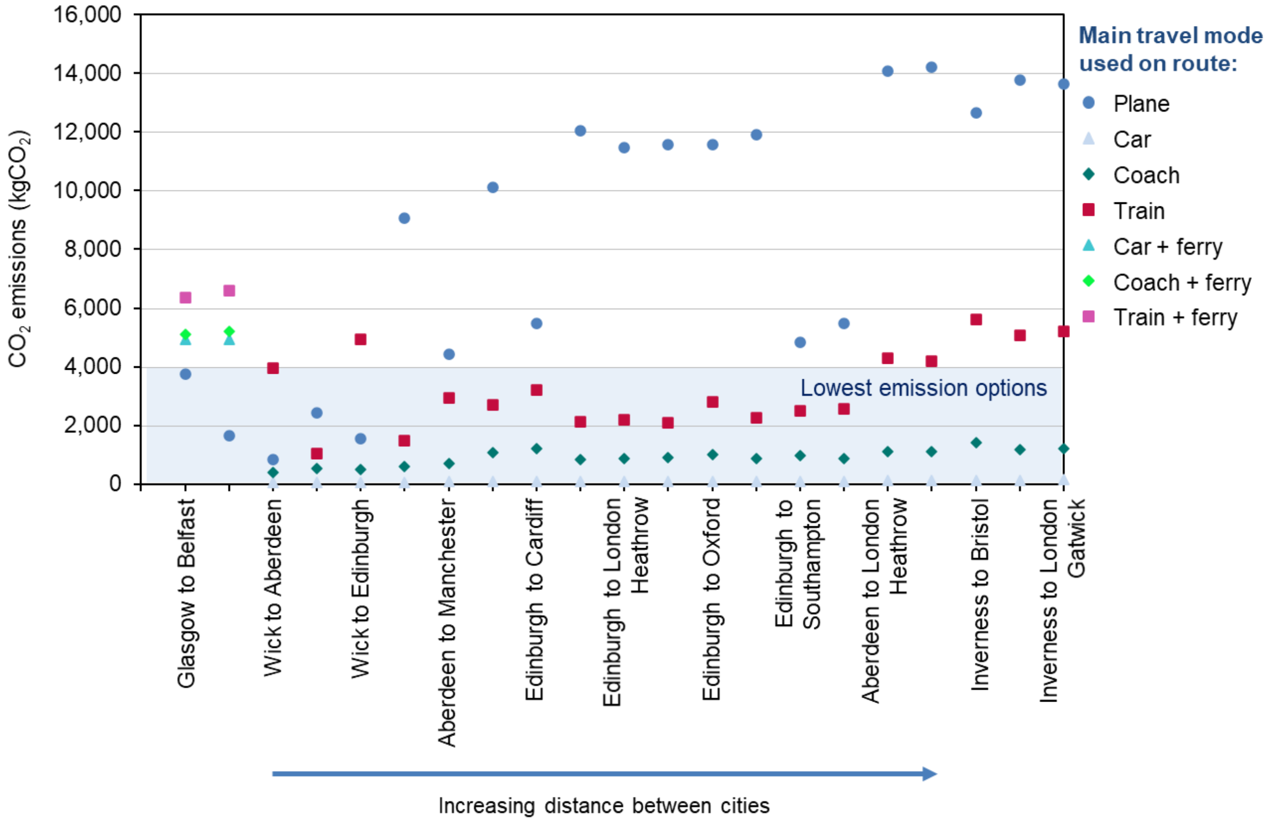


Figure 3: Total CO_2 emissions per vehicle (counting all passengers transported) of routes for each journey and main mode of transport. Note: the emissions shown are the total emissions from the entire route. Includes emissions from main transport mode and additional modes of transport used during the route.

Over the next 10 years we expect to see significant further progress in the decarbonisation of coach, train and car routes due to the electrification of powertrains. Over the same time period plane and ferry routes are not expected to have decarbonised at the same rate as other transport modes. This will reinforce the emission trends presented above, widening the gap in emissions per vehicle between lower emission vehicles (car, train and coach) and higher emission vehicles (plane and ferry).

3.1.2 Emissions per passenger

Figure 4 shows the spread of CO_2 emissions per passenger of routes for each journey and mode of transport. As for the total CO_2 emissions per vehicle, the variation in the CO_2 emissions per passenger for each route increases with journey distance. For very short journeys, there is a small variation in the CO_2 emissions per passenger across the different transport modes (ca. 15kg CO_2 per passenger for Edinburgh to Belfast), while at longer distances there is a larger spread (ca. 100kg CO_2 per passenger for Inverness to London). This is due to the longer distances exacerbating the differences in the emissions factors, and the fact that larger planes with higher fuel consumptions are used on longer flightpaths.

