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RESEARCH ARTICLE

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Walking school bus line routing for efficiency, health and walkability: A multi-objective optimisation approach

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Abstract

Walking School Bus (WSB) has been recognised as an innovative solution to promote walking to school, bringing a wide spectrum of benefits, including: health benefits from the physical exercise, social skills and traffic reduction. To facilitate the success of WSB, one vital element is its route planning, which directly affects the catchment for the service and the realisation of all the potential benefits. Previously, time has been the only factor that has been considered in WSB routing problems. Other important factors including air quality, safety and comfort will also be considered in this paper. Air quality along a WSB route is important to help realise the health benefits of walking. Traffic safety has been the biggest barrier to walking to school and must be addressed in planning a WSB route. Ensuring children have an enjoyable and comfortable experience is vital for the sustainability and success of WSB. A walking network is introduced to enable modelling pedestrian movements in detail, including walking movements on different sides of the road and crossing movements. This approach enables detailed route-based analysis to assess the localised effect of air quality on pollutant dose. We define walkability as a measure of children's needs in safety and comfort, which can also be assessed in detail on each route. We propose a multi-objective optimisation model to generate *efficient* WSB routes with three objectives representing the potential benefits of WSB: (1) to minimise time; (2) to minimise pollutant dose; and (3) to maximise walkability. We apply our model to a selected school in Bradford in the UK, generating three WSB lines following *efficient* routes. These lines go through a predetermined sequence of 'WSB Stops', with the final stop as the school. All children within the catchment area will be able to join a WSB within 1–2 min walk from their home to the nearest stop. Our multi-objective WSB route planning model is highly transferable to any selected school in any WSB targeted area. Planners will be able to select a combination of WSB lines to offer, based on the requirement of coverage area and resource availability.

KEYWORDS
multi-objective route planning, walkability, walking network, walking school bus

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1 | INTRODUCTION

1.1 | Motivation—urbanisation and its effect on children's health

Over the course of the last 50 years the world has modernised significantly. Intertwined with this modernisation are the various technological advancements, which are commonplace in today's society. Whilst the vast majority of these developments present a significant improvement to people's quality of life, they have also created a number of unforeseen consequences. Urbanisation is one phenomenon that has brought wealth and convenience for many but it also came with some detrimental effect on the environment and undesirable subsequent negative impact on public health (Nieuwenhuijsen, 2020). For instance, the development of the motorway network in the 1960s in developed countries might have led to a dominated strategy of road-oriented residential development, which in turn leads to urban sprawl. Urban sprawl might lead to longer distance (inactive) travel mostly in private vehicles; increase in vehicle emissions in turn might lead to poor air quality in some areas; deterioration of air quality and lack of physical activity might lead to poor health, which is an undesirable result one might have never anticipated.

Perhaps one particular group in our society that might suffer most from this phenomenon is the children, our next generation. Parents are facing challenges in their everyday life to get to work themselves as well as taking their children to school (Easton & Ferrari, 2015; Ferrari & Green, 2013). The increase in distance from the school and the increase in traffic in urban areas around the school have become the two major factors that gave parents the feeling of having no choice but chauffeuring their children to school (see e.g., Ahern et al., 2017; Mammen et al., 2012; McDonald & Aalborg, 2009; Smith et al., 2019). The modal share of walking to school has been declining (Hastie, 2007; McDonald & Aalborg, 2009; Schoeppe et al., 2016). Obesity and lack of physical activity have now become one important health problem affecting our quality of life and eventually will increase mortality of our next generation (Aubert et al., 2018; Hinckson et al., 2014; Nieuwenhuijsen, 2020).

1.2 | A global decline in walking to school modal share

Walking used to be the major mode for school trips. Let us look at some statistics of school trip modal shares around the world. Hastie (2007) cited some extreme statistics in the United States: 87% of children within a mile of their school walked or cycled in 1970; 37 years later this has turned ‘up-side-down’ that only 13% walk or bike to school in New York city. In the UK, the percentage of children walking to school decreased from 74% to 46% between 1975 and 2019, while those being driven increased from 15% to 47% (Department for Transport, 2020). In New Zealand, the number of children regularly driven to school has more than doubled in less than 10 years between 1989/1990 and 1997/1998 (Hinckson et al., 2011). Hinckson et al. (2011) cited that in Australia, 23% of school children (age 5–9 years) were driven to school in 1971 as compared to 67% in 2003; while 58% walked to school in 1971 versus only 26% in 2003. In this paper, we focus on the dichotomy between being driven to school and walking. While in other countries a significant number of primary school pupils may travel to school by other modes of transport, such as school bus (United States), public transport (Germany), these other modes are negligible in some areas in the UK. For example in Bradford, where the school we selected for the case study is located, 66% of primary school children walk to school and 31% are driven, see Hayes et al. (2022).

