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Spatial multicriteria decision analysis for Walking School Bus target development strategies

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A R T I C L E I N F O

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A B S T R A C T

Introduction: Around the world there has been a decline in the mode share of walking to school. This is the result of many factors influencing the mode choice decisions of parents for their own journeys to work and their children's journeys to school. Walking School Bus (WSB) has been proved to be an effective strategy that can be an innovation to promote walking to school and combat the 'vicious circle' of chauffeuring children to school. This modal switch can thus be a key for enhancing the sustainability of our transportation system and more importantly the health of our next generation.
Methods: This paper proposes an innovative decision analysis model to identify areas for targeting WSB development. By applying spatial multicriteria decision analysis (SMCDA) to existing aggregate data on both work and school trip mode choices and relevant zonal characteristics, the proposed model can help planners and policy decision makers to identify where investments on setting up/enhancing WSBs might be most effective in enabling modal shift. We apply our SMCDA model to a case study in Bradford, UK. We highlight zones/schools within the study area where WSB programmes can be most effective to help realise the full potential of walking to school in health, environmental and social inclusion terms.
Results: Six zones in Bradford have been identified as the areas with the highest potential for the uptake of WSB schemes. These present characteristics that are favourable conditions for walking but with less than ideal current walking mode shares. They have large numbers of school aged children, lower level of work trips by car and higher parents' availability.
Conclusions: Our SMDCA method for WSB target development is highly transferable and can be applied to other cities in the UK or around the world; providing genuine applied value as an apparatus for supporting, informing and systematising the implementation of potentially successful (in engagement and usage terms) WSB schemes.

1. Introduction

1.1. Impact of transport mode choice on health and wellbeing

Throughout the twentieth and twenty-first centuries, there has been a clear shift by road users around the world towards the use of

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automobiles (Alyavina et al., 2020; Nikitas et al., 2021) making the private car a 'flawed' symbol of hyper-connectivity (Musselwhite, 2021), social inclusion (Mattioli et al., 2020) and status (Pojani et al., 2018). There is a scientific consensus that this travel behaviour shift is detrimental in environmental, economic and societal terms as excessive car use is associated with increased greenhouse gas emissions, local air and noise pollution, climate change, mortality and morbidity from traffic incidents, chronic diseases, obesity and physical inactivity (Morton, 2018; Nikitas et al., 2016; Potoglou et al., 2020; Tsigdinos et al., 2021).

Air pollution, in particular, a pandemic responsible for around 7 million premature deaths worldwide (Smith et al., 2021) is a phenomenon linked with such unsustainable transport choices. The adverse impact of air pollution generated from the tailpipe emissions of vehicles on air quality has become the source of a 'vicious circle of driving'. Li and Kamargianni (2017) found that the modal choices of travellers were heavily affected by the presence of air pollution in differing seasons, which have hugely varying air quality in Taiyuan, China. When pollution is high, more people were likely to travel by motorised modes; something creating additional traffic congestion and subsequently further increase on the levels of local air pollution (Mitsakou et al., 2021). Non-motorised choices, such as walking and cycling are far more prevalent when air quality is better (Marquart et al., 2022). The deterioration of air quality in our living environment, especially when coupled with physical inactivity during travels, can have an enormous impact on both our physical and mental wellbeing (Xia et al., 2015).

Lack of physical activity has indeed turned into a serious quality of life deteriorator (Nieuwenhuijsen, 2020) that directly relates to unhealthier transport choices. The promotion of walking, on the other hand, is a promising strategy to address not only the traffic bottlenecks or environmental pollution but to also provide health benefits to individual road users and society as a whole (Lopez-Lambas et al., 2021).

1.2. The chauffeuring-and-walking-to-school vicious circle

Among many travel decisions in our daily life, how to take children to school plays a key part of many parents' travel plans (Benson et al., 2020). School commute mode choice decisions are often entirely that of the parents' (Mehdizadeh et al., 2017, 2018; Scheiner et al., 2019; Woldeamanuel, 2016), particularly when they have children of a younger age. It is not surprising to find that the trend of children being driven to school also follows an increasing trend (Rothman et al., 2018). This is the result of a rather complex and challenging decision made by many parents (Ferrari and Green, 2013; Easton and Ferrari, 2015).

Safety concerns, in particular in negotiation with high traffic volume and speeds, and traffic incident risks at crossings or road intersections have become the major concerns in their decisions (see e.g. Collins and Kearns, 2005; Ermagun and Samimi, 2015; Nikitas et al., 2019; Rothman et al., 2014). Naturally many parents would want to protect their children. They might feel that they simply do not have a choice but to chauffeur their children to school, sometimes even if they are within walking distance from the school (see e.g. Ahern et al., 2017; Babb et al., 2017; Hastie, 2007; McDonald and Aalborg, 2009; Mammen et al., 2012; Smith et al., 2019). Walking to/from school, in reality, could have offered to their children a strong health-improving contribution to their overall physical activity (Bejarano et al., 2021; Larouche et al., 2014).

Ironically, chauffeuring children to school to avoid traffic danger has created a rarely discussed vicious circle. If parents' choice is to chauffeur their children to school (instead of walking them), their car trips will add to school traffic, reducing traffic safety around the school and exposing them to higher pollution levels (An et al., 2021). These car trips, therefore, will make the environment worse for those walking (or cycling) to school. This will only make chauffeuring children to school become even more attractive instead of walking to school, as shown in Fig. 1.

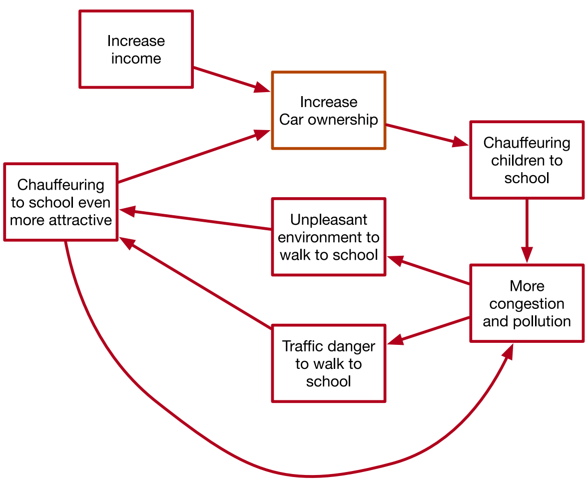

Fig. 1. The chauffeuring-and-walking-to-school vicious circle.

1.3. Creating a walking-and-chauffeuring-to-school virtuous circle

The most effective way to break this vicious circle is to reverse the modal shift from walking to being driven to school by creating a virtuous circle, as shown in Fig. 2. If there is less traffic, there will be a more pleasant environment for walking and reduced traffic risk or danger (Pucher and Buehler, 2010). Children will then really enjoy the health benefits from physical exercise during their journey to school and could possibly have better learning outcomes from their time in school (Nikitas et al., 2019). The improved environment will make walking (to school and beyond) even more attractive (Pucher and Dijkstra, 2003) and healthier children will certainly be more willing to walk to school (Vandoni et al., 2018).

1.4. WSB as an apparatus for pro-walking modal shift

The purpose of this study is to investigate where Walking School Bus (WSB) schemes might be targeted as a policy instrument to create and promote the modal shift from children being chauffeured to walking to school. We believe that this might be the best starting point for a walking-and-chauffeuring-to-school virtuous circle as parents always want the best for their children.