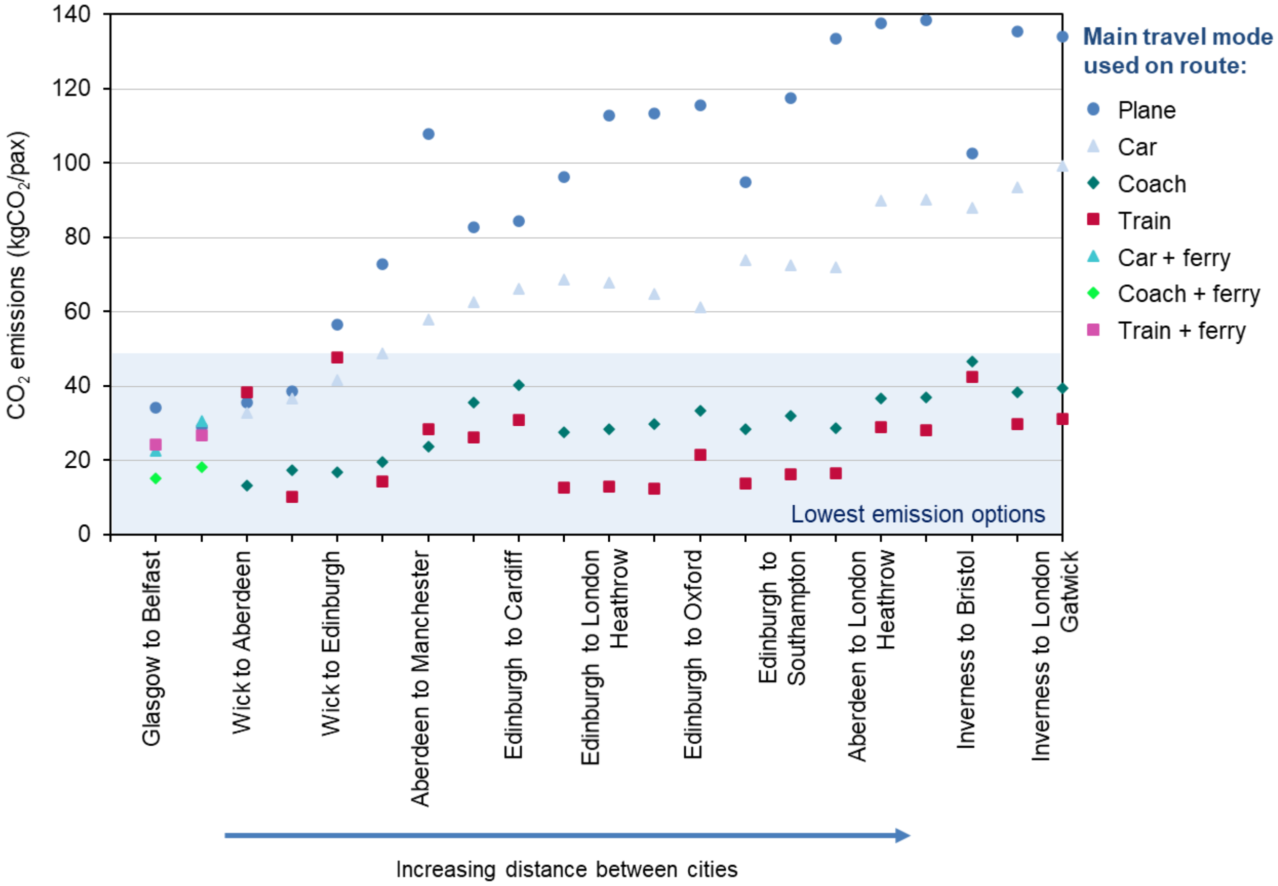


Figure 4: Total CO_2 emissions per passenger (kgCO_2/pax) of routes for each journey and main mode of transport. Note: the emissions shown are the total per passenger emissions from the entire route. Includes emissions from main transport mode and additional modes of transport used during the route.

Travelling by plane is generally the transport option with the highest CO_2 emissions intensity on a per passenger basis. The exceptions found in this analysis are the journey from Edinburgh to Belfast, for which travelling by car and ferry has higher emissions per passenger than by plane, and the journey from Wick to Aberdeen, for which travelling by rail has the highest emissions per passenger, just higher than travelling by plane.

The effect on the overall emissions factor as a result of the electrification of rail track is large. For example, the train journey from Edinburgh to London uses a long-distance, high-speed train on entirely electrified track, while the journey from Wick to Aberdeen uses regional, diesel-powered trains. The emissions per passenger are considerably higher for Wick to Aberdeen than for London to Edinburgh, despite the shorter journey distance. This, in addition to the use of a small aircraft with low fuel consumption, leads to the train route having the highest CO_2 emissions intensity for travelling from Wick to Aberdeen.

As for the CO_2 emissions per vehicle, the use of the ferry alongside other land transport modes in routes leads to higher emissions per passenger than for other journeys of similar distance.

Figure 5 presents the lowest emission travel option (CO_2 emissions per passenger) between each of the city centres. In all cases, the lowest emission option is to primarily travel either by coach or by train.

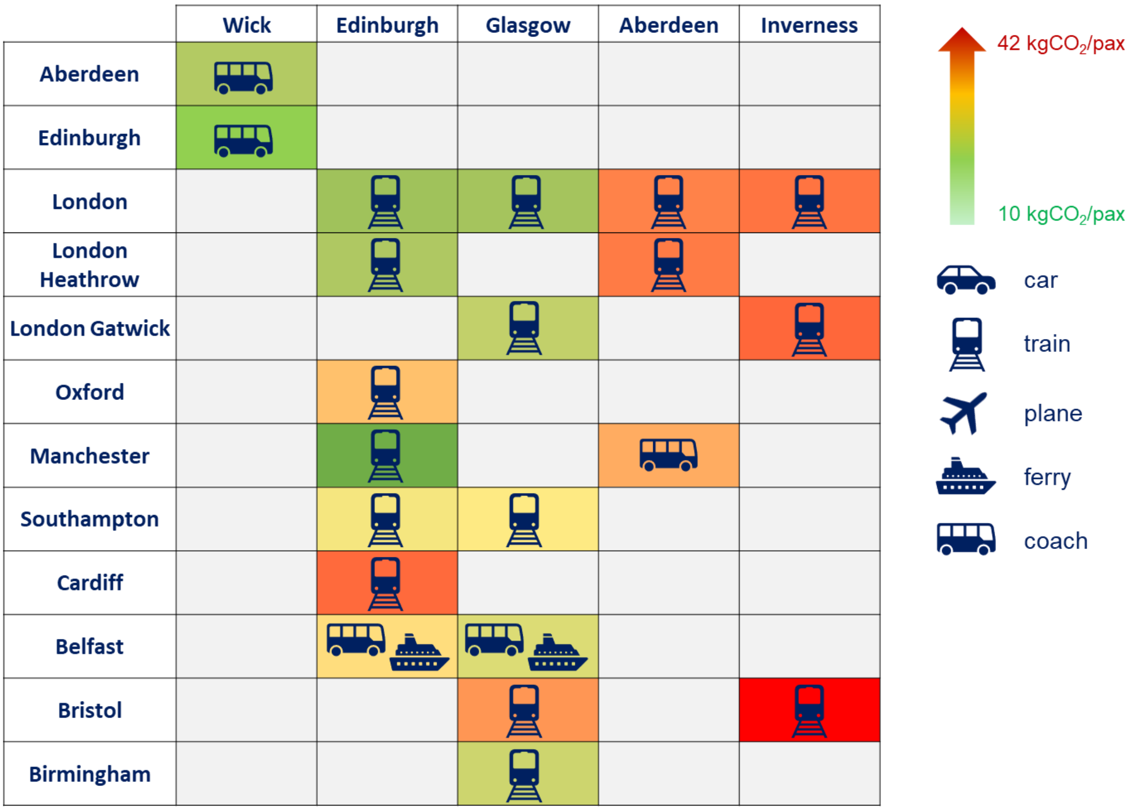


Figure 5: Lowest emissions mode of transport for travelling between each city centre. Note: per passenger CO_2 emissions indicated by colour scheme.

When the lowest emission journey is by coach as opposed to rail, this tends to be when the rail journey involves regional trains that are not operated on electrified track.

3.2 Convenience for consumers

3.2.1 Fastest transport modes between city centres

As shown in Figure 6 and Table 4, aviation is the fastest mode of transport for all journeys considered. The waiting time between journey legs for all other modes of transport can be set at 10 minutes to calculate the travel time in a case where rail and coach routes have regular scheduling. However, aviation is still considerably faster than all other modes of transport. Note that car, coach and rail journeys to Belfast include the use of the ferry.