1.3 | The chauffeuring vicious circle

Traffic generated from children being driven to school has been found to contribute significantly to traffic congestion as well as vehicle emissions affecting air pollution in urban areas. For instance, experiments conducted by Yang et al. (2016) in Beijing comparing observations during school term time and non-school season have shown that both CO_2 emissions and pollutant concentration related to vehicle emissions are significantly higher during term time. Ferrying school children might have induced over 10% higher CO_2 emissions and higher average daily concentrations of HC, CO, NO_x & PM in the range of 6.3%–8.3% in Beijing.

Safety concerns associated with the increase in traffic volume together with the deterioration of air quality of the environment naturally have induced some parents' decision to use their car rather than walking their children to school. Ironically, chauffeuring children to school will only become additional traffic, that is, the parents' choice to drive made them become part of what they tried to avoid. Parking of school traffic around the school creates concern on safety for some parents (Ahern et al., 2017). Those who shifted to chauffeuring will continue to make walking to school less enjoyable or even unpleasant with the deterioration in air quality caused by vehicle emissions, which will only cause more decline in children's active commuting to school. Unfortunately, this has become a chauffeuring-and-walking-to-school vicious circle as demonstrated in Hayes et al. (2022).

1.4 | Walking school bus as a means for breaking the chauffeuring vicious circle

Walking School Bus (WSB) is an instrument that can help combat this situation. It was a scheme originally introduced in Canada by David Engwicht in 1992 based on a simple concept involving a number of pupils walking to school supervised by one or more adults (Kingham & Ussher, 2007; Neuwelt & Kearns, 2006). WSB schemes have continued to operate in Canada until today (Benson et al., 2020), while numerous cities around the globe have also adopted the walking school bus idea, for example, in New Zealand (Collins & Kearns, 2010; Kearns et al., 2003; Kingham & Ussher, 2007), Spain (Perez-Martin et al., 2018), the United States (Kong et al., 2009; Mendoza et al., 2009; Oreskovic et al., 2014), and so forth.

Over the years, WSB has evolved into different forms of arrangements. A WSB could be as small as two families walking their children to school and alternating which adult supervises the walk. Alternatively, it could be as large as 50+ children walking to school with 'bus stops' and multiple adult supervisors at both the front and back of the bus (National Center for Safe Routes to School, 2020).

The benefits of WSB have proved to be substantial covering a wide spectrum, namely, physical exercise, social skills and traffic reduction (Collins & Kearns, 2005, 2010; Heelan et al., 2008; Kearns et al., 2003; Kong et al., 2009; Neuwelt & Kearns, 2006; Paquette, 2007). They include not only improvement of road safety by traffic reduction around schools (Mendoza et al., 2012), but also the health benefits from the physical exercise (Mendoza et al., 2011). Children, in particular, found the interactions between themselves most enjoyable, enabling the development of social skills between peers as well as with adults (Hinckson, 2016). The traffic reduction also creates a more pleasant environment for walking in terms of air quality and safety. Making walking to school an enjoyable experience can become a catalyst to attract more participants to join the WSB.

This can also be the first step to help children acquire skills for independent mobility (Kingham & Ussher, 2005). Modal shifts from being driven to school to walking to school can be initiated, that is, breaking the vicious circle of chauffeuring children to school becomes possible (Hinckson & Badland, 2011; Mammen et al., 2014; Mendoza et al., 2009). The sense of community in organising WSB and making it happen together will continue to contribute to its success (Collins & Kearns, 2005, 2010; Waygood et al., 2017). Hayes et al. (2022) have shown that introducing WSB schemes can be the beginning of a virtuous walking-and-chauffeuring-to-school circle to induce a pro-walking modal shift.