Since the inception of the first WSB in Canada introduced by David Engwicht in 1992 (Neuwelt and Kearns, 2006; Kingham and Ussher, 2007), this simple concept of involving a number of pupils walking to school supervised by one or more adults has been recognised as a powerful instrument (Nikitas et al., 2019; Perez-Martin et al., 2018). Evidence from many studies has shown that the implementation of WSBs can bring a wide range of benefits, namely, physical exercise, social skills, improved learning and traffic reduction (see e.g. Collins and Kearns, 2005, 2010; Heelan et al., 2008; Kearns et al., 2003; Kong et al., 2009; Neuwelt and Kearns, 2006; Paquette, 2007).

In particular, modal shift from parents' driving their children to joining a WSB scheme will generate plausibly a *full* range of benefits, i.e. from traffic reduction induced by the modal shift to the wider health benefits from increased physical activities as well as the development of social skills from the full experience. Kelly and Fu (2014) have shown that WSB schemes can be a functional substitute for chauffeuring, which might also help reduce parental time constraints for their own journeys to work (McDonald, 2008). WSB schemes potentially can be a promoter that work for both the parents and the school children. For parents, they may be able to consider modal shift from driving to other modes of transport, e.g. public transport, ride-sharing, cycling, after being *released* from chauffeuring. For children, walking to school might become *normal* to them and they would make the same decisions for their own children in the future.

Sims and Bopp (2020) highlight that children's habits are often similar to those of their parents, finding direct correlations between parental active transport (AT) rates and children's active school travel (AST) rates. They also found direct correlations between lower parental Body Mass Index (BMI) and increased AST for children, as a result of the increase in physical exercises during travel. Kotoula et al. (2021) also found that parental attitudes affect the rates of AST in children, and that children who partook in AST were more likely to undertake AT in their wider lives. Making the modal switch from chauffeuring their children to school to let (or even incentivise) them join a WSB programme might have a prolonged positive snowball effect for generations.

1.5. Research questions

To help us identify the target zones for WSB scheme development, we deploy an aggregate and spatial approach to answer the following research questions:

1. What are the factors driving the current (and future) uptake of walking to school for different areas?

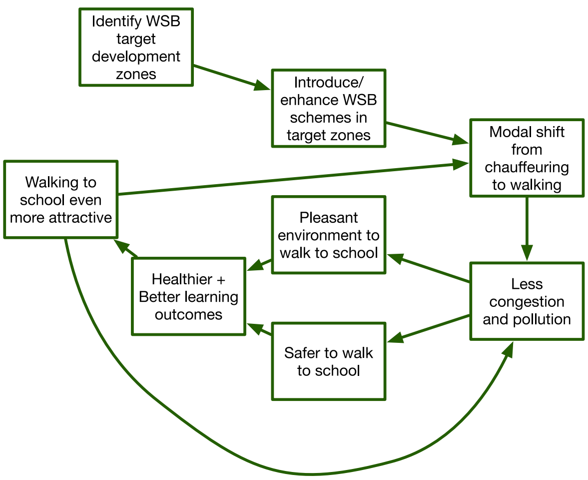

Fig. 2. Breaking the chauffeuring-and-walking-to-school vicious circle.

2. What are the factors deterring the modal shift from being chauffeured to walking to school for different areas?
3. If we were going to select target areas to promote WSB schemes, how can we identify the area(s) to which WSBs can be the most effective as a policy instrument aiming to increase modal shift?

1.6. Organisation of the paper

This paper is organised as follows. Section 2 introduces our two-stage Spatial Multi-Criteria Decision Analysis (SMCDA) model developed to answer the research questions. The study area, Bradford, West Yorkshire, UK, is introduced in Section 3.1. Stage 1 of the model development process is presented in Section 3.2, where influencing factors on the current school trip mode choice patterns are determined by spatial and regression analyses. Section 3.3 presents the Stage-2 SMCDA model in which Pareto frontier analysis is performed to help identify the zones where WSB schemes will have the highest potential as a promoting mechanism for modal shift from being driven to walking to school. Finally, Section 4 concludes the paper discussing our contribution to the state of the art, presenting a reflective commentary and future research and highlighting pro-WSB policy adjustments.

2. A Spatial Multi-Criteria Decision Analysis (SMCDA) approach

2.1. Understanding parents' decisions with a spatial aggregate approach

Our goal is to develop a decision support tool to help locate target development zones for WSB schemes, where WSBs will have the highest potential to help parents make the modal shift from chauffeuring their children to school to having them joining a local WSB scheme.

The complexity of parents' mode choice decision for school trips has been well recognised. For some parents, especially for those who are in full-time employment, this would be a joint work-and-school-trip decision. Deka (2013) applied the Heckman approach (Greene, 2012) to address the joint nature of the decisions by introducing simultaneous equations, representing the possible causal relationship between the work trip and school trip mode choice decisions. Ermagun et al. (2015); Ermagun and Samimi (2018) applied a nested Logit model to jointly consider mode choice and escort decisions. The results from both methods have shown that if a parent decided to escort a child to school, their transport mode choice may well be a private car. Another interesting finding in Deka's study is that the influence is one-way, i.e. there is evidence to suggest that parents' work mode choice affects the children's but not vice versa. Potoglou and Arslangulova (2017) found that children's age, mother's unavailability and home ownership were negatively associated with active travel to school, while Mehdizadeh et al. (2017) found that perceived walking time to school, mother's driving license, car ownership, access to public transit were the factors that define pro-walking to school decision-making.

2.2. Overview of a two-stage analytical model

In this paper, we demonstrate a two-stage process developed to answer our research questions:

2.2.1. Stage 1 – Understanding influencing factors on current mode choice patterns

We apply spatial and linear regression analyses on school-based mode choice and zone-based work trip mode choice and demographic data, to understand the most influential factors that have been driving parents' mode choice decisions.

2.2.2. Stage 2 – Identify WSB target development zones to facilitate modal shift

Based on the influential factors identified in Stage 1, we develop a multi-objective spatial decision analysis (SMCDA) model to identify target zones where WSB schemes might bring the highest effectiveness as a mechanism promoting modal shift from being chauffeured to walking to school.

2.3. Stage-1 Model – Spatial and linear regression analyses

There is a rich literature on the econometric analysis of school trip mode choices. As highlighted earlier, the decision-making around the school commute is often strongly influenced by the parents and made jointly with their own work travel choices. To model such complex decision processes, econometric analyses on school mode choices have been conducted based on disaggregate data typically collected by surveys designed for specific purposes, enabling specific forms of discrete choice models (see a comprehensive review in Ermagun et al., 2015) such as classical binary or MNL Logit (Deka, 2013; Kelly and Fu, 2014; Mitra et al., 2010), nested Logit (Ermagun et al., 2015; Ermagun and Samimi, 2018; Ewing et al., 2004; Hasnine et al., 2018), crossed-nested Logit (Hasnine et al., 2018), and mixed-Logit (Helbich et al., 2016; Noland et al., 2014) models to be applied.

The purpose of this study is to identify target zones where WSB scheme development will have the highest potential to *boost* the modal shift from chauffeuring children to joining a WSB scheme. Parents' own work trip mode choices might have influenced their decisions to chauffeur their children (Deka, 2013). Offering WSB schemes, as a substitute for dropping off their children enroute to work, might help parents to be released from chauffeuring, so that they might then have the opportunity to reorganise their own route choice or even mode choice to work.

For this specific purpose, an aggregate approach based on zonal characteristics is needed as we will need to see a broader spatial picture of the influencing factors that have led to the current school trip mode choices. In particular, what factors might have positive influence on zones with high walking mode shares, and in contrast, what factors might have deterred children from walking and favouring them to be driven instead.

Our study approach is to first utilise the findings from the literature to identify the potential influencing factors. We then collect zonal aggregate data on the relevant factors or their proxy variables, including car work trip mode share data as a proxy variable representing the aggregate influence of parents' own mode choices for work within each zone.