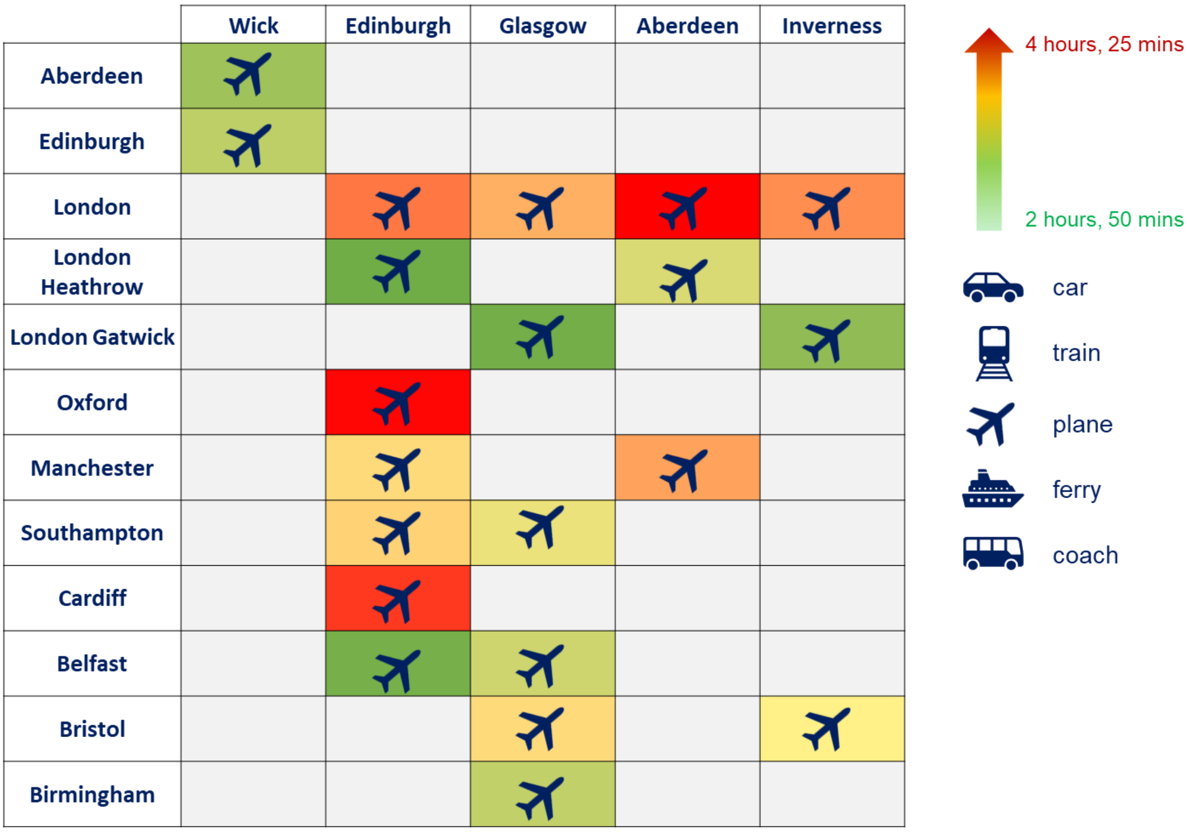


Figure 6: Fastest mode of transport for travelling between city centres. Note: journey time indicated by colour scheme.

Table 4: Summary of journey times (hrs. min.)

	Aviation	Car	Coach	Rail
Wick to Aberdeen	3 hrs, 4 mins	4 hrs, 46 mins	6 hrs, 41 mins	7 hrs, 25 mins
Wick to Edinburgh	3 hrs, 12 mins	5 hrs, 22 mins	7 hrs, 55 mins	8 hrs, 27 mins
Edinburgh to London	3 hrs, 56 mins	7 hrs, 39 mins	11 hrs, 18 mins	4 hrs, 54 mins

	Aviation	Car	Coach	Rail
Edinburgh to London Heathrow	2 hrs, 51 mins	7 hrs, 18 mins	10 hrs, 10 mins	5 hrs, 31 mins
Edinburgh to Oxford	4 hrs, 23 mins	6 hrs, 25 mins	11 hrs, 11 mins	5 hrs, 55 mins
Edinburgh to Manchester	3 hrs, 33 mins	4 hrs, 3 mins	7 hrs, 21 mins	3 hrs, 42 mins
Edinburgh to Southampton	3 hrs, 35 mins	7 hrs, 39 mins	13 hrs, 10 mins	6 hrs, 21 mins
Edinburgh to Cardiff	4 hrs, 11 mins	7 hrs, 10 mins	17 hrs, 26 mins	6 hrs, 32 mins
Edinburgh to Belfast	2 hrs, 53 mins	6 hrs, 33 mins	8 hrs, 22 mins	9 hrs, 32 mins
Glasgow to London	3 hrs, 43 mins	7 hrs, 7 mins	10 hrs, 59 mins	5 hrs, 11 mins
Glasgow to London Gatwick	2 hrs, 52 mins	7 hrs, 17 mins	10 hrs, 56 mins	5 hrs, 40 mins
Glasgow to Southampton	3 hrs, 24 mins	7 hrs, 10 mins	11 hrs, 39 mins	7 hrs, 28 mins
Glasgow to Belfast	3 hrs, 16 mins	5 hrs, 41 mins	6 hrs, 28 mins	8 hrs, 12 mins
Glasgow to Bristol	3 hrs, 33 mins	6 hrs, 7 mins	16 hrs, 45 mins	6 hrs, 30 mins
Glasgow to Birmingham	3 hrs, 13 mins	4 hrs, 53 mins	7 hrs, 41 mins	4 hrs, 48 mins
Aberdeen to London	4 hrs, 24 mins	9 hrs, 13 mins	15 hrs, 7 mins	8 hrs, 31 mins
Aberdeen to London Heathrow	3 hrs, 19 mins	8 hrs, 58 mins	13 hrs, 49 mins	9 hrs, 8 mins
Aberdeen to Manchester	3 hrs, 46 mins	5 hrs, 54 mins	10 hrs, 14 mins	6 hrs, 35 mins
Inverness to London	3 hrs, 51 mins	9 hrs, 59 mins	15 hrs, 53 mins	8 hrs, 36 mins
Inverness to London Gatwick	3 hrs, 0 mins	10 hrs, 8 mins	16 hrs, 17 mins	9 hrs, 7 mins
Inverness to Bristol	3 hrs, 29 mins	8 hrs, 59 mins	21 hrs, 44 mins	10 hrs, 3 mins

Figure 7 indicates the difference in CO_2 emissions per passenger between the fastest and lowest emissions transport option for each journey. The fastest option, on average, has per passenger CO_2 emissions over three times higher than the lowest emission option.

Figure 7 additionally compares the journey time for the fastest and lowest emission transport options for each journey. If passengers chose to travel using the lowest emission transport option rather than the fastest option, the journey there would be 3 hours, 30 minutes longer, on average.

