# A Framework for Assessing Spatial Vulnerability to the Introduction of Low Emission Zones: A case study of Edinburgh, Scotland

Dr Craig Morton
Lecturer
Transport Studies Group, Loughborough University

Dr Giulio Mattioli
Research Fellow
Institute for Transport Studies, Sustainability Research Institute, University of Leeds

Professor Jillian Anable
Professor of Transport and Energy
Institute for Transport Studies, University of Leeds

**Abstract**

The introduction of Low Emission Zones (LEZs) is being considered as a policy measure to address the persistently high concentrations of local air pollutants observed across many urban areas of the United Kingdom and wider afield. These zones may substantially alter the operation of the transport system and could lead to adverse consequences for certain segments of the car-using population. Such consequences may include reductions in accessibility, whereby the ability of certain segments to travel to the zone is diminished. This paper considers this issue of accessibility by outlining a spatial vulnerability assessment for the city-region of Edinburgh, Scotland, which evaluates spatial units (in this case, DataZones) according to three criteria. First, a DataZone's *exposure* to a LEZ is determined by using vehicle registration data to calculate the proportion of the privately owned car fleet that does not meet the compliance threshold and locally modelled origin-destination data to determine the degree of interaction by car between the DataZone and the LEZ. Second, a DataZone's *sensitivity* to a LEZ is assessed by using the mean household income of the population. Third, the *adaptive capacity* of 'potentially vulnerable' (i.e. exposed and sensitive) DataZones to a LEZ is evaluated by measuring their proximity to direct public transport links to the LEZ, travel time from the LEZ, and level of physical disability. The paper concludes by demonstrating how the outputs of the assessment can inform LEZ policy development, mitigate adverse consequences on accessibility, and increase public acceptability.

## 1. Introduction

Global cities are facing a growing problem concerning low air quality levels resulting from high concentrations of local pollutants such as nitrogen oxides, sulphur dioxide, and particulate matter (World Health Organisation, 2017). These local pollutants are primarily generated from the combustion of carbon based fuels, such as wood for cook stoves and coal for domestic heating. In the United Kingdom (UK), the use of fossil fuel vehicles (i.e. petrol and diesel) within urban areas is the largest contributor of local pollutants, with 391 Air Quality Management Areas being in effect in the UK in 2017 (Department for Environment, Food and Rural Affairs, 2017a). This situation has substantial implications for the health and wellbeing of citizens, with 40,000 deaths attributed to low outdoor air quality per annum (Royal College of Physicians, 2016). Presently, national and local government agencies are in the process of designing strategies through which to address this situation, such as implementing more stringent vehicle emission testing regimes to improve the compliance to regulatory thresholds and the optimisation of traffic management systems to smooth the flow of vehicles through congested areas (Department for Environment, Food and Rural Affairs, 2017b; Scottish Government, 2016).

One strategy which is attracting considerable levels of attention is the introduction of Vehicle Access Regulations (Ricci et al. 2017), which control the entry of vehicles to set areas. Such regulations can take multiple forms dependent on the timing of operation, the restriction imposed, the vehicles restricted, the areas covered, the process of enforcement, and the primary objectives which are being pursued. A particular variant of such strategies are Low

Emission Zones (LEZs; also referred to a Clean Air Zones and Environmental Zones), which have seen application across the cities of Europe[1]. LEZs generally set a minimum emission standard which vehicles must comply to in order to enter the zone, with either charges or fines imposed on non-compliant vehicles.

It is possible that the introduction of an LEZ may generate adverse consequences which are not equitably distributed across society. Such adverse consequences could involve the mobility of certain social groups or residents of certain areas being hampered as a result of an LEZ's operational parameters. With this in mind, it is important to consider whether the pursuit of one objective through the introduction of an LEZ (i.e. improving air quality) may be to the determinant of another socially important aim (i.e. accessibility). The aim of this paper is to demonstrate an approach to identifying areas that would be the most negatively affected (in terms of reduced accessibility) by the introduction of a LEZ. To do that, a theoretical framework is proposed that sees *vulnerability* as the product of *exposure*, *sensitivity,* and *adaptive capacity*. To demonstrate the value of this spatial vulnerability assessment, the method is applied to a case study of LEZ implementation in Edinburgh, Scotland.

This paper progresses by offering an overview of previous research examining Vehicle Access Regulations and the situation regarding LEZs in Scotland in order to provide context to the research. The approach followed to conduct the spatial vulnerability assessment is then detailed in terms of the theoretical framework adopted, the data utilised as indicators for the assessment components, how these data are combined, and the limitations of the approach. The case study of Edinburgh is then used to demonstrate the strengths and weaknesses of the approach. To conclude, a series of implications are proposed which illustrate how the findings of the assessment can inform policy development.

## 2. Background

### 2.1. Situation in Scotland

Introduced in 1995, the Environment Act requires that UK local authorities conduct annual reviews of air quality levels within their jurisdiction in terms of concentrations of nitrogen dioxide, sulphur dioxide, and particulate matter. If concentrations are above set limit values, an Air Quality Management Area (AQMA) is designated, which necessitates that local authorities develop and implement a strategy in order to improve the situation.