We apply a binary aggregate Logit model in this case as in Equation (1),

$$P_m = \frac{1}{1 + e^{-Z_m}} \tag{1}$$

where P_m is the proportion or probability of pupils using mode m, i.e. mode share of mode m; and Z_m represents the attractiveness of mode m.

Based on a binary Logit model, i.e. the probabilities of choosing mode m being P_m and not choosing mode m being $1 - P_m$, we apply a Logistic regression model as in Equation (2), for the two main mode choices for school commute ($m = 1, 2$), i.e. walk and car (being driven), respectively. Please note that the mode choice of *being driven* for school trips is labelled as *car* herein and onwards.

$$\ln \frac{P_m}{1 - P_m} = Z_m = \lambda_0 + \lambda_1 X_1 + \lambda_2 X_2 \ldots + \lambda_n X_n + \varepsilon_m \tag{2}$$

where X_i's ($i = 1, 2, \ldots, n$) are the potential explanatory variables, i.e. the zonal factors/proxy variables as identified in Table 1.

Equation (2) is applied for all possible subsets of the potential explanatory variables, where highly correlated variables are treated in a mutually exclusive manner. For example, school density & population density might be highly correlated with each other and they will not be included in the same equation. The best fitted models for the two modes, i.e. walk and car, are determined in a forward stepwise process.

To assess the impact of each explanatory variable on mode shares, ΔP_m is calculated to represent the absolute increase on mode share m from a 10% increase over the mean value of each explanatory variable, holding the remaining variables constant. The percentage increase $\%\Delta P_m$, measuring mode share (in)elasticities, can also be calculated based on Equations (3)–(5), for X_1 as an example.

$$\Delta P_m = \lambda_0 + \lambda_1 X_1' + \lambda_2 X_2 \ldots + \lambda_n X_n + \varepsilon_m - P_m \tag{3}$$

where

$$X_1' = 1.1 X_1 \tag{4}$$

$$\%\Delta P_m = 100 \times \frac{\Delta P_m}{P_m} \tag{5}$$

2.4. Stage-2 Model – Spatial multi-criteria decision analysis

2.4.1. Rationale of MCDA in WSB target development planning

The complexity of parents' decision making process in planning for their work trips as well as for their children's school trips has been well recognised. They would have to consider their own criteria, tradeoff the pros and cons of different alternatives, and choose the mode for work and school trips that they consider the *best* for themselves and for their children. In effect, each household would have performed their own multi-criteria decisions. As a result, we end up with mixed mode choices, which vary spatially from one zone to another, and from one household to another within the same zone. Our approach is to look at the current mode choices made by parents as the outcome of their own multi-criteria decisions, and then apply a multi-criteria decision analysis (MCDA) approach to address what some of the parents might need, i.e. to offer a WSB scheme as an attractive alternative to enable the modal switch from chauffeuring their children to joining a WSB scheme. Our goal is to perform MCDA spatially and identify the target zones where introducing or strengthening existing WSB schemes might be needed to help the parents to make this modal shift.

Table 1
Zonal influencing factors/proxy variables at MSOA level.

Zonal factor/Proxy variable	Measure (units)	Data source
School density	Schools per km^2	Census 2011
Population density	Population per km^2	Census 2011
School age population	Proportion of population aged 5–11	Census 2011
Crime rates	Monthly crime rate	West Yorkshire Crime Data 2020
Road accident rates	Yearly road accident rate	Road Safety Data Stats19 2017
Car ownership	Cars per household	Census 2011
Household income	Weekly household income	Census 2011
Gender proportions of employed population	Proportion of employed population that is male/female	Census 2011
Work trips by car	Proportion of work trips by car	Census 2011

2.4.2. *Pareto frontier analysis*

Pareto frontier analysis is a technique in MCDA, most often applied in multi-objective optimisation, to identify what might be the set of efficient solutions in terms of multiple criteria. With this technique, an *efficient* set of solutions known as the Pareto frontier solutions can be identified. For example, Latinopoulos and Kechagia (2015) applied multi-objective optimisation to identify suitable sites for wind farms in Greece based on a spatial MCDA model.

In this study, once we have identified the factors with significant influence on parents' mode choice between driving and walking their children to school, we may apply Pareto frontier analysis in an innovative manner to assess the potential of different zones within the study area. The factors that we have identified from Stage-1 will become the criteria. For instance, if high school density is one of the significant variables favourable for walking instead of driving, school density will become one of the criteria. Similarly, we may find low modal share of car work trips as another significant factor. The idea is that zones at the *frontier* are the ones with relatively high school densities and low car work trip modal shares. They would have high proportions of walking trips to school already.

Our innovation is that we are looking for zones *near* the frontier rather than ones *at* the frontier because these are the zones with relatively favourable conditions for walking, yet they are not performing as well as the frontier ones. These would be the target areas where WSB schemes may be most effective in enabling modal shift and thus achieving wellbeing, inclusion and environmental benefits.

3. A case study

3.1. *The study area – Bradford*

3.1.1. *Bradford's reliance on cars and the associated air quality issues*

Bradford is the second largest city in West Yorkshire, after Leeds, with an estimated population size of 534,300 in the Bradford area, as compared with 780,000 in Leeds (Office of National Statistics, 2017). Based on analysis of the Census 2011 data, car is the dominating mode of transport for work trips, with over 60% mode share in the region. In contrast, as shown in Fig. 3, walking is the main mode for primary school trips with a mode share of 66%. As shown in Fig. 4, there is a big variation in the mode shares of being driven to school in the range of only 7% to up to 64%. In contrast, walking to school has a mode share of a minimum of 33% to up to 93%. This means that there is a possibility of over 90% of primary school children within a zone suffering from the vehicle emissions generated by traffic constituting 35%–76% of the mode share of work trips. This has significant implications on those who choose to walk to school (or work) within the Bradford area, especially in terms of the exposure to air pollutants generated by both work and school traffic.

Bradford is one of the eight cities in the UK with planned Clean Air Zones (CAZ) (Bradford Council, 2021), where a charge for entering the zone will be set to discourage the use of older, more polluting vehicles from entering the zone. It is notable that Bradford has already been identified as having air pollution and congestion problems affecting school travels in previous studies (Ahern et al., 2017; Dirks et al., 2016; Nikitas et al., 2019). Introducing CAZ in Bradford hopefully will help improve air quality. WSB schemes can work hand-in-hand with schemes such as CAZ to promote the desirable modal shift and increase walking mode share for both work and school trips.

3.1.2. *Schools in Bradford and the school trip mode choice data*

Within the 61 Middle layer Super Output Area (MSOA) zones of Bradford, there are a total of 210 educational institutions, as shown in Fig. 5, and 161 of these teach primary school years (58,398 pupils), as shown in Fig. 6. We focus on these pupils, aged 5–11, due to their extreme susceptibility to parental influence when travelling to school. It is at these ages that parents would have the predominant role in mode choice decisions for their children, and hence this is the group that should be targeted for a modal shift from being driven to walking. Encouraging children at this age to walk to school using WSBs maximises the learning potential for the children, improves the potential for further growth of uptake in the schemes, and maximises the years ahead in which the children may convert to increased use of AT in day-to-day life (Kearns et al., 2003; Kotoula et al., 2021; Sims and Bopp, 2020).