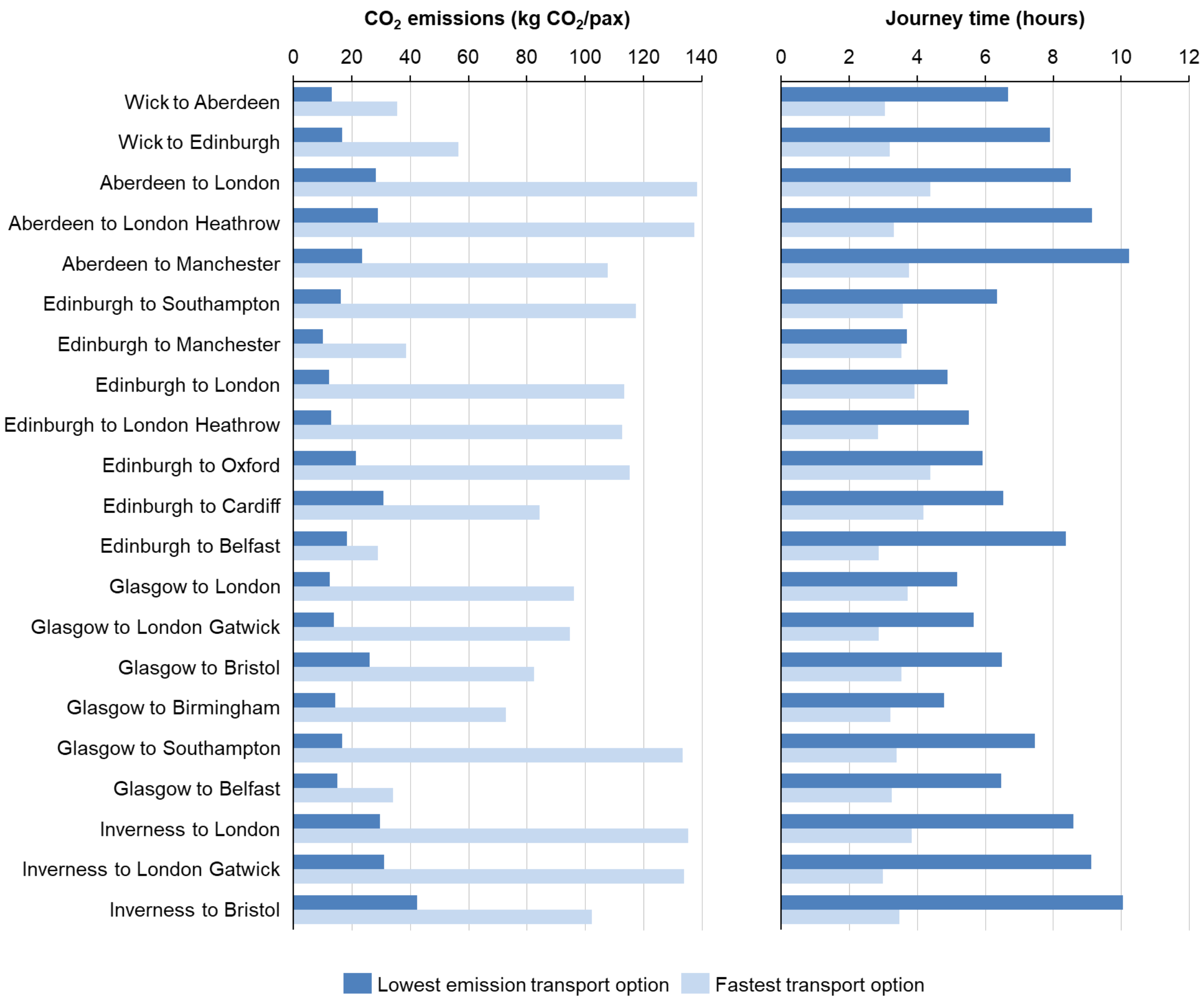


Figure 7: Comparison of the CO_2 emissions per passenger ($kgCO_2/pax$) and journey time (hours) of the fastest and lowest emission mode of transport between city centres

Figure 8 shows the lowest emission transport option for each journey, considering only transport modes that result in journey times within 2 hours of the journey time of the fastest transport option. This takes into account customer behaviour around travel duration, as it is unlikely that passengers will choose to take transport options that are significantly longer than a faster option, despite the lower emissions impact.

The fastest mode of transport on each of the considered journeys is to travel by plane. For many journeys, there is no other mode of transport that results in a total travel time within 2 hours of that of travelling by plane, and therefore Figure 8 shows the plane as the lowest emissions option.

Of the domestic routes that do have alternative, lower-emissions transport options that take within 2 hours of the fastest route time, the majority involve travelling by train. The single exception is the journey from Wick to Aberdeen. The relatively short distance between the two cities results in a car route time within two hours of that of the plane route. Although the car is not the lowest emissions transport option between the two cities when no time restrictions apply, it does result in lower per passenger CO_2 emissions than travelling by plane.

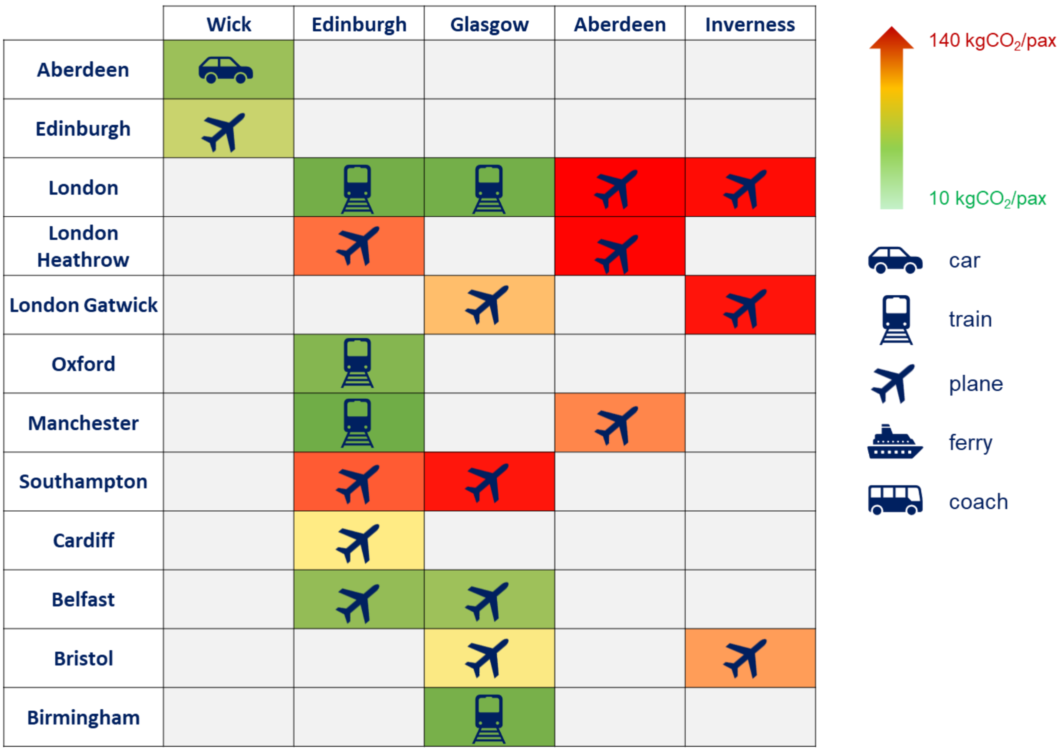


Figure 8: Transport options with the lowest per passenger CO_2 emissions between city centres, considering only transport options that take within 2 hours of the fastest option. Note: per passenger CO_2 emissions indicated by colour scheme.