As of writing, there are thirty-nine AQMAs in effect across Scotland, with all but one local authority having at least one area in which the level of air quality falls below the limit values. To address this issue, the Scottish Government (2015) introduced a national strategy, termed Cleaner Air for Scotland (CAFS), through which to achieve their legal responsibilities as quickly as possible. Within CAFS is a National Low Emission Framework and National Modelling Framework (Transport Scotland, 2017), which act as the procedure through which policy options to tackle air quality are generated and evaluated. The introduction of LEZs represents one possible option, which would encapsulate AQMAs and restrict the entry of vehicles in order to reduce concentrations of local pollutants. The Scottish Government is considering LEZs which restrict the access of cars that do not comply with the Euro 4 emission standard (i.e. cars manufactured before January 2005) if fuelled by Petrol and the Euro 6 emission standard (i.e. cars manufactured before September 2014) if fuelled by Diesel. Non-compliant cars would be prohibited from entry to the LEZ, with fines being levied to cars that enter the LEZ that do not meet the specified emission standards. Currently, no LEZ has been introduced in Scotland, with the case study presented in this paper being used to inform the Scottish Government about the potential social exclusion implications of implementing LEZs.

In order to illustrate the assessment, the remainder of this paper considers a hypothetical example of the introduction of an LEZ into the city centre of Edinburgh, Scotland. It is assumed that that the regulated area corresponds to a current AQMA (see Figure 3 below)

[1] See http://urbanaccessregulations.eu/userhome/map

and that the LEZ restricts the entry of cars that do not comply with either the Euro 4 (Petrol) or Euro 6 (Diesel) emission standard.

## 3. Approach, Methods and Data

### 3.1. Vulnerability

Research on climate change and natural hazards has put forward conceptualisations of *vulnerability* as constituted by three components: *exposure*, *sensitivity,* and *adaptive capacity* (Adger, 2006, Brooks, 2003). In transport research, this framework has been adopted to investigate vulnerability to fuel price increases (Büttner et al. 2013; Leung et al. 2015; Mattioli et al. 2017). In this paper, this framework is adapted to investigate the possible negative accessibility impacts of LEZs. Table 1 presents definitions for the three vulnerability components, alongside indicators used in previous research on fuel price increases, while the third column outlines how these can be adapted to the case of LEZs.

**Table 1:** Definitions of the components of the spatial vulnerability assessment, previously used indicators, and proposed indicators for LEZ introduction

| Component | Definition [A] | Indicator for fuel price [B] | Proposed indicator for LEZs |
|---|---|---|---|
| Exposure | "the nature and the degree to which a system experiences (…) stress" | Level of fossil fuel consumption in passenger travel | Flow of non-compliant vehicles between area and LEZ |
| Sensitivity | "the degree to which a system is modified or affected by perturbations" | Households' ability to pay for more expensive fuel | Households' ability to pay for vehicle compliant with LEZ regulation |
| Adaptive capacity | "the ability of the system to evolve in order to accommodate (stress) and to expand the range of variability with which it can cope" | Ability to shift to modes alternative to the private car | Ability to shift to modes alternative to the private car for trips to LEZ |

[A]: taken from Adger, 2006
[B]: applied by Büttner et al. 2013; Leung et al. 2015; Mattioli et al. 2017

It is important to note that the vulnerability approach was originally developed for stresses or natural hazards that are out of human control and unequivocally negative for society (e.g. floods, earthquakes, and fires). Clearly, LEZs are different in at least two respects. First, they are policy measures which are deliberately introduced by local policy makers. Second, they are introduced in order to reduce the negative effects of air pollution, which can be serious. In that sense, there is an issue of *vulnerability to car emissions*, and LEZs aim to reduce it. On the other hand, the introduction of CAZ may have its own negative effects, through reducing access to services and opportunities for households with non-compliant cars who have few alternatives to the use of private cars. These negative effects may in turn lead to resistance to the introduction of LEZs if they are perceived as being unfair (Rye et al. 2008).

With regard to the component indicators, an area is classified as more *exposed* if a large proportion of its private car fleet is non-compliant to the access standard and habitually travel to the LEZ. *Sensitivity* is evaluated by household ability to acquire a vehicle that is compliant with the LEZ access standard. This corresponds to one of the main intended outcomes of the measure, encouraging fleet renewal and the adoption of cleaner vehicles. Households with lower ability to pay will be more *sensitive* to the introduction of a LEZ. The ability to shift away from car use altogether by using alternative modes to travel to the LEZ is used as an indicator of *adaptive capacity*. This reflects the fact that modal shift is another intended outcomes of the measure. Overall, the assessment identifies vulnerable areas as those where a high proportion of drivers would be affected by the LEZ, while at the same time having limited capacity to keep travelling to the area with either a compliant vehicle or with

an alternative mode of transport. This leaves only two further coping strategies, shifting trips to other destinations (if possible) or foregoing them altogether, both of which would result in reduced accessibility. Overall, the vulnerability assessment is based on a consideration of how households in the area may react to the introduction of a LEZ.