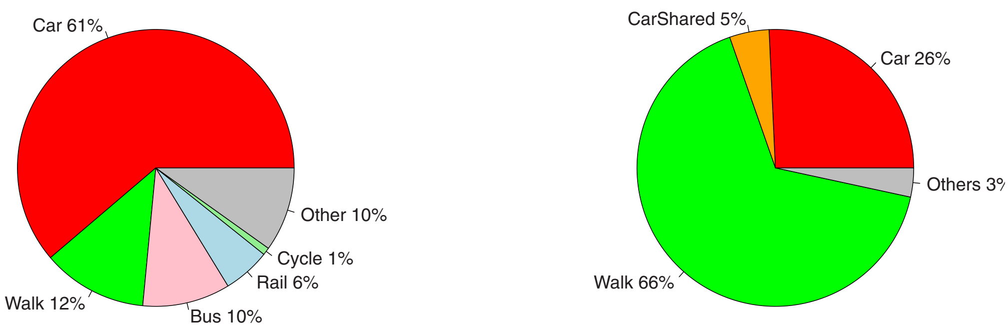

Fig. 3. Work & School trips mode shares in Bradford.

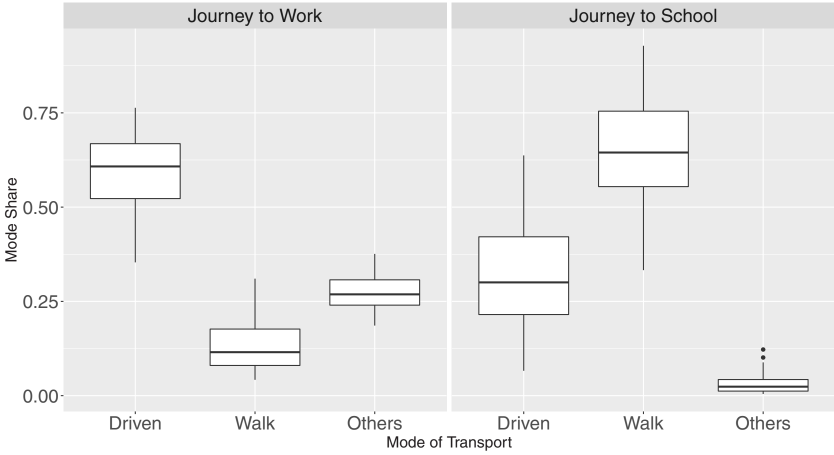

Fig. 4. Variations of work & school trips mode shares in Bradford.

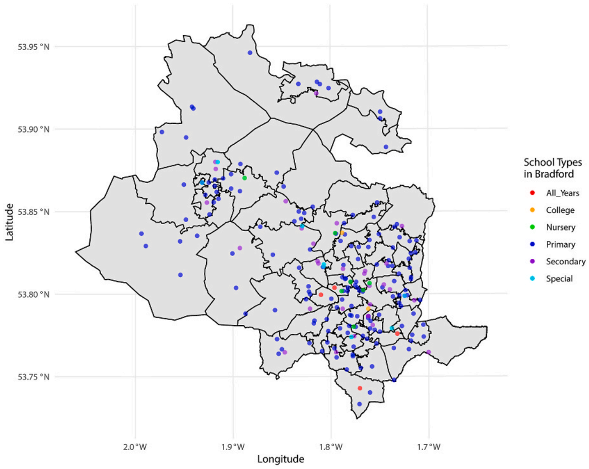

Fig. 5. Overview of Bradford study area and all school locations.

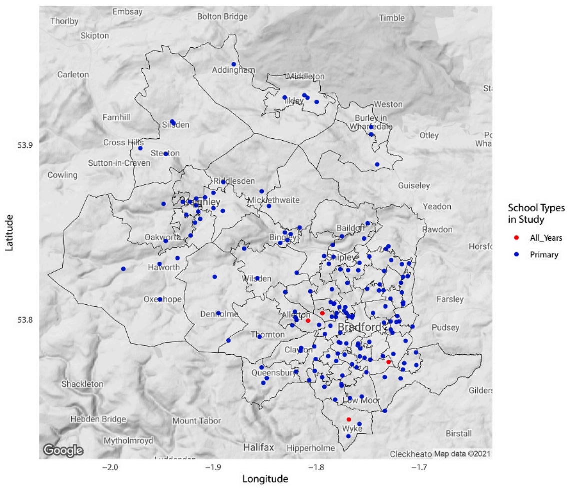

Fig. 6. Overview of Bradford study area and primary school locations.

The locations of the schools for children aged 5–11, as shown in Fig. 6, are predominantly clustered in the city area of Bradford and the towns of Keighley and Shipley. Demographic data for all of the 61 MSOA zones are available from the 2011 Census, which also collected data on the mode of transport used by each household for their children to get to school. The sources of travel mode choice data for this study include: (1) aggregate school trip mode choice data by school provided by Born in Bradford (2016); and (2) aggregate work trip mode choice data for West Yorkshire by MSOA zone provided by Leeds City Council. Based on the school locations of the 161 selected schools, the school trip mode choice data was then further aggregated into MSOA zones, allowing all spatial analyses to be performed based on MSOA zoning level.

3.1.3. Interdependence between work and school trips

It has been commonly identified in the literature that there is a strong interdependence between school trip and work trip mode choice, with many parents opting to combine the two to suit their schedules, particularly if this combination involves the use of a private car (Ahern et al., 2017; McDonald and Aalborg, 2009). It is therefore unsurprising that, in Bradford, there was found to be a correlation between zones where people commonly drove to work and children were commonly driven to school. A moderate correlation factor of 0.60 is found between the proportion of trips to school and work made by car; and the corresponding correlation factor for walking trips to school and work is also moderate at 0.50.

The mapping of mode shares as shown in Fig. 7 is geographically logical, with the cities and towns in the region showing lower rates of work trips and school trips being made by car, whilst the rural areas of Bradford showing the reverse trend.

3.2. Stage-1 Model – Spatial and linear regression analyses

3.2.1. Potential influencing factors and proxy variables

In order to represent spatially the possible influences of these factors affecting parents' mode choice and escort decisions, the following zonal factors/proxy variables, as depicted in Table 1, have been identified and data has been collected from secondary sources at MSOA levels for the study area.

3.2.1.1. Safety concerns & escort decisions. Safety concerns, including traffic incidents, stranger danger and local air pollution are the major barriers to many parents around the world for committing to a WSB scheme (Nikitas et al., 2019). These concerns have had a major impact on their decisions about school travel mode choice and whether they will escort their children (see e.g. Ahern et al., 2017; Aranda-Balboa et al., 2020; Curtis et al., 2015; Hsu and Saphores, 2014; Huertas-Delgado et al., 2017; Mammen et al., 2012; Palma et al., 2020; Scheiner et al., 2019; Smith et al., 2019; Waygood and Susilo, 2015). Some parents choose to escort their children by chauffeuring them to school, while some choose to accompany their children to walk to school together (Babb et al., 2017; Ermagun and Samimi, 2016; Hastie, 2007; McDonald and Aalborg, 2009).

3.2.1.2. Distance to school, parent and car availability. Distance is another key factor that determines whether walking is feasible at all for both the parents and their children. A reasonable walking distance has been found to be within 2 km (Ermagun et al., 2016; Kelly and Fu, 2014). However, living within walking distance does not mean that parents can be available to walk to school with their children. Having an unemployed parent in the household has been considered as a significant influencing factor facilitating the decision to walk to school; on the contrary, parents' own mode choice to drive to work and the number of cars owned by a household have been found to have a negative impact and possibly enhance the choice of escorting children by car (Ermagun and Samimi, 2016; Kelly and Fu, 2014; Kontou et al., 2020; McDonald and Aalborg, 2009; Sims and Bopp, 2020).