When the lowest emissions transport option within the time restrictions is to travel by train, this is additionally the option with the lowest per passenger CO_2 emissions for travelling between the city centres without limits on travel time. They generally involve well-travelled, direct rail routes between the city centres, on electrified tracks.

3.2.2 Number of route sections

Journey complication can be understood by looking at the number of route legs, which is effectively the number of changes that have to be made. For all journeys, the least complex routes are by car as no changes are required (routes to Belfast use the ferry in addition to the car). However, this is unrealistic, as passengers are unlikely to be able to park their cars directly in the centre of their journey's start and end cities. In reality, it is likely that there will be additional steps from the city centre to reach their parked car and vice versa.

Figure 9 compares the number of route legs for the travel modes with the lowest per passenger CO_2 emissions and the shortest travel time. There is very little difference in terms of number of legs between these two travel options for each journey. On average, the fastest route has 0.4 more legs than the route with the lowest per passenger CO_2 emissions.

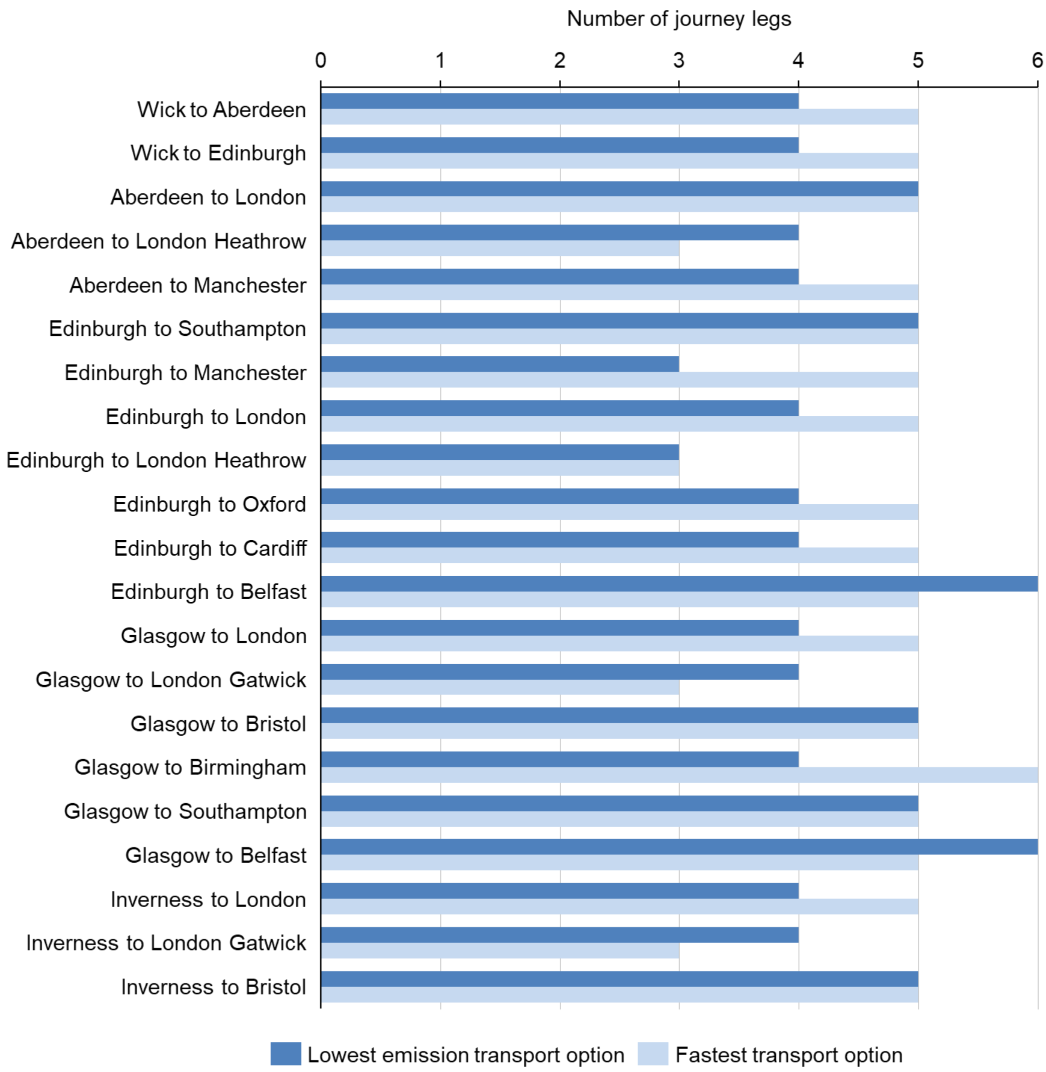


Figure 9: Comparison of the number of route legs of the fastest and lowest emissions routes for each journey.

Journey quality is determined by the journey complication (number of legs), and also the possibility of doing other meaningful activities while travelling. This is of particular consideration for passengers travelling for business. Travelling between city centres by car, although the least complicated option, is likely to have a lower overall journey quality for completing other activities as the traveller is often the driver. Train journeys with few changes generally require a smaller proportion of time travelling to or waiting at transport hubs than other convenient transport modes such as plane journeys, allowing more time to complete other task (especially tasks on electronic devises which are hampered on plane journeys due to a restriction on the use of electronic devises at take-off and landing). Many trains additionally have tables, power sockets, internet etc. which is uncommon for standard ticket holders on the other modes and can make the completion of other tasks more convenient. As a result, train journeys with few changes are likely to have the best journey quality for completing other tasks.

3.3 Passenger load factor sensitivity

A passenger load factor sensitivity was carried out to understand the extent to which certain transport modes see a significant variation in CO_2 emissions intensity depending on if the passenger load factor is taken at peak or off-peak times or seasons and to check that the results presented in the last section are robust. The CO_2 emissions per passenger for each journey and transport mode were calculated at both a high and low passenger load factor, in addition to the emissions at an average passenger load factor.