1.5 | Walking school bus as an innovation

WSB routing design can potentially be an innovation to address children with special needs. For example, Oreskovic et al. (2020) suggest that the efficacy of walking routes can be a novel approach to increase physical activity among children with autism spectrum disorder (ASD), as physical activity is linked to motor skills, sleep, cognitive function and academic performance, and mental health for children with ASD. Active commuting to school is important for children with asthma (Oreskovic et al., 2009); ironically, Oreskovic et al. (2009) found that there are significantly fewer (16%) children with asthma who travel actively to school. We believe that if WSB routing is designed carefully to avoid pollutants, children with asthma might be able to enjoy walking to school together as much as the others, enabling the realisation of the health benefits of active commuting for them.

WSB programmes can be part of an education programme for the community. Johnston (2020) partnered with a WSB programme in a Sociology of Education community-engaged learning course in Washington for 3 years. College students became volunteers enjoying hour-long early morning walks with pupils of elementary schools in the area. This has proved to have positive influence in enhancing learning for the volunteers, helping them to develop deep authentic relationships with the children. At the same time, WSB leaders and volunteers help children to arrive safely to school. They educate the children about the environment and traffic safety along the way. In this process, a strong community consisting of university students and pupils with very different social background is developed by walking together.

1.6 | The vital role of WSB route planning

The success of WSB in breaking the chauffeuring vicious circle is dependent on sustainable modal shifts from being driven to school to WSB uptake. Our objective is to look at a particular element that is required for any WSB planning and implementation, that is, the WSB routing problem.

WSB routing is vital for the success of WSB schemes as it directly affects the catchment for the WSB; the route quality will affect the enjoyability of the experience of walking; the environment along the route, for example, in terms of pollutant concentrations, will affect whether the desirable health benefits can be achieved. All the potential benefits identified above can only be realised if children are walking in a safe environment that would allow them to enjoy socialising with each other; and the physical environment, for example, air quality, would allow them to gain the health benefits from physical exercise. WSB routing is also vital for the success of using WSB as an innovation to address children with special needs or as an education programme for the community.

Lots of studies have been devoted to what factors might be barriers to walking to school and what factors might sustain its success, see a comprehensive review in Nikitas et al. (2019). However, there are only very few papers looking at route choice behaviour for active transport to school. Dessing et al. (2016) compared the route choice of 184 children from seven different schools in the Netherlands. They observed that children mainly travel through residential areas; they prefer traffic signals to zebra crossings and try to avoid streets with high occurrence of traffic incidents. Ahern et al. (2017) made some interesting observations from their in-depth interviews with parents regarding their mode choice and route choice behaviour. Their route choice behaviour is somewhat different, depending on whether the parents are accompanying the children. Interestingly, parents would prefer children to avoid stranger danger by being visible on the main road if they are unescorted; while when they are accompanying the children, they would prefer to avoid the busy roads to make their journey more comfortable. This shows that safety is above all the most important influencing factor on their route choice behaviour.

To address parents' concern on safety, in Spain, Perez-Martin et al. (2018) developed a mobile app for a WSB service provided by professional monitors for a primary school in Cordoba. Perez-Martin et al. (2018) designed three WSB routes based on proximity to families who are willing to participate or who were driving to school within a designated catchment area for each route. The use of the mobile app enables parents to be informed of the real-time location of the

WSB and they are also informed when their children have arrived at the school safely. Feedback from parents has shown that this can help address their concern and as a result promote the uptake of the WSB scheme.

As shown in the step-by-step guide from the California Department of Public Health (Safe Routes Partnership, 2020a), after some initial planning and having an idea of the number of routes in Step 1, Step 2 is all about planning the routes. There are very few guidelines for WSB routing in practice, mostly provided as a checklist with some simple questions. For example, in the United States, National Center for Safe Routes to School (2020) provide four main questions: (1) Do you have room to walk? (2) Is it easy to cross the street? (3) Do drivers behave well? (4) Does the environment feel safe? The guidelines from Safe Routes Partnership (2020b) provide a checklist with 16 yes-or-no questions to be answered covering different safety aspects of the route categorised under: sidewalks, crosswalks, traffic and overall surroundings. Both checklists follow the same principles of ensuring that there will be enough room for the comfort of walking; crossings are safe; and traffic danger can be minimised. Planners can have these criteria in mind when looking for a route. These guidelines would be useful as a checklist once a route is designed. Generating the routes remains to be a matter of judgement by the planners rather than a scientific process.