In this paper, the vulnerability assessment is used as a heuristic tool to investigate the possible negative impact of LEZs. It should not be construed as suggesting that CAZ are unfair and should not be introduced. LEZ come with intended benefits (e.g. emission reductions) and unintended costs (e.g. possible reductions in accessibility). Finding a fair balance between those is ultimately a normative question, requiring some form of democratic deliberation Walker, 2012; Martens, 2016).

### 3.2. Data Sources and Preparation

To conduct the assessment, a series of data sources are combined which cover vehicle registrations, vehicle movements, household incomes, public transport services, and demographic characteristics. These sources are summarised in Table 2 which outlines what indicator is assigned to what component.

**Table 2:** Outline of the datasets and variables utilised in the spatial vulnerability assessment

| Dataset | Year | Description | Variable | Vulnerability component |
|---|---|---|---|---|
| Department for Transport<br>Vehicle Licensing Statistics Database | 2016 | This database holds a record of all vehicles registered for use on UK roads and includes a series of characteristics such as fuel type and year of first registration which can be used to infer European Emission Standards | Percent of privately owned vehicles that are not compliant to either the Euro 4 emission standard (Petrol) or Euro 6 emission standard (Diesel) | Exposure |
| SESTran<br>Regional Transport Model | 2016 | The South East Scotland regional transport model incorporates an Origin-Destination matrix which records AM-Peak car trips and allows for the level of interaction between areas to be measured | Number of trips by car between each TravelZone and Edinburgh city centre in the AM peak | Exposure |
| Scottish Government<br>Local Level Average Household Income Estimates | 2014 | The Scottish Government estimate median weekly household income through a series of ancillary surveys and data sources | Median weekly household income (GBP) | Sensitivity |
| National Records of Scotland<br>Population Census | 2011 | The census records a series of demographic characteristics such as disability levels | Percent of residents that state their day-to-day activities are “limited a lot” by a disability | Adaptive capacity |
| General Transit Feed Specification | 2017 | This database holds a record of public transport services operating in the UK in terms of modes, routes, and timetables | Public transport routes | Adaptive capacity |

The data covering vehicle registrations, demographic characteristics, and household incomes are aggregated at the DataZone level of administrative geography (n = 2,134). DataZones are spatial units which contain between 500 and 1,000 household residents and attempt to respect natural communities (i.e. delineate neighbourhoods which are partially homogenous). The data covering vehicle movements is aggregated at the TravelZone level of administrative geography (n = 873). The TravelZone spatial resolution is similar in size and layout to DataZone (and often identical) but is orientated around understanding travel behaviour, not population demography[2]. The analysis is confined to the area covered by the South-East of Scotland Regional Transport Partnership (SESTran), as this represents the government body which has jurisdiction over the regional transport system of the Edinburgh city region. The SESTran region is illustrated in Figure 1 in terms of its situation in Scotland and with reference to the boundary of the City of Edinburgh.

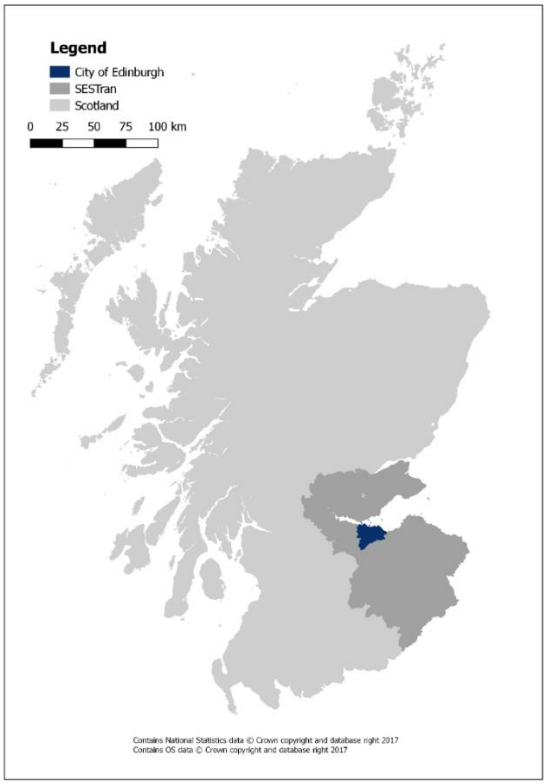


**Figure 1:** Contextual map of the South-East of Scotland Regional Transport Partnership (SESTran) and the City of Edinburgh

### 3.3. Assessment Procedure

The assessment is applied through a site selection tool built into a Geographical Information System as a series of overlays which map the variables outlined in Table 2. Figure 2 provides an illustration of the assessment procedure covering the components of exposure, sensitivity, and adaptive capacity.

A two stage approach to considering the vulnerability of an area is followed. In the first stage, the indicators of exposure and sensitivity are examined in order to identify potentially vulnerable areas. Areas which are, *at the same time*: i) in the top two quintiles (i.e. top 40%) in terms of the proportion of their private cars that are not compliant to the Euro 4 emission

[2] Due to this difference in spatial resolution, there are regions where marked differences between the configuration of the DataZones and TravelZones exist. An example is a region that covers an out-of-town retail park which may represent a distinct TravelZone due to it being a destination and origin of traffic but, due to its low level of daytime and residential population, would not represent a distinct DataZone.

standard (Petrol) or Euro 6 emission standard (Diesel); ii) in the top two quintiles in terms of the number of car trips made to Edinburgh city centre in the AM peak; iii) in the bottom two quintiles for median household income are identified. That is to say, areas that have relatively high levels of both exposure and sensitivity are classified as being potentially vulnerable.