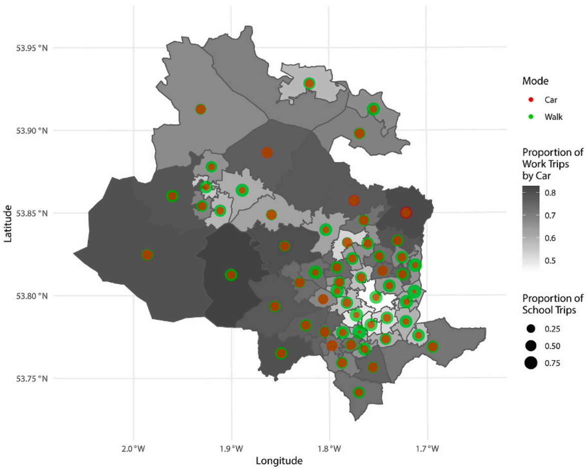

Fig. 7. Work trips by car versus school trips mode shares.

3.2.1.3. School density, population density. Higher school or population density would reduce distance to school and hence increase school accessibility, which might have a positive influence on walk-to-school mode share (Ahern et al., 2017; Mammen et al., 2012; McDonald and Aalborg, 2009).

3.2.1.4. School age population, crime rate, traffic incident rates. Higher school age population would embrace a safer environment for children reducing both traffic and stranger danger that might be perceived as they would be more visible to everyone, in particular, to drivers. On the contrary, higher crime rate and/or traffic incident rates might deter parents from walking to school (Mammen et al., 2012; Neuwelt and Kearns, 2006; Scheiner et al., 2019; Shamshiripour et al., 2020). Therefore, a higher proportion of school age population might have positive effect on the overall zonal walk-to-school mode share, while higher crime and/or traffic incident rates might lead to a lower overall share.

3.2.1.5. Car ownership, household income, gender proportions of employed population, work trips by car. Higher car ownership and/or household income might lead to higher chances of parents choosing to drive and drop off their children to school, leading to high traffic intensity and traffic incident rates, which will deter walking to school (McDonald and Aalborg, 2009; Nikitas et al., 2019; Scheiner et al., 2019). Depending on the household structure and car availability, gender of employed population and work trips by car might have influences on the overall zonal walk-to-school mode share (Kotoula et al., 2021; McDonald and Aalborg, 2009; Sims and Bopp, 2020).

3.2.2. Spatial analysis & regression analysis – walking school trips

3.2.2.1. AST in areas with many children. Within the three models identified for walking school trips, Model (i) to (iii) in Table 2, it is abundantly clear that the School Age Population variable has a significant impact on the number of trips made on foot in Bradford. Whilst the R^2 values being slightly low means these models cannot entirely explain the trips completed, the percentage changes to mode share affected by increasing the variable represent a consistent finding. An increase in School Age Population of 10% inducing a 5–7% increase in share of school trips completed on foot is consistent with the findings of other authors, particularly suggesting that a safety in numbers trend can be seen (Ahern et al., 2017; Kotoula et al., 2021; Neuwelt and Kearns, 2006). Further to this, it suggests a reliable uptake in WSBs would be possible in areas with more school children, addressing previous concerns that WSB schemes are often hindered by uptake (Carlson et al., 2020; Kearns et al., 2003; Nikitas et al., 2019). The models finding a clear relationship to the School Age Population variable is further supported by the spatial analysis as demonstrated in Fig. 8. The areas with far more children aged 5–11, centred in the city of Bradford and the town of Keighley, also demonstrate a far higher proportion of school trips completed on foot, allowing confidence in the increased uptake of AST in areas with more young children.

3.2.2.2. The expected impact of car trips on AST. As highlighted earlier, as shown in Fig. 7, an inverted trend is seen in the geographic distribution of mode shares and Work Trips by Car. Areas that are more rural, and have lower rates of AST, are clearly correlated to areas that have higher proportions of trips to work completed by private vehicle. In particular, inner city Bradford has by far the lowest share of work trips completed in private vehicles, whilst having many of the highest shares of AST. With existing literature findings suggesting that there is an elevated chance a child is driven to school if their parents drive to work (Ahern et al., 2017; McDonald and Aalborg, 2009), it is unsurprising that there is a strong correlation between Work Trips by Car and AST. The regression results for Model (ii), as shown in Table 2, indicate a sizeable change in AST rates when the proportion of work trips completed by car fluctuates. A 10% increase in Work Trips by Car results in a 4.2% reduction in AST within the model, and shows how the impact of parental decisions is so fundamental in the routines of school aged children. Previous findings that the AST and AT rates of children are heavily linked to the decisions of their parents mean this finding was expected, but one that is still important to address (Kotoula et al., 2021; Sims and Bopp, 2020).

3.2.2.3. A maternal effect on AST. Finally, the impact of working or non-working parents is seen to have another effect on AST in

Table 2
The best fitted regression models for walking school trips.

Model	Variables	Estimate	Standard Error	t Value	p Value	ΔP_i	$\%\Delta P_i$	R^2	Adjusted R^2
(i)	Intercept	−1.396	0.340	−4.070	0.000	–	–	0.400	0.390
	School Age Population	19.432	3.130	6.200	0.000	0.042	6.466		
(ii)	Intercept	0.218	0.850	0.260	0.800	–	–	0.440	0.420
	Work Trips by Car	−1.808	0.870	−2.070	0.040	−0.027	−4.150		
	School Age Population	15.703	3.540	4.440	0.000	0.034	5.251		
(iii)	Intercept	−2.509	0.650	−3.840	0.000	–	–	0.440	0.420
	School Age Population	15.340	3.690	4.160	0.000	0.033	5.141		
	Proportion of employed population that is male	2.773	1.400	1.990	0.050	0.032	4.962		

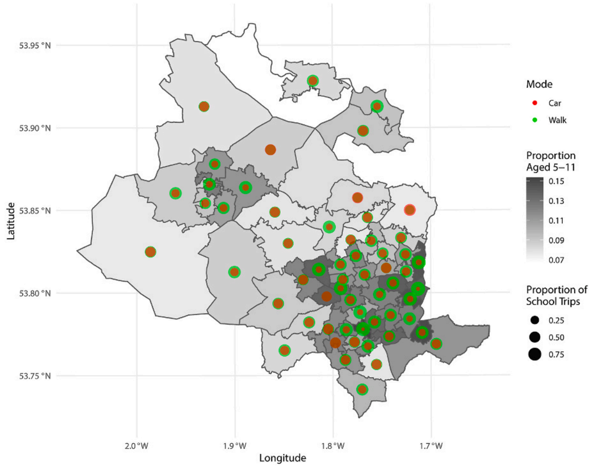

Fig. 8. Comparison of school aged population and school trip mode share in Bradford.

Bradford based on the gender of the parents. Akin to the findings from Figs. 7 and 8, Fig. 9 shows that the Gender Proportions of Employed Population is one of the variables that has an extremely clear correlation to school trips in Bradford. Parents' employment status and their availability to drop off or walk their children to school can have an impact on these trips (He and Giuliano, 2017; Rafiq and Mitra, 2020; Scheiner et al., 2019; Singh and Vasudevan, 2018), with areas that are dominated by male employees seeing substantially higher rates of AST. Model (iii) as shown in Table 2 has shown an increase in AST rates of 5.0% when there is a 10% increase in the Male share of the Gender Proportions of Employed Population variable. It is suggested that this might be linked to the historical stereotype that mothers are more likely to impact their child's school trip mode choice than fathers (Scheiner et al., 2019; Singh and Vasudevan, 2018).