1.7 | Research gaps in walking-to-school route planning problem

There are only very few papers that have looked at Walking-to-School or WSB routing scientifically with optimisation specifically. Tanaka et al. (2016) are the first to look at walking-to-school routes for children to walk together to school in Japan. It is common to walk to school without adult supervision in Japan. Their rationale is that walking together might extend the route a bit but greatly improve the safety when children are walking together as they become much more visible to traffic. Tanaka et al. (2016) applied bi-objective optimisation considering time and safety as two objectives. The idea is to generate routes with common sections that children can walk together. Each pupil will start alone from his/her own home and then join together at a certain point to continue walking together. Sections where they walk together are considered to have lower risk but these routes should not deviate too far away from their individual shortest paths. By considering both time and safety as objectives in the optimisation, they are able to find good solutions which are better than all children walking to school alone. For instance, an 11% increase in distance can reduce the length of sections walking alone to only 27%.

On WSB route optimisation, Bolkhanian and Reyers (2019) look at the WSB routing problem for a school in Canada with optimisation. Their objective is to minimise the total time for pupils walking to school by designing a set of WSB routes in a specific area to collect all the potential pupils who might be joining the WSB from their home. Each route will serve a specific cluster and the optimisation includes clustering as well as route optimisation formulated as a vehicle routing problem. Tresoldi et al. (2021) developed a two-stage process to optimise the design of WSB lines to pick up children from their home and take them to school. They applied their model to a case study in Italy. The optimisation consists of two processes: (1) to determine the minimum number of 'drivers' to walk all children to school; and (2) given the number of drivers and their locations, to design a set of lines to serve all the demand. The objective is to minimise the maximum ratio of actual walking distance to the shortest path distance for each child. The focus is, therefore, again on time using distance as a proxy variable.

Time is the only factor considered in both Bolkhanian and Reyers (2019) and Tresoldi et al. (2021), which is not sufficient to help realise all the potential benefits WSB might bring. Children love the experience of walking when it is enjoyable and they never complain about walking longer distances even though the WSB route is normally longer than the direct one (Heelan et al., 2008). Time is important but perhaps it might not be the most important among all the factors that can make walking to school a more enjoyable experience. Safety and comfort are certainly important for children.

WSB routing design and optimisation is an area that requires attention and this paper will focus on the following research gaps identified:

1. What might be the most important criteria for designing walking routes to school for children?
2. How do we find the most efficient routes to walk to school in view of multiple criteria?
3. How do we design a set of WSB routes to maximise the coverage and efficiency?

The main aim of this paper is to address the above research questions with a multi-objective optimisation approach. We identify the most important route planning criteria vital to the success of WSB programmes and formulate the optimisation of walking routes in a walking network. This paper contributes to both social and network modelling sciences, that is, on how to model complex route performance criteria as well as the optimisation of WSB routes in a walking network with multiple objectives.

2 | THE MODEL

2.1 | The rationale of a multi-objective WSB routing optimisation model

Our ultimate goal is to provide a practical tool that can help promote and sustain WSB or help anyone who might consider walking to school to enjoy their experience, ensuring that WSB routes are designed to realise all the potential benefits of walking to school, in particular the health benefits and enjoyability of walking to school. In order to achieve this goal, we must consider the needs of children, their parents and anyone involved in planning and operation of the WSB. The children might not worry too much about the time, but they would need a safe environment to socialise with each other, for example, through green areas without traffic. Time might be important for parents as they will need to make sure the children will not be late for the WSB. At the same time, parents might be concerned about the traffic safety along a more direct route and they would also wish for their children to be able to gain the maximum health benefits from walking. For the planners, the routes need to be able treach the maximum catchment area within walkable distances, and the walking time must be reasonable. The school might wish to be able to educate children about the environment and traffic safety along the route.

Mathematically, this would involve tradeoffs of different objectives favoured by different parties. The question is how do we look after all the different objectives with different levels of importance to different parties? How can we find all the possible good solutions? How can we assess the performance of different routes so that the planners can trade off the differences and determine perhaps a best possible set of routes that might be operationally feasible for the given resources they have.

To address all of these requirements, we propose a multi-objective optimisation approach. The key advantage of adopting a multi-objective approach is that it allows the tradeoff between different criteria so that all *efficient* routes with good quality in terms of the set of criteria can be identified. Depending on the special needs or preferences of different groups, a route can then be recommended by selecting one of the *efficient* routes for the group. This approach has been successfully applied to help commuter cyclists in making their route choices in Ehrgott et al. (2012) and Wang et al. (2018). Ehrgott et al. (2012) consider suitability of a route based on safety and comfort versus time; and Wang et al. (2018) consider time versus dose of pollutants along the route for cyclists in order to support those who are concerned about the potential negative health impact of pollutants from vehicle emissions.