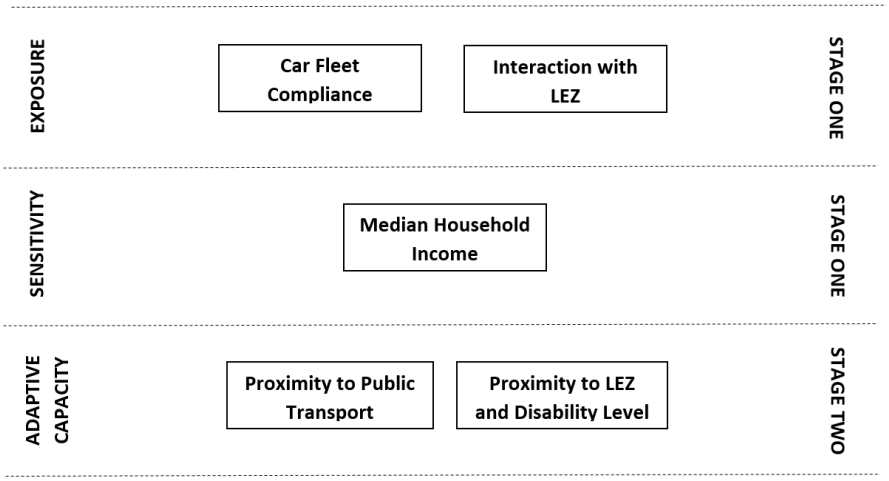


**Figure 2:** Assessment framework which covers the indicators of the vulnerability dimensions and the different assessment stages of [1] identifying potentially vulnerable areas and [2] evaluating the adaptive capacity of potentially vulnerable areas

In the second stage, potentially vulnerable areas are examined on a case-by-case basis to determine their level of adaptive capacity which covers two types of modal shift. The first shift relates to the ability to access Edinburgh city centre by public transport and considers the proximity of an area to direct public transport corridors into the city. Potentially vulnerable areas that are nearby to direct train, bus, or light-rail links into the city which have a service schedule amenable to day-to-day activities (i.e. at least hourly services between 07:00 and 19:00) are deemed to have adaptive capacity to the implementation of an LEZ. The second alteration concerns the potential to access Edinburgh city centre by an active form of transport. Potentially vulnerable areas that are within either a 30 minute walking time to the city centre (which denotes a threshold for walking distance) or a 30 minute cycling time to the city centre (which denotes a threshold for cycling distance) and have relatively low levels of physical disability are deemed to have adaptive capacity to the introduction of a LEZ. These active travel journey times are assessed by specifying Isochrones using the *Openrouteservice* accessibility profiler, which makes use of average mode speed, network distance, and topography to estimate travel time boundaries.

### 3.4. Assessment Limitations

While the assessment has been designed to take advantage of the best practice regarding social equity assessments in transport and the best available data, there are a number of issues which limit its operation.

First, there is temporal disparity across the different data sources used to apply the assessment. While most data are from 2016 sources, median household income estimates are for 2014, and the prevalence of disability in the population refers to 2011. This is not ideal, although it is unlikely that substantial alterations in the spatial variation of income and disability have occurred in the intervening period. Second, there is spatial disparity across the different data sources. While the data concerning car fleet compliance, household incomes, and disability levels is aggregated at DataZones, the vehicle flow data from the SESTran regional transport model is aggregated at TravelZones. In order to mitigate this issue, best fit procedures were employed to assign TravelZones to DataZones. Third, the accuracy of the data sources is, in places, restricted. For instance, car fleet compliance to

the LEZ emission standard is inferred from the fuel type and year of first registration of the vehicle in the Vehicle Licensing Statistics Database. However, the year of registration may not match the year of manufacture for all vehicles, such as when a car is imported from aboard. Fourth, the assessment relies on an overlay of different characteristics which are not naturally connected with one another in order to identify potentially vulnerable areas. For instance, an area may display relatively high levels of non-compliance to the LEZ standard and high levels of interaction with Edinburgh city centre, but this does not necessarily mean that non-compliant cars which are registered in that area are the ones which are driving into the city centre.

## 4. Case Study: City of Edinburgh

### 4.1. Stage 1: Identification of 'potentially vulnerable' areas

To conduct this case study, a hypothetical LEZ is introduced into the centre of the City of Edinburgh. This LEZ is defined in Figure 3 and covers the main rail station and retail district. Additionally, this area is a current AQMA, meaning that the implementation of a LEZ in this location is likely in the near future.