3.2.3. *Spatial analysis & regression analysis – car school trips*

3.2.3.1. A reversed trend for car versus walking trips. Critically, Table 3 presents us with six models that all contain at least one of the variables that are prominent in the walking trip models in Table 2. Gender Proportions of Employed Population, Work Trips by Car and School Age Population all appear consistently in the models for trips to school by car and on foot, which is further to their clear geographical trends discussed in Section 3.2.2. Since walking and car are the two main transport modes for school trips in all of Bradford, Figs. 7, 8 & 9 present a reversed trend for car school trips as compared to walking trips, which would be expected: increases in numbers of jobs filled by men and increased numbers of children aged 5–11 cause school trips by car to fall, whilst increasing the proportion of work trips undertaken by car causes the number of school trips by the same mode to increase.

3.2.3.2. Mode share elasticities. The impacts of the variables are seen to be even more sizeable on the car mode share than they were on the walking mode share, with 10% increases in male Proportion of Employed Population and School Age Population causing falls in car

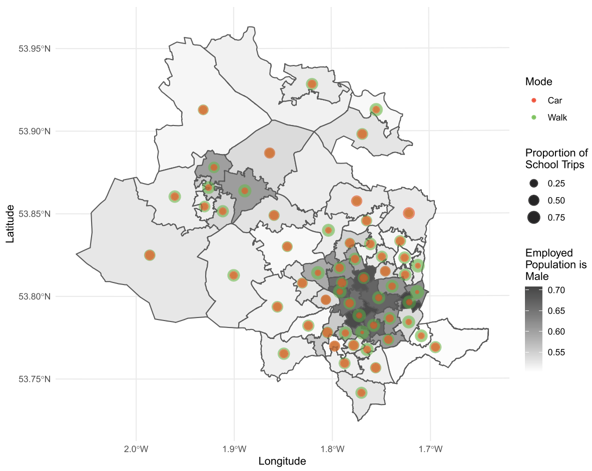

Fig. 9. Comparison of male proportion of employed population and school trip mode share in Bradford.

Table 3
The best fitted regression models for car school trips.

Model	Variables	Estimate	Standard Error	t Value	p Value	ΔP_i	$\%\Delta P_i$	R^2	Adjusted R^2
(iv)	Intercept	0.972	0.350	2.790	0.010	–	–	0.390	0.380
	School Age Population	−19.317	3.190	−6.060	0.000	−0.035	−12.874		
(v)	Intercept	−0.346	1.040	−0.330	0.740	–	–	0.400	0.380
	Cars Per Household	1.106	0.320	3.450	0.000	0.022	8.256		
	Proportion of employed population that is male	−3.341	1.460	−2.290	0.030	−0.033	−12.045		
(vi)	Intercept	−4.168	0.530	−7.830	0.000	–	–	0.400	0.380
	Household Income	0.002	0.000	2.340	0.020	0.021	7.783		
	Work Trips by Car	2.978	1.010	2.940	0.000	0.040	14.669		
(vii)	Intercept	−1.499	0.820	−1.83 0	0.070	–	–	0.480	0.470
	Work Trips by Car	2.768	0.840	3.280	0.000	0.037	13.516		
	School Age Population	−13.608	3.420	−3.97 0	0.000	−0.025	−9.194		
(viii)	Intercept	−3.064	0.650	−4.710	0.000	–	–	0.420	0.400
	Work Trips by Car	3.371	0.870	3.860	0.000	0.045	16.661		
	Population Density	0.000	0.000	−2.700	0.010	−0.005	−1.780		
(ix)	Intercept	2.192	0.660	3.320	0.000	–	–	0.430	0.410
	School Age Population	−14.828	3.730	−3.970	0.000	−0.027	−10.016		
	Proportion of employed population that is male	−3.042	1.410	−2.15 0	0.040	−0.030	−11.000		

trips to school by as much as 10–12%. This is similar to the sizeable 13–16% increases in school trips by car seen from a 10% increase in Work Trips by Car. These sizeable impacts on mode shares seen by three variables that have already proven significant in affecting school trips made on foot only further highlights why they are the key three variables to have significant influences on school trip mode choices in Bradford.

It is acknowledged that three other variables appeared in the models for school trips by car in Bradford, as shown in Table 3. However, Population Density, Household Income and Cars Per Household are seen to be variables that do not appear consistently and show less sizeable impacts on mode shares.

3.2.4. The three common zonal variables with highest influence

The corroboration of the variables found in spatial and regression analyses for walking and car mode shares shows Bradford's school trips to be following a number of trends already identified around the world as discussed above. Three common variables have been identified that give a good overarching picture of Bradford's demographics and characteristics and how they have affected the school commute mode choices of walking and car, as summarised in Table 4.

3.3. Stage-2 Model – Spatial Multi-Criteria Decision Analysis

From the spatial and regression analyses presented in Section 3.2, the zonal characteristics of higher school age population, lower work trips by car and higher proportion of male employed population have been found to have positive influences on zonal walking mode share in the study area of Bradford. These three variables are effectively proxy variables of zonal conditions favourable for walking to school, which have led to a relatively high walking mode shares. Higher school age population can provide a safer environment for walking as children would be more visible to drivers and the risk of stranger danger can be reduced. Lower work trips by car can provide a more present environment with lower traffic level, which also reduces traffic incident risks and improves air quality of the area. Higher proportion of male employed population means a lower proportion of female, i.e. it is more likely that a female

Table 4
Zonal variables with highest influence on school trip mode shares.

Variable	Impact on mode share	
	Walking	Car
Proportion of School Age Population	+ve	–ve
Proportion of Work Trips by Car	–ve	+ve
Proportion of Employed Population that is Male	+ve	–ve

parent might be available to walk the children to school. All three conditions have been proved to have made walking to school an attractive alternative as opposed to chauffeuring the children to school for a lot of the parents in Bradford.

By using these three criteria spatially, we will be able to identify the *efficient* zones in the study area that have had non-dominated conditions for walking to school. It is anticipated that these zones would have had high walking mode shares already. The idea is to identify target zones that might have only slightly less superior condition(s) as compared with the *efficient* zones in terms of one or more of the three criteria. Offering WSB schemes in these target areas will have the highest potential to enable the desired modal shift to happen.

3.3.1. Bi-criteria Pareto frontier analysis

We perform bi-criteria Pareto frontier analysis for each of the three possible bi-criteria pairs, I, II & III, as depicted in Table 5. The three criteria are expressed such that a lower value would favour walking to school. Thus, zones at the Pareto frontier are expected to be in advantageous conditions for walking to school. This means that the Pareto frontier would be at the lower left corner, and this is also where the conditions would be the best for high walking mode shares. Our interest is to locate zones near the Pareto frontier within each graph, Figs. 10 and 11 & 12, where walking mode shares have the highest potential to increase by introducing WSB schemes.

3.3.2. Selection of WSB development sites with highest potential

3.3.2.1. Bi-criteria pair I. Fig. 10 shows Proportion of Work Trips by Car versus Proportion Employed is Female, where three *efficient* zones, i.e. MSOA zones 039, 042 & 044 in as shown in Table 6, have been identified. These zones are considered to be *efficient* in terms of the two criteria as there are no other zones with lower values of one criterion without sacrificing the other. The size of the dots in Fig. 10 represents the proportion of population at school age. The colour of the dots represent the current mode shares of school trips walking to school. As expected, all three dots are green with walking mode shares in the range of 0.781–0.851 in Table 6. To identify the target zones for WSBs, what we are looking for in Fig. 10 would be dots of moderate sizes (proportion of population at school age) in blueish green colour (moderate walking mode share) near the frontier (within the lower left quadrant).