Another challenge we have is that we must be able to assess the performance of each route in terms of all the criteria. Most of the existing research focuses on the assessment of built environment of an area or a city and their influences on mode choice (e.g., see Broberg & Sarjala, 2015; Curtis et al., 2015; Mitra et al., 2014; Mitra & Buliung, 2014; Rothman et al., 2014, 2021; Smith et al., 2019). What we need to look at here is a route-based (rather than area-based) assessment of walking routes to school. Movements along a route will need to be modelled at a level of detail which has not been conducted before. For instance, walking on different sides of the road or movements through crossings will need to be modelled. We, therefore, propose a walking network modelling approach, so that walking routes can be represented at an appropriate level of detail for the assessment of their performances in terms of a selected set of most important criteria. Multi-objective optimisation can then be applied in a walking network to determine a set of most efficient routes for children to walk to school.

2.2 | Formulation of the route performance criteria

To facilitate the success of WSB, we must be able to attract parents to join the programme for their children and address any concerns they might have associated with walking to school. To make sure that WSB is sustainable, we must make it an enjoyable experience for the children. This means that our route performance criteria should be from the perspectives of *both* the parents and children. We will consider all the factors needed to fully realise the potential benefits of WSB as well as what has been proved most important for the parents and for the children.

2.2.1 | Distance and time

The key questions we need to answer here include: how far is comfortable for children to walk and how far is perhaps too far? Ermagun et al. (2016) studied these questions specifically. They found that the distance to school is negatively correlated with the choice to walk, with a notable decline in the number of children walking when the distance is longer than 1.6 km. This finding is consistent with the opinion of parents interviewed by Nikitas et al. (2019) who expressed that distance was a dominating factor deterring them from walking. Although the parents can hardly define the exact distance that is ‘too far for walking’, most of them suggested an acceptable maximum of 20 min walking time. This is consistent with the range of 1.6–1.9 km walkable distance as identified by Ermagun et al. (2016) based on their econometric analysis of data collected in Iran and a maximum of 2 km from Kelly and Fu (2014) based on GIS and census data of Dublin, Ireland.

We consider time as a proxy variable of distance. This is also a good measure of the level of physical activity that can be achieved from walking to school. Egli et al. (2020)'s study on children's perspectives of walking routes to school in New Zealand has found that they are aware of both time and distance. All the previous studies in optimisation of WSB routes have considered this objective (Bolkhanian & Reyers, 2019; Tanaka et al., 2016; Tresoldi et al., 2021), that is, to minimise *walking time*.

2.2.2 | Health, wellbeing and air quality

WSB initiative brings health and wellbeing benefits. As active commuters, children will benefit from walking, which keeps them fit, improves their heart and helps grow their muscles (Kearns et al., 2003). Similarly, Kingham and Ussher (2007) reported a significant improvement in the fitness levels of at least half of the participants on WSBs. This could be an effective way to address the increasing obesity problems due to sedentary lifestyles. Some partaking parents also believed that children might be better prepared for learning when they arrived at school (Carlson et al., 2020; Neuwelt & Kearns, 2006).

Different WSB routes could also make a huge difference to the impact on the participants' physical health and wellbeing. Evidence of a correlation between exposure to traffic pollutants and adverse health issues such as asthma and cancer has been proved by Mejia et al. (2011). In contrast to people who sit in their cars, pedestrians are often exposed to a higher concentration of pollutants due to a lack of physical barrier between the exhausts and their respiratory system (Dirks et al., 2016). Whilst all active commuters are at risk of air pollution exposure, studies have found that children are more vulnerable than adults under the same conditions (Kulkarni & Grigg, 2008).

On the other hand, the air pollution dose taken in by the commuters is not only dependent on the concentration but also the commuting time (Dirks et al., 2016). Given that children can be walking up to 5 days a week on a WSB, they have the potential of an exposure to a significantly high level of pollutants (Dirks et al., 2018). At a route level, a study in London suggested that pedestrians experience notably lower exposures when there is a more effective separation from the traffic (Kaur et al., 2005). Routes away from congested roads and intersections are considered more suitable for pedestrians from a health-oriented point of view (Ribeiro et al., 2022). This is especially important for children walking to school (Dirks et al., 2016, 2018).