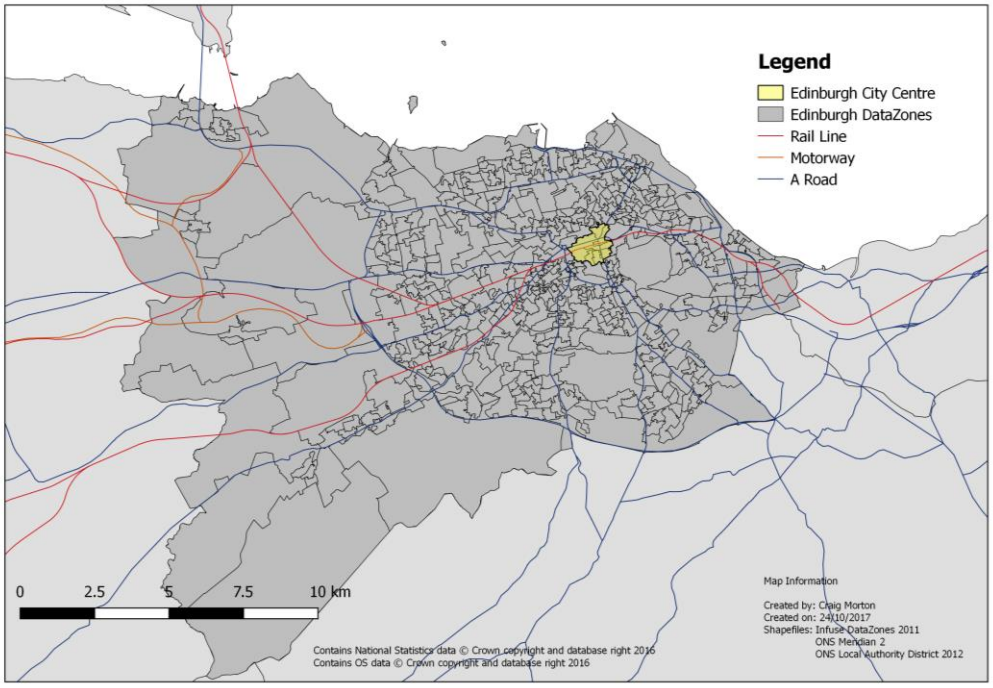


**Figure 3:** Map illustrating the hypothetical Low Emission Zone (highlighted in yellow) utilised in the case study in reference to the City of Edinburgh

Figure 4a displays the spatial variation in private car fleet compliance to the LEZ standard, with the colour ramp increasing with higher rates of non-compliance. One of the most apparent observations is that rural regions of the Scottish borders (lower part of the map) and Fife (upper right part of the map) tend to contain areas that have relatively high levels of non-compliance to the LEZ standard. This is due to rural areas being more inclined to own diesel cars, which are required to meet a higher emission standard to gain entry to the LEZ.

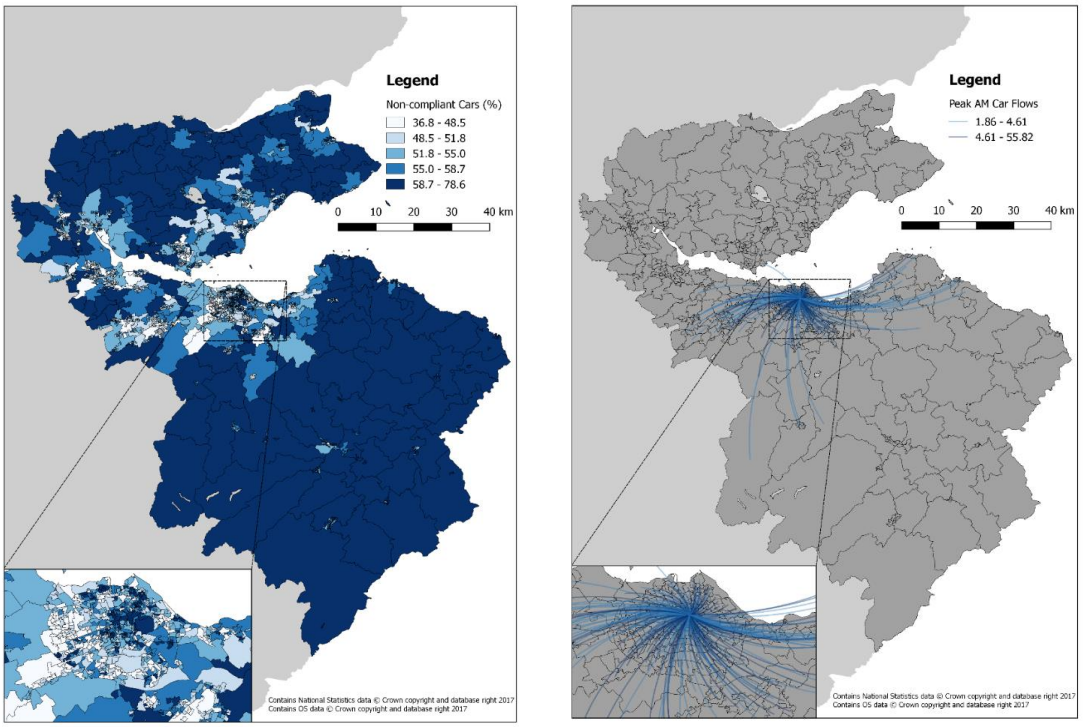


**Figure 4:** [a] Choropleth map illustrating private car fleet compliance to the LEZ emission standard across the South-East of Scotland [b] Flowmap of the number of car trips in the AM peak with a desitnation of Edinburgh city centre from across South-East Scotland