The range of CO_2 emissions per passenger across low, average and high passenger load factors is shown for two example journeys (Wick to Aberdeen, and Edinburgh to London) in Figure 10. This represents the range in emissions per passenger (shown as error bars in the figure) expected to be observed across peak and off-peak times or seasons.

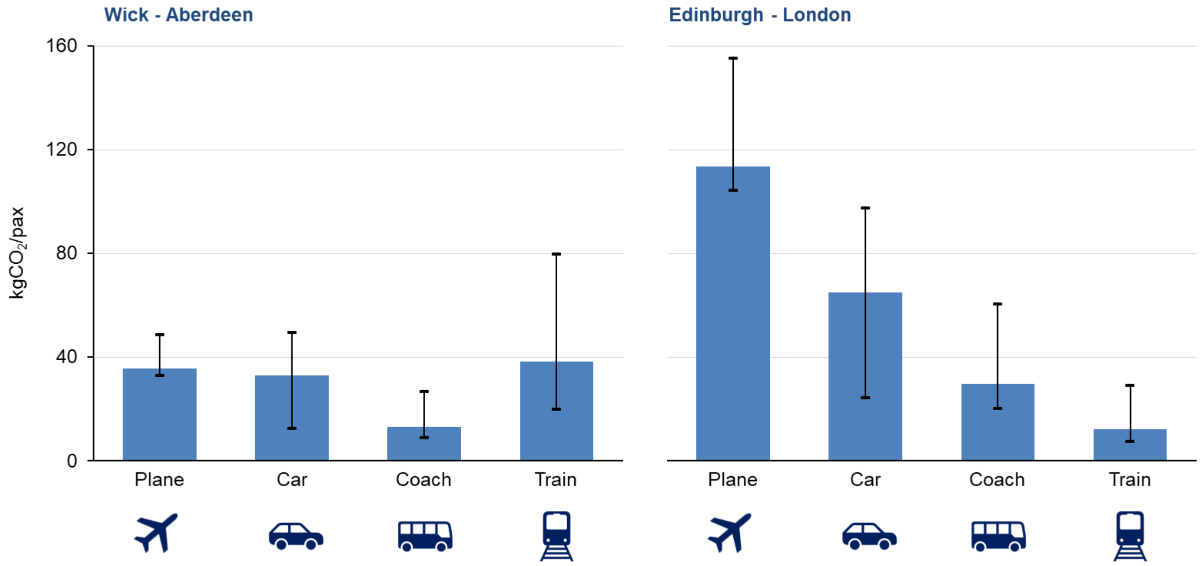


Figure 10: Comparison of CO_2 emissions ($kgCO_2$/pax) by mode of transport for journeys from Wick to Aberdeen and from Edinburgh to London. Error bars show impact of high and low passenger load factors.

There is a large variation in CO_2 emissions intensity as a result of the variation in passenger load factor across all transport modes for each journey. The range between CO_2 emissions per passenger at high and low passenger loading are larger than the total emissions per passenger at average loading for all transport modes for the two example journeys, with the exception of aviation. The smaller variation in the emissions of the plane routes is likely to be because planes do not see a large variation in passenger load factor during peak and off-peak seasons (low passenger load factor modelled as 60%, high as 90%).

The two journeys shown in Figure 10 can be considered as extreme cases in terms of route development and convenience. Routes from Edinburgh to

London, although long-distance, are direct, highly travelled and developed. In contrast, routes between Wick and Aberdeen are less developed (road routes do not follow the motorway, and rail track is not electrified) and must deviate around the sea, unless flying. Journeys between other city centres are likely to fall somewhere in between these two examples, with most routes to England likely to be closer to the Edinburgh to London route.

For the journey from Edinburgh to London, travelling by plane at its highest passenger loading (best-case aviation emissions) has similar per person CO_2 emissions to travelling by car with only one passenger (worst-case car emissions). The worst-case train emissions (passenger loading at off-peak times) is comparable to the best-case emissions of car and coach routes and is ca. 25% of the best-case per passenger emissions of travelling by plane. This demonstrates that while some uncertainty exists in the inputs to this analysis, for the most popularly travelled domestic aviation routes from Scotland, rail will always significantly outperform aviation on an emissions basis.

In contrast, for the journey between Wick and Aberdeen, at low passenger loading, the per passenger CO_2 emissions of travelling by train are almost double the worst-case per passenger emissions by plane. The best-case per passenger emissions of travelling from Wick to Aberdeen by train is still ca. 40% lower than the best-case emissions when travelling by plane. The lowest emissions option remains the coach across high and low passenger load factors, however, the per passenger CO_2 emissions of the coach at low passenger load factor is comparable to the emissions of the plane journey at high and average loading.

Figure 11 compares the lowest emissions transport mode for each journey under low and high passenger loading. Although the low passenger load factor leads to considerably higher emissions than at a high passenger load factor, the lowest emissions transport options for each journey changes in only two cases. In general, as for the journeys with an average passenger load factor, the lowest emissions options with low/high vehicle loading are either train or coach.