In order to determine which zones are those of interest, it is necessary to set limits to the values that are considered suitable for sufficient uptake of WSB schemes for the three variables. As a result, the graphs in Figs. 10 and 11 & 12 have been divided into quadrants. The dividing lines are at the median points of the data, albeit rounded to the nearest tenth for clarity. Therefore, this creates a quadrant of the graphs in the lower left that is a high potential area for WSB implementation.

It becomes clear in Fig. 10 that the zones with a larger School Age Population and a position closer to the frontier generally present a higher walking mode share for school trips, as would be expected from our models. It is clear though that not all of the zones presenting these favourable conditions have walking mode shares as strong as would be expected. In particular, Fig. 10 highlights the disparity between zones 034, 041, 053 and those with similar characteristics. Most zones with similar characteristics present walking mode shares of 0.8 and 0.9, whilst these three zones exhibit mode shares of 0.5 and 0.6. It is this disparity that shows the potential the zones have for improved walking rates, given the popularity of walking in locations with similar characteristics. Five potential zones are identified in this manner, as highlighted in Fig. 10, and their zonal characteristics are summarised in Table 7. By implementing WSB schemes in the five potential zones (007, 033, 034, 041 & 053) where these favourable conditions exist, it is hoped that the parents and children will receive the encouragement required to shift these mode shares towards the improved AST rates seen elsewhere.

3.3.2.2. Bi-criteria pair II. Fig. 11 presents Proportion of Work Trips by Car versus Proportion of Population Not School Aged. Based on the same principles, there are four efficient zones, i.e. MSOA zones 039, 048, 051, & 052, as shown in Table 6. The size of the dots in Fig. 11 represents the proportion employed is male; and the colour of the dots represents the mode share of walking school trips. Three out of the four frontier dots are green, i.e. they have high mode share in the range of 0.781–0.916, while Zone 052 has the lowest share of 0.746 walking to school.

To identify the target zones for WSB in Fig. 11, we would also be looking for dots of moderate sizes (the proportion employed is male) in blueish green colour (moderate walking mode share) near the frontier (within the lower left quadrant). We have identified six zones in this case, i.e. one more potential zone (009) as compared to the five identified in Fig. 10, as shown in Table 7.

Zone 009 represents a zone that does not appear in the high potential area in Fig. 10, due to its middling value for male Proportion of Employed Population at around 56%; in Fig. 11 it becomes clear that this zone is still one of the zones most suitable for high walking rates, with this male Proportion of Employed Population being in the upper half, the School Age Population being one of the highest zonal proportions, and the Work Trips by Car variable being the sixth most favourable in Bradford. Therefore, with a walking rate of

Table 5
Bi-criteria Pareto frontier analysis.

Variable	Bi-criteria pair		
	I	II	III
Proportion of Employed Population is Female	$x-$ axis	–	$y-$ axis
Proportion of Population Not School Aged	–	$x-$ axis	$x-$ axis
Proportion of Work Trips by Car	$y-$ axis	$y-$ axis	–
Graph	Fig. 10	Fig. 11	Fig. 12

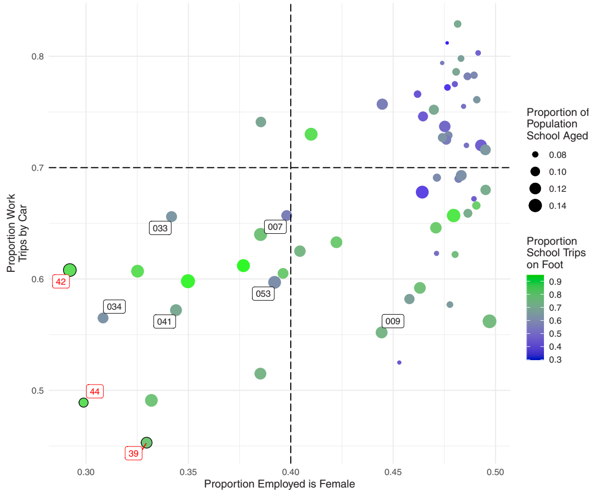

Fig. 10. Proportion Work Trips by Car vs Proportion Employed is Female.

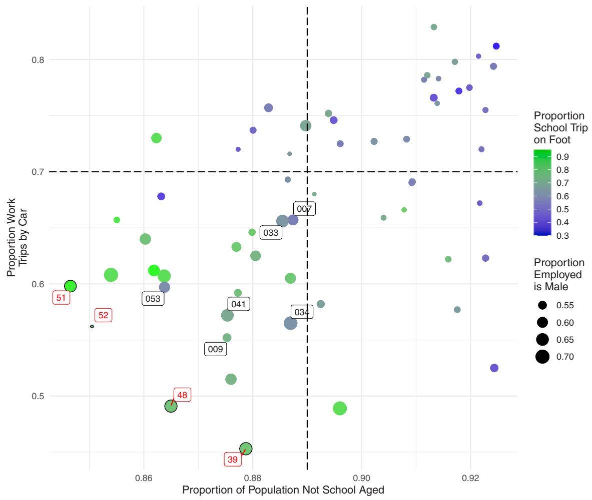

Fig. 11. Proportion Work Trips by Car vs Proportion of Population Not School Aged.

0.73, the zone is still identified as one in which walking can be further encouraged. This is in line with the findings of Carlson et al. (2020); Tresoldi et al. (2021), that there are issues around uptake for WSB schemes, and the findings of Neuwelt and Kearns (2006); WSB schemes help to improve neighbourhood safety and lead to a snowball effect in usage. Zone 009 has the numbers of walking students to sustain a WSB scheme already, whilst showing the potential to capitalise on further uptake in the future.

3.3.2.3. Bi-criteria pair III. Finally, the graph of Proportion Employed is Female versus Proportion of Population Not School Aged is depicted in Fig. 12. Two efficient zones have been identified, i.e. MSOA zones 042 & 051 as shown in Table 6. The size of the dots in Fig. 12 represents the proportion of work trips on foot and the colour of the dots represents the mode share of walking school trips.

By applying the principles of choosing those near the Pareto frontier with higher walking work trip mode shares and moderate mode share of walking trips to school, the same five potential zones (007, 033, 034, 041 & 053) as identified in Fig. 10 are also good target zones for WSB scheme development in Fig. 12, as shown in Table 7.

The characteristics of Zone 033 become clearer as an area for attention in Fig. 12. Having appeared in fringe positions in Figs. 10 and 11, the zone is much more obviously inside the high potential area here. Despite its lower walking rate than zones with similar characteristics in Fig. 12, Zone 033 does present one of the highest rates of male employees in Bradford and a notable School Age Population, which should help to encourage WSB uptake and improve its walking mode share.

Fig. 12 highlights another zone of interest; Zone 007, for the third time, appears near the very centre of the graph, narrowly inside the high potential area on all three occasions. Whilst these middling values for all three variables do not, in themselves, make the zone remarkable, it does highlight that the zone has some potential in all areas. This, combined with a notably reduced walking rate to school of 0.564, mean the zone still has room for a significant improvement in walking mode shares. With the rounded characteristics

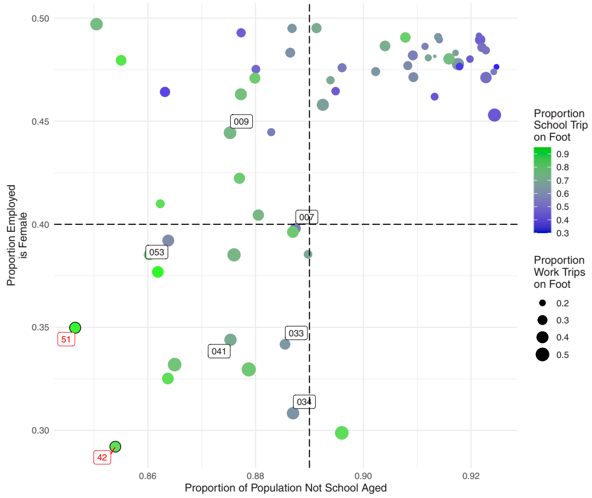

Fig. 12. Proportion Employed is Female vs Proportion of Population Not School Aged.