The number of trips by car in the AM peak between the TravelZones of the SESTran regional transport model and Edinburgh city centre are displayed in Figure 4b. To ensure that the graphic is legible, only the top 40% (i.e. highest two quintiles) of flows are illustrated. The most obvious result is that almost all of the areas that have relatively high levels of interaction with Edinburgh city centre are located to the south of the Forth of Firth (the large estuary to the north of the City of Edinburgh). This is likely due to the limited crossing points for this estuary, though this may change now that a new road bridge has completed construction. In particular, areas to the west and east of the City of Edinburgh, as well as areas within the city boundary, represent the point of origin of a high proportion of trips by car into the city centre.

The spatial variation in median household incomes is illustrated in Figure 6a, which acts as indicator of the sensitivity of areas to the introduction of a LEZ. For this characteristic, a less clear spatial patterning is present, with regions of high, medium, and low household income irregularly spread across the South-East of Scotland. Regions of medium household income appear to cluster in the the rural areas of the Scottish Borders and Fife, with a band of high household income areas also surrounding the City of Edinburgh. Areas of low household income are typically located in urban settings, such as the City of Edinburgh and the towns of Kirkcaldy, Methil, and Leven which are located on the north shores of the Firth of Forth.

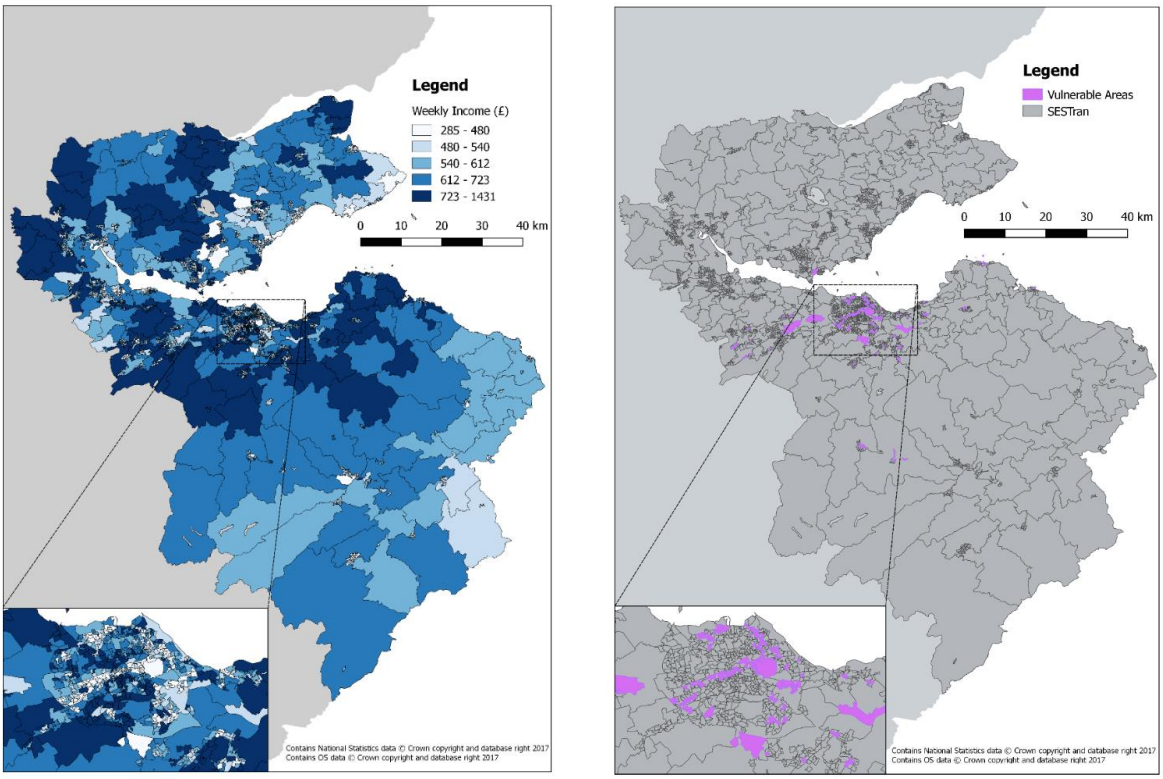


**Figure 6:** [a] Choropleth map displaying median weekly household income across the South-East of Scotland [b] Map highlighting potentially vulnerable areas which have relatively high levels of exposure and sensitivity to the introduction of a Low Emission Zone

Areas that are in the top two quintiles (i.e. top 40%) for non-compliance to the LEZ standard and interaction by car with Edinburgh city centre as well as the bottom two quintiles for median household income have relatively high levels of exposure and sensitivity to the introduction of an LEZ and are thus classified as being potentially vulnerable. A total of 136 potentially vulnerable areas are identified by stage one of the assessment, which represents 6.37% of the DataZones contained in the South-East of Scotland. These potentially vulnerable areas are illustrated in Figure 6b and are located primarily in the urban and peri-urban region of the City of Edinburgh, with 93 potentially vulnerable areas being within the city limits.