In order to minimise any potential negative effect caused by air pollutants along the route, we estimate the dose along a route by applying the same principles as in Wang et al. (2018)'s model to support cyclists' route choice. This method takes into account the pollutant concentration, walking speed and time, and breathing rate of children walking to school. Our second objective for route optimisation is to minimise the *pollutant dose*.

2.2.3 | Walkability—safety and comfort

The viability and success of WSB is dependent on the support of its participants, which in turn depends on the parents' view of its safety and the children's view of the *enjoyability* of walking to school together. The two objectives identified so far, that is, time and pollutant dose, are some of the measurable characteristics for the planning of the routes, which might partially influence parents' decisions. Yet whether parents will join the programme is dependent on their *perception* of safety, the potential benefits from walking and the anticipated enjoyability their children might experience.

Safety is above all the major concern for parents (see e.g., Collins & Kearns, 2005; Ermagun & Samimi, 2015; Nikitas et al., 2019). In particular, Rothman et al. (2015) have looked at parents' perceptions of traffic danger along the school route and identify built environment features associated with perceived route danger. They concluded that routes to school should be planned along low speed roads, with more traffic signals, fewer and safer road crossings. A comprehensive review by Rothman et al. (2014) also highlighted the importance of walkability assessment to include the risk of injury in the assessment. For example, separating children in space (e.g., in a playground) from traffic is a possible way to reduce the risk. Applying this concept in WSB routing, green routes will certainly be more comfortable and safer for children. Safety and comfort are naturally interrelated qualities that we are looking for in WSB route planning.

We propose a third criterion named as *walkability*. The concept of walkability has been developed to assess what attributes of the built environment might enable pedestrian friendliness (Fonseca et al., 2022). In our model, *walkability* represents specifically both the safety and comfort of walking from children's and parents' perspectives at a route level. Our objective is to maximise *walkability*, enabling children (and their parents) to feel safe such that children can enjoy walking together on a selected route to school.

2.3 | Modelling a walking network

To model a walking network, we follow the principles of a conventional network modelling approach, where road sections are represented as links and intersections as nodes. For example, a T-junction in a road network as shown in Figure 1a can be modelled with three links representing the three arms of the junction as depicted in Figure 1b. Note that for simplicity, the links are bi-directional in this representation; in practice, all links are directional.

In order to model pedestrian movements, as well as to be able to evaluate the potential impact of their route choice on their health, we will need to model their movements in more detail. The evidence from experiments conducted by Dirks et al. (2016) in Bradford have shown that walking on different sides of the road might lead to very different dose of pollutants due to the difference in traffic conditions. Stationary traffic has found to cause spikes of high pollutant concentration, which induces a significantly higher level of exposure than when traffic is moving. Dirks et al. (2016) also found that pollutant concentrations at intersections are also relatively high. Therefore, the pollutant dose, caused by delays at intersections, might also be higher.

In a walking network, we will need to be able model delays at crossings as well as to represent the pavement on each side of a busy road. Here, we introduce crossing links that represent the crossings, where exposure to higher levels of concentration of pollutants might be experienced. We also introduce a walking link on each side of a main road, to represent the pavement on each side. With this method, a T-junction at the intersection of two main roads, with two pedestrian crossings, as shown in Figure 1a can now be represented by Figure 1c for pedestrians, where walking links and crossing links are represented by solid and dotted green lines, respectively.

2.4 | Modelling safety and comfort

We model the perceived safety and comfort jointly named as 'walkability' from the perspectives of both parents and children. In order to be able to assess this criterion quantitatively, we applied the concept of Pedestrian Level of Service (PLOS) (Mozer, 1994) focussing on the needs of the children walking to school. Pedestrian safety and comfort has been well studied in the literature (see e.g., Carter, 2007; Dowling et al., 2008; Jensen, 2007; Miller et al., 2000; Sarkar, 2003; Tanaka, 2012; Transportation Research Board, 2000). Some studies have looked at pedestrian needs in more detail, covering their feeling of safety and comfort (e.g., Asadi-Shekari et al., 2015; Landis et al., 2001). Our approach is to select the factors relevant to the needs of children and then apply a method of assessment based on a point system to the selected factors.