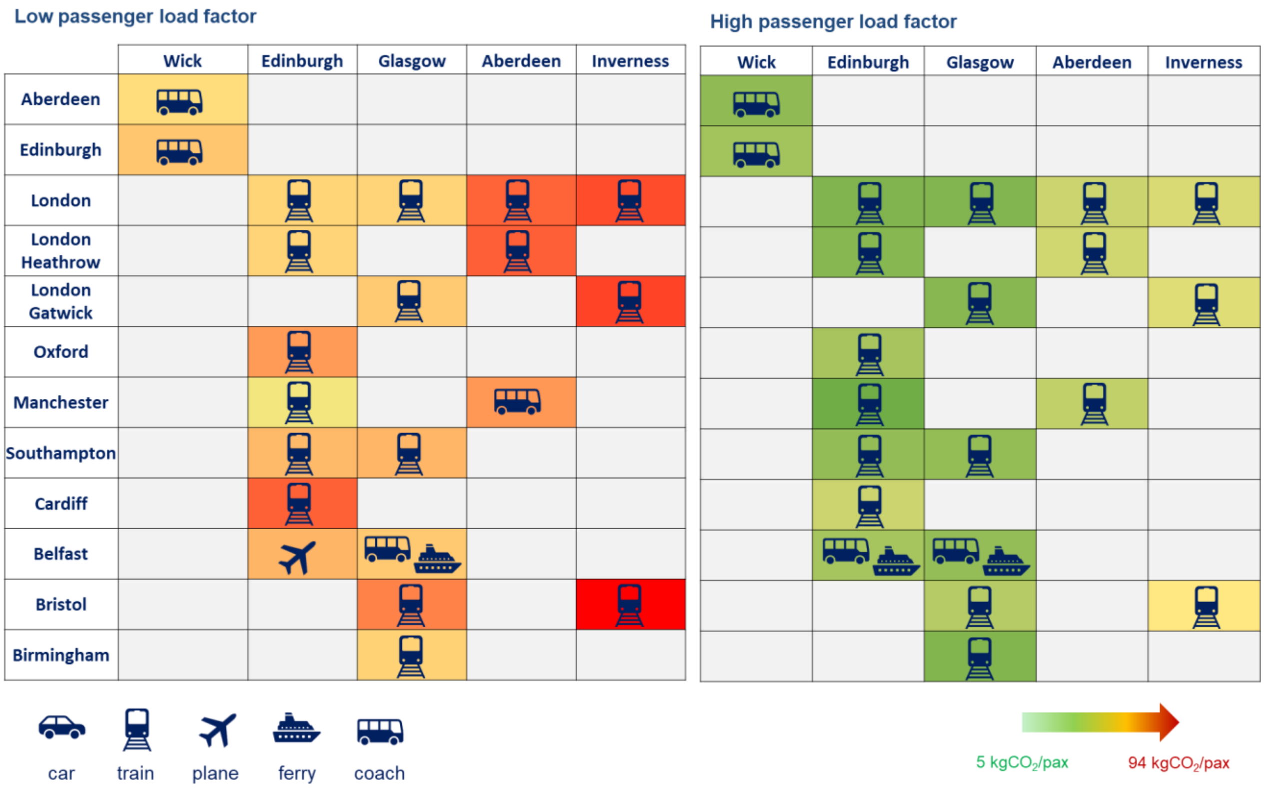


Figure 11: Comparison of lowest emission modes (kgCO_2/pax) of transport for each journey at low and high passenger load factors. Note: per passenger CO_2 emissions indicated by colour scheme.

The two journeys that do change in Figure 11 are Edinburgh to Belfast and Aberdeen to Manchester. At low passenger loading, the lowest emission option to travel from Edinburgh to Belfast is by plane, rather than by coach and ferry. This is consistent with the result that, on a per vehicle basis, the plane journey from Edinburgh to Belfast has the lowest total CO_2 emissions, as shown in Section 3.1.1. This result is likely to be due to the use of a small aircraft with low fuel consumption on this flight route, and also the high emissions factor of the ferry which, at a low passenger loading, leads to high CO_2 emissions per passenger.

At high passenger loading, the route with the lowest per passenger CO_2 emissions for the journey from Aberdeen to Manchester is by train. With an average passenger load factor, the lowest per passenger emissions option is by coach. However, the per passenger emissions of the train is only 20% higher at average passenger loading than the coach. The high peak train occupancy rate means that at peak times, the train is the option with the lowest CO_2 emissions per passenger for journeys from Aberdeen to Manchester.

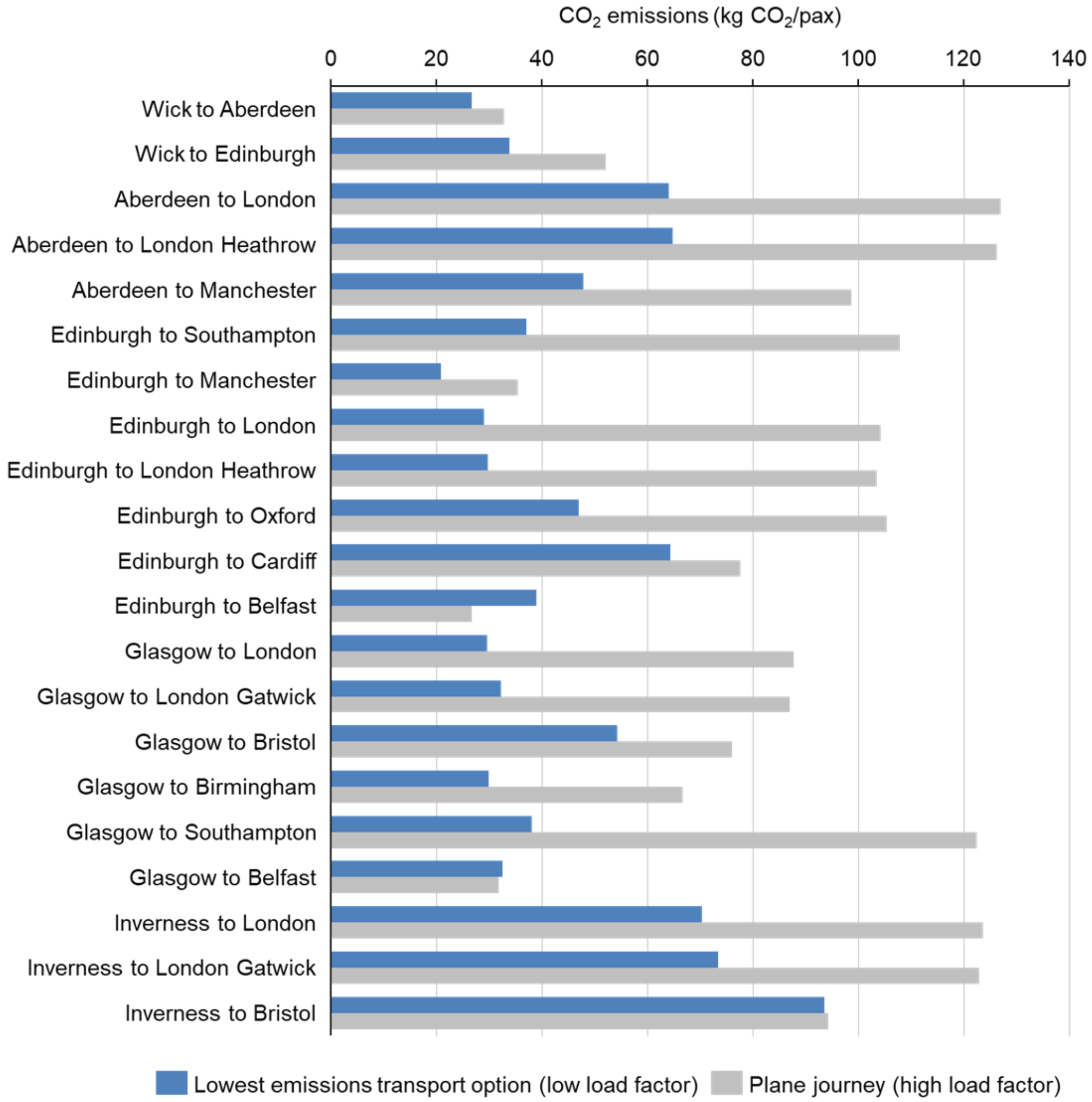


Figure 12: Per passenger CO_2 emissions (kg CO_2/pax) of journeys taken by the lowest emissions transport option with a low passenger load factor, and journeys taken by plane with a high passenger load factor. Note: lowest emissions transport option taken as the transport option with the lowest emissions at an average passenger load factor.