### 4.1. Stage 2: Assessment of adaptive capacity for selected 'potentially vulnerable' areas

The most rigorous way to evaluate adaptive capacity would be to assess the opportunity to shift to alternative modes in order to access Edinburgh city centre for each area identified as potentially vulnerable. For reasons of brevity, this section contains only a partial evaluation, focusing on four potentially vulnerable areas across the urban and peri-urban region of the City of Edinburgh.

Figure 8 displays two potentially vulnerable areas in the peri-urban region, with the settlement of Pumpherston located in the west and Straiton situated in the south. The Pumpherston settlement is within a close proximity to a train station which has frequent direct services into Edinburgh city centre. Similarly, Straiton is located adjacent to a park-and-ride station which provides frequent direct bus services to the city centre. From this evaluation, it can be concluded that, while the residents of Pumpherston and Straiton may find their ability to access Edinburgh city centre by car somewhat curtailed by the introduction of a LEZ, they have the capability to travel to the city centre by public transport. As such, the residents of these settlements have adaptive capacity to the implementation of a LEZ.

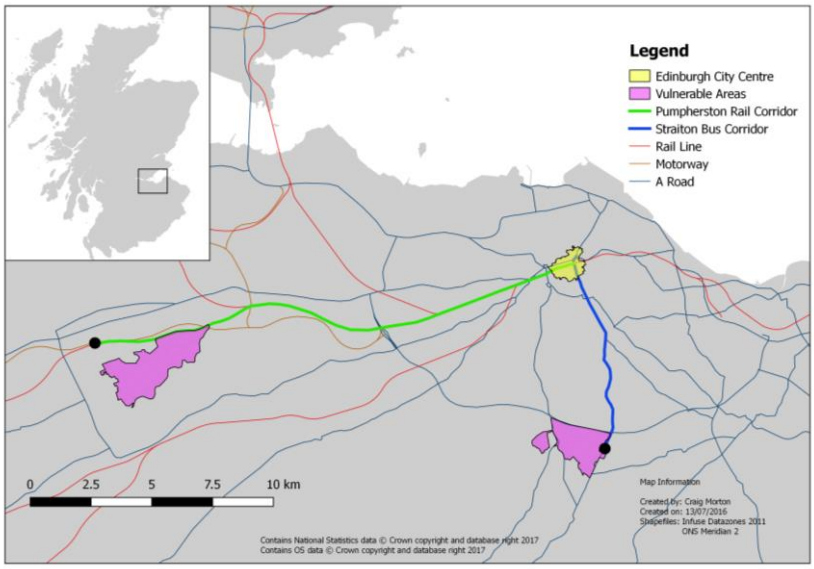


**Figure 8:** Adaptive capacity assessment of potentially vulnerable peri-urban areas taking into account proximity to direct public transport services to Edinburgh city centre

Figure 9a and 9b highlights two areas within the City of Edinburgh that have been identified as potentially vulnerable to the introduction of a LEZ. In both instances, the areas are outside a comfortable walking range to the city centre, but are between a 10 to 25 minute cycling time. However, both areas also display relatively high levels of physical disability (i.e. day-to-day activities "limited a lot"), marked by the deep blue shading of the Choropleth element of the map. With these observations in mind, it can be concluded that these two urban areas may have low levels of adaptive capacity to the introduction of a LEZ in terms of their ability to access the city centre by active modes. Residents of these two areas may have to make use of Edinburgh's bus services to access the city centre, which would require an appraisal of the services currently operating in the vicinity of these areas to consider if they allow for direct transit to the city centre and have the capacity to absorb demand from displaced car trips.