Table 6
Pareto frontier zonal characteristics.

Bi-criteria Pair	MSOA Zone at frontier	Work Trips by Car	School Age Population	Gender of Employed Population is Male	Car Trips to School	Walking Trips to School	Other Trips to School
I, II	Bradford 039	0.453	0.121	0.670	0.157	0.781	0.062
I, III	Bradford 042	0.608	0.146	0.708	0.124	0.850	0.026
I	Bradford 044	0.489	0.104	0.701	0.110	0.851	0.039
II	Bradford 048	0.491	0.135	0.668	0.167	0.772	0.061
II, III	Bradford 051	0.598	0.153	0.650	0.053	0.916	0.031
II	Bradford 052	0.562	0.150	0.503	0.155	0.746	0.099

Table 7
WSB target zone characteristics.

Bi-criteria Pair	Target Zone for WSBs	Work Trips by Car	School Age Population	Gender of Employed Population is Male	Car Trips to School	Walking Trips to School	Other Trips to School
I, II, III	Bradford 007	0.657	0.113	0.602	0.143	0.564	0.293
II	Bradford 009	0.552	0.125	0.556	0.135	0.728	0.137
I, II, III	Bradford 033	0.656	0.115	0.658	0.279	0.639	0.082
I, II, III	Bradford 034	0.565	0.113	0.692	0.252	0.625	0.123
I, II, III	Bradford 041	0.572	0.125	0.656	0.251	0.691	0.058
I, II, III	Bradford 053	0.597	0.136	0.608	0.261	0.608	0.131

the zone shows, there is a lot of potential to be drawn on, such as plenty of children to take up WSB schemes, plenty of parents who do not drive to work, and fewer employed mothers; this final characteristic has repeatedly been shown to impact AST rates far more than reduced male proportion of employed population (Scheiner et al., 2019; Singh and Vasudevan, 2018).

3.3.3. Spatial distribution of WSB target development zones in Bradford

With the identification of six key zones in Bradford where walking school trips can be increased through the use of targeted WSB schemes, Fig. 13 presents the geographic distribution of the key zones within Bradford. It highlights the Pareto frontier zones and the zones in which WSB schemes should be targeted. Notably, the zones' locations follow similar trends to those seen in the mapping of the explanatory variables in Figs. 7, 8 & 9. The more densely populated urban centres, where School Age Population and male Proportion of Employed Population are higher and Work Trips by Car are less common have been identified as regions where increased AST rates are present. These Pareto frontier zones fall in the inner city, with the expected key criteria for children to walk to school. Meanwhile, a number of other localised areas of Bradford city and Keighley also present favourable values for the three variables of interest, albeit without the corresponding increased AST rates, and it is expected that the introduction of WSBs in these six zones will help to improve AST rates in Bradford as a whole.

The data for the six zones is also presented in Table 7, highlighting the characteristics that make these regions such strong candidates for WSB uptake. As is made clear by Figs. 10, 11 & 12, the data in each of Tables 6 and 7 is not dissimilar, with the zones in Table 7 lying close to the frontier itself. The most notable difference is the disparity in the walking rates of the two tables, with the

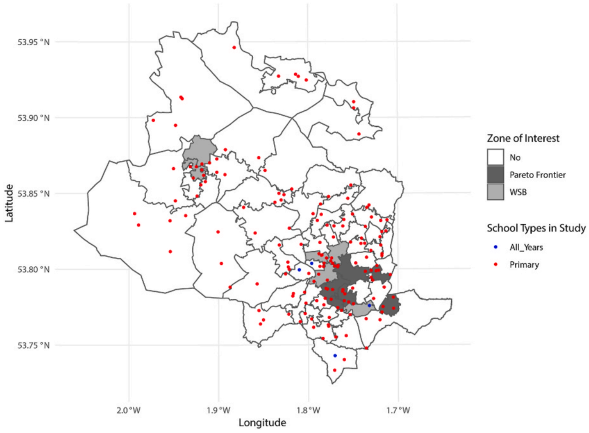

Fig. 13. Walking school bus target zones of interest.

zones of interest for WSB schemes predominantly experiencing walking mode shares of 0.55–0.65, a substantial drop from the rates seen in Table 6.

4. Discussion and conclusions

The key contribution of this paper is to propose a new two-stage SMCDA model to support WSB strategic development planning. The proposed model has been developed based on the essence of multi-objective nature in decision making for parents, planners and policy decision makers.

In Stage 1, the spatial and linear regression model has been built on the use of aggregate data to support strategic decision analysis for WSB planning in a quantitative and spatial manner. This gives the new model an advantage in terms of applicability since it is based on aggregate data, specifically MSOA zonal work and school trip mode choice data and demographic data from Census (2011), which is often readily available in many cities and less costly for data collection if such data is not available.

In Stage 2, by performing bi-criteria Pareto frontier analysis for different pairs of significant influencing factors, we are able to identify the benchmark of walking-to-school mode shares under the favourable conditions that have been offered. The innovation of looking into the sub-Pareto-frontier has allowed us to capture all zones with the highest potential in each graph. This new model, therefore, has opened a new application of SMCDA in an innovative manner, that can help achieve the purpose of this study effectively, i.e. to select the best target sites for WSB scheme development.

We demonstrate in this paper how this new model can be applied to a case study in Bradford, which is a deprived area in the UK where investments on policy instruments such as WSB schemes are much needed. Findings from our analysis are consistent with the literature, showing that the key factors identified are indeed factors with significant influences on walking-to-school mode shares in many other cities (see e.g. Carlson et al., 2020; Kearns et al., 2003; Nikitas et al., 2019; Scheiner et al., 2019; Singh and Vasudevan, 2018). The zones, whilst presenting characteristics that are found to be favourable for walking, also present favourable conditions for the uptake of WSB schemes. They have large numbers of school aged children, lower level of work trips by car and higher parents' availability, especially mothers, which has already been shown to be key, i.e. mother's unavailability is negatively associated with active travel to primary school (Potoglou and Arslangulova, 2017).

The method of SMDCA for WSB target development strategies developed in this study is, therefore, highly transferable to applications to other cities in the UK or around the world. In other words, this work has genuine applied value as an apparatus for supporting, informing and systematising the implementation of potentially successful (in engagement and usage terms) WSB schemes for urban planners that aim to support active travel to school as a sustainable ethos-building activity for societies looking to craft pathways to more liveable futures.

The strength of our model lies in the innovative application of SMCDA. We benchmark the performance by identifying the zones at the Pareto frontier analysis. Simultaneously it has enabled us to identify zones that are *near* the frontier, where introducing WSB schemes might be most effective in enabling modal shift and would be genuine generators of environmental, wellbeing and social inclusion benefits. However, the success of the Stage-2 SMCDA model depends on whether a representative set of influencing factors could be identified from the Stage-1 spatial and regression analyses. The use of aggregate data for the regression analysis conducted in Stage 1 has imposed limitations on the set of independent variables that might be included in each potential equation due to the high correlations between some of the potential independent variables. The methods developed for both stages are highly transferrable. At the same time we do acknowledge that linear regression analysis using aggregate data has a limit to what it can support. Further research could include primary data collection and more advanced econometric approaches.

Data availability

The authors do not have permission to share data.

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