Figure 12 compares the CO_2 emissions of travelling using the lowest emissions transport mode (lowest emissions transport mode is the transport mode with the lowest per passenger CO_2 emissions at an average passenger load factor, as shown in Figure 5). under its worst-case passenger loading scenario, with travelling by plane with its best-case passenger load factor. In most cases, the best-case scenario plane journeys have considerably higher per passenger CO_2 emissions than the worst-case scenario lowest emissions option.

For the journeys from Glasgow and Edinburgh to Belfast, travelling by coach and ferry with a low passenger load factor results in higher CO_2 emissions per passenger than travelling by plane with a high passenger load factor. This is largely a result of the use of the high per passenger emissions factor of the ferry at low passenger loading, in addition to the use of small aircrafts with low fuel consumption.

4 Conclusions

For most domestic journeys considered in the analysis, travelling between city centres by plane is the transport option with the highest CO_2 emissions on a per passenger basis. This is most noticeable for long journeys that use large, fuel intensive planes. Routes that use small aircrafts with low fuel consumption have closer CO_2 emissions to other travel modes. The study found that routes travelled by train or coach are consistently the options with the lowest per passenger CO_2 emissions. Train routes that use an electrified track have considerably lower emissions than other transport modes for a particular journey.

The analysis found that variations in the passenger load factor of the main transport mode for each route have a large impact on the per passenger CO_2 emissions of a route but very little impact on which mode has the lowest emissions. Passenger load factors for planes, cars, coaches, ferries and trains are highly variable on a daily and seasonal basis, but the lowest emissions option for travelling between city centres is generally consistent across all expected load factors.

Although plane routes have the highest per passenger CO_2 emissions for most journeys, they are the fastest option for all journeys considered in the analysis. Planes are likely to be the preferred mode for most routes analysed here, as passengers are unlikely to choose routes that take significantly longer than the plane route. The exceptions found in this analysis are for the busy major routes where direct rail infrastructure is in place including Edinburgh to London, Oxford and Birmingham, and Glasgow to London, and Birmingham, where other transport modes can complete the journey in a competitive time (within 1-2hours of the plane journey time) to planes and reduce emissions.

In reality, passengers will base their route decision on cost in addition to journey time. Cost was not included in the analysis as ticket prices over the past 12 months have been highly affected by the COVID-19 pandemic and the subsequent lockdown restrictions. It is unclear how ticket prices will continue to be impacted in the near future. As a result, it was difficult to collect representative price data to carry out an analysis. Cost must be considered as an additional factor when assessing the convenience of different routes between city centres.

5 Appendix

5.1 Route analysis inputs and data sources

Main mode	Shortest route	Distance (km)	Time (hr, min)
Plane	Google maps, checked against service providers' service details	Actual flightpath distance from a recent flight taken from FlightAware website	Actual flight time taken from a recent flight taken from FlightAware website
Car	TomTom API	TomTom API	TomTom API
Coach	Google maps, checked against service providers' service details	TomTom API, checked against service providers' service details	TomTom API, checked against service providers' service details
Train	Google maps, checked against service providers' service details	Element Energy analysis in QGIS	Google maps, checked against service providers' service details
Ferry	Google maps, checked against service providers' service details	TomTom API, checked against service providers' service details	Service providers' service details

5.2 Emissions analysis inputs and data sources

Main mode	Powertrain	CO_2 emissions factor ($kgCO_2/vkm$)	Load factor
Plane	Aircraft type recently flown on that flightpath, taken from FlightAware website.	Emissions factor calculated from the fuel consumption of the aircraft type and flightpath distance, as specified by the ICAO's Carbon Emissions Calculator Methodology.	Fuel consumption adjusted to account for freight transport using intra-Europe passenger to freight load factors, then adjusted according to intra-Europe passenger occupancy rates (percentage of

Main mode	Powertrain	CO_2 emissions factor ($kgCO_2$/vkm)	Load factor
			maximum seat capacity) both taken from ICAO's Carbon Emissions Calculator Methodology. Maximum capacity of aircrafts taken from aircraft manufacturers' websites.
Car	Based on Great Britain 2019 car fleet mix by fuel type, size and emissions standard. Fuel type taken from Table VEH0203, Department for Transport. Emissions standard based on vehicle age, taken from Table VEH0211a, Department for Transport. Vehicle size taken from Element Energy's ECCo model.	Emissions factor data taken from COPERT which provides real-world fuel consumption figures by vehicle speed and road condition which can be weighted according to vehicle characteristics.	Average car passenger occupancy taken from Scottish Household Survey: Travel Diary 2019, Table 9.
Coach	Diesel powertrain assumed on all coach routes.	Emissions factor data taken from COPERT which provides real-world fuel	Average occupancy rate (percentage of maximum capacity

Main mode	Powertrain	CO_2 emissions factor ($kgCO_2$/vkm)	Load factor
		consumption figures by vehicle speed and road condition which can be weighted according to vehicle characteristics.	occupied) taken from National Express. Maximum capacity taken from coach manufacturer website (Caetano).
Train	Proportion of rail route on electrified and diesel tracks calculated for each route, using information from Network Rail.	Regional and long-distance emissions factors for electric and diesel trains taken from the UIC Railway Handbook (2012).	Regional and long-distance load factors calculated based on passenger kilometres and passenger train kilometres by operator in 2019, as reported by the Office of Rail and Road (Tables 1233 and 1243).
Ferry	Ferry size and type taken from service providers' service details.	Per passenger emissions factor taken from UK Government GHG Conversion Factors for Company Reporting 2020, and scaled according to analysis load factor.	Calculated based on annual numbers of passengers (Transport Scotland, Scottish Transport Statistics 2019 Edition, Table 9.13a) and service providers' service details.
Local bus (Collected to calculate emissions of journeys from use		Emissions factor taken from UK Government GHG Conversion Factors for	Average local bus passenger occupancy taken from Department for Transport bus

Main mode	Powertrain	CO_2 emissions factor ($kgCO_2$/vkm)	Load factor
alongside additional, local travel modes.)		Company Reporting 2020.	statistics, Table BUS0304.
London Underground (Collected to calculate emissions of journeys from use alongside additional, local travel modes.)		Emissions factor taken from UK Government GHG Conversion Factors for Company Reporting 2020.	Average passenger occupancy of tubes calculated from Transport for London Underground Services Performance data and Department for Transport data on public transport (Table TSGB0601).

5.2.1 Road type speed assignment

Road type	Average car speed (mph)	Average coach speed (mph)
Motorway	65	55
A road	55	55
Inner city A road	35	35
Inner city	15	15
Other	30	30