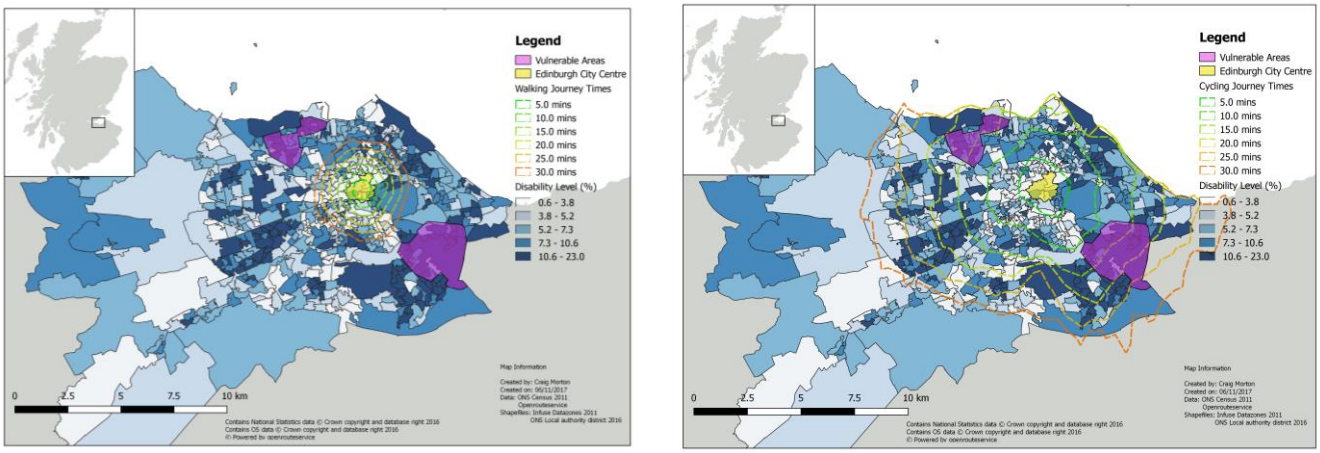


**Figure 9:** Adaptive capacity assessment of potentially vulnerable urban areas taking into account physical disability level and [a] walking times to the city centre and [b] cycling times to the city centre

## 5. Discussion

This paper sets out a spatial vulnerability assessment which evaluates the exposure, sensitivity, and adaptive capacity areas have to the introduction of an LEZ. Through a case study of a proposed LEZ implementation in the City of Edinburgh, Scotland, the assessment is applied in order to illustrate its practicality. From this demonstration, it is possible to critically evaluate the advantages and shortcomings of the assessment. In terms of the advantages, the assessment is effective at conducting a universal appraisal which allows areas to be compared and contrasted. The assessment can also be deployed in different regions, so long as the data necessary to conduct the analysis is available, allowing the assessment to be integrated with national transport policy appraisal guidelines. The identification of potentially vulnerable areas across the region being assessed facilitates the targeting of follow-up appraisals. Such follow-ups could involve ground-truthing exercises to validate if a high degree of vulnerability in a particular area is present and, if this is the case, the views of local residents regarding the appropriateness of mitigating policies. The assessment can also act as a means through which to engage local residents due to the visual appeal of the tool. One such approach could involve printing off layers of the site selection tool which are bounded to the local area and asking residents to annotate the map with their own knowledge. Moreover, the assessment can be augmented through the inclusion of ancillary datasets to provide additional content. For instance, deprivation indices could be superimposed onto potentially vulnerable areas to enrichen the understanding by considering whether the residents are already marginalised in society.

In terms of the shortcomings, the assessment is reductionist by its nature and constrains the evaluation of vulnerability to easily observable and quantifiable phenomenon. For instance, the treatment of public transit availability in potentially vulnerable areas is currently ad-hoc and does not consider such issues as the capacity levels for existing services. The appropriateness of the data used as proxies for the assessment components is debatable, which can have substantial consequences on the ability of the method to precisely triangulate on vulnerability. A case in point is the use of median household income as a proxy for the ability of an area to respond to the introduction of a LEZ without residents having to alter their behaviour. It is arguable whether disposable median household income would be a more appropriate proxy, as this may more precisely measure the ability of residents to acquire a car which is compliant to the LEZ emission standard. Similarly, the assessment is lacking in terms of the depth of data that in integrates, which means the assessment can seem superficial. For instance, the appraisal of adaptive capacity on an area to access the city centre by active means assumes that residents have access to bicycles to allow for trips to be conducted.

A number of these shortcomings could be addressed through future refinements in the method. New data could be incorporated into the assessment to allow for a more precise treatment of exposure, sensitivity, and adaptive capacity. For example, Scottish accessibility statistics currently provide average journey times by car and public transport to the nearest post office, doctor's office, and retail centre for each DataZone. If these statistics also covered trips to the nearest city centre, then the difference between the average journey time by car and public transport could be used to evaluate adaptive capacity as it would indicate the time penalty of not being able to travel by car (Mattioli et al. 2017). Moreover, data regarding the appropriateness of active travel routes (e.g. if conducive facilities such as segregated bicycle lanes exist) between DataZones and the city centre could be ascertained to determine if cycling and walking are feasible alternatives.

## 6. Conclusions

A practical question to consider when the results of the assessment have been interpreted is what policy relevant implications can be proposed? A series of recommendations regarding mitigating actions that a government can pursue to reduce the occurrence of adverse consequences on social inclusion generated by the introduction of a LEZ can be proposed.

For areas that are classified as potentially vulnerable and having low levels of adaptive capacity, a series of policies could be pursued to limit any negative outcomes to city centre accessibility. First, new public transport routes could be established or existing routes could be extended to provide services to areas that are currently underprovided for. In the short-

term, this would likely involve modifications to bus corridors as this represents one of the most flexible forms of public transport, though infrastructure intensive modes (e.g. light-rail) could be planned as medium-term solutions. Second, new shared transport assets could be introduced to an area to augment the options which are present. For instance, new car club vehicles or bicycle hire schemes could be located in the vicinity of potentially vulnerable areas to provide residents with an alternative means through which to access the city centre.

Overall, the proposed approach allows for the conduct of a preventive assessment of vulnerability to the introduction to LEZs, which is valuable in two ways. First, it enables local government to identify and prioritise policy measures to reduce the negative accessibility impacts of the LEZ (e.g. improved public transport links for selected areas). Second, if such measures are implemented early enough and effectively communicated, this could help improve the public and political acceptability of the LEZ, which has so far proven to be one of the main obstacles to their implementation.

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