Perceived safety is the feeling about the traffic condition and potential danger. To a certain extent, WSB can help reduce the risk

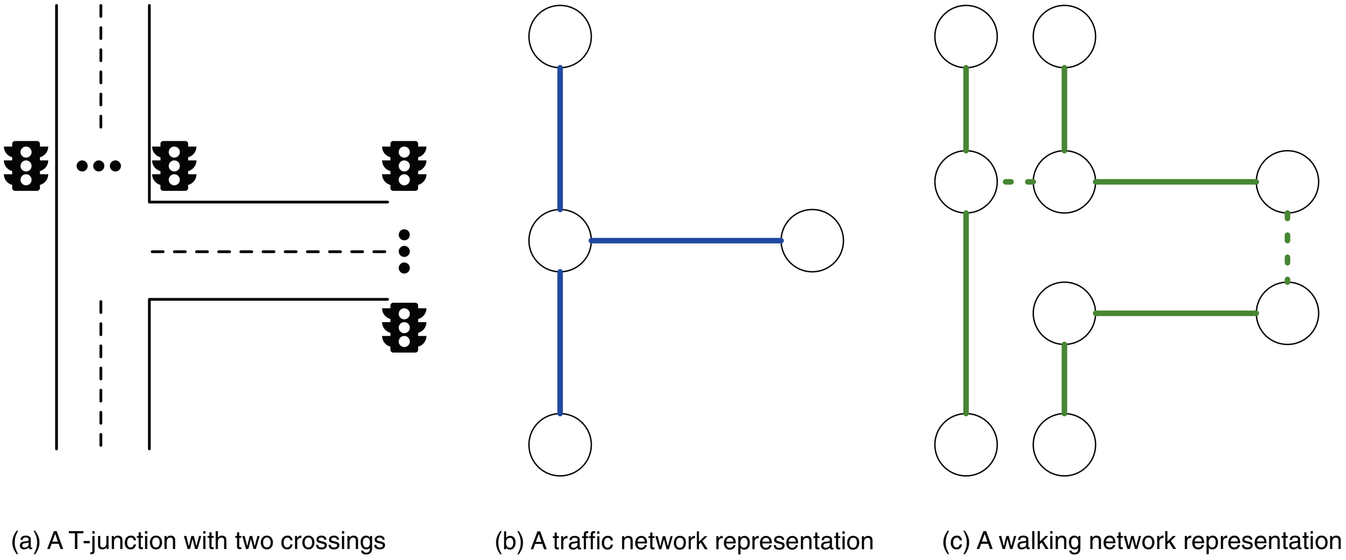

(a) A T-junction with two crossings (b) A traffic network representation (c) A walking network representation

FIGURE 1 Representation of a T-junction with two crossings for traffic and pedestrians.

and protect children from potential traffic incidents as there will be adult supervisors to guide them. However, parents might still be worried as both traffic conditions and drivers' behaviour are unpredictable, and children's behaviour and their perception of dangers are immature (Nikitas et al., 2019). Factors affecting parents' perceptions on traffic and risk of injury such as traffic speed and volume, presence of crossing facilities or traffic signals, and so forth will be considered (Rothman et al., 2014, 2015).

Comfort for walking is associated with the feeling of walking, especially from children's perspective. Egli et al. (2020) have looked at the feeling from children's perspective to understand their travel perceptions and preferences for their routes to school in New Zealand from a large sample of children aged 8–13 years. They dislike crossings, especially when cars are speeding while they try to cross the road. They do not like pollution from cars either. They would prefer good pavement conditions with relaxing views along the route. What has been found most important to children is to enjoy the opportunity for social interactions. If the route is comfortable and enjoyable, children will be energised and more willing to walk to school. Urban design features, such as the quality of footpath in terms of pavement conditions, sidewalk width, presence of trees, and so forth can improve the comfort and the attractiveness of a walking route for children. Crossings should be avoided and children would appreciate better air quality being away from sources of pollution from traffic in natural spaces.

2.4.1 | Factors influencing walkability for children

Traffic speed and volume

Rothman et al. (2015) have identified traffic speed and volume as two key factors affecting parents' perception of traffic safety and risk of injury. Rothman et al. (2014) have shown that higher speed and more traffic are positively correlated to child pedestrian injury due to the increased exposure. For the same reasons, both factors are also identified as important factors in PLOS in many studies, as summarised in Table 1.

Sidewalk width and buffer

Rothman et al. (2014) suggest that separating children in space from traffic is a possible way to reduce the risk of injury. Providing a buffer between the edge of a roadway and the sidewalk is an effective way to enhance safety for pedestrians (Dixon, 1996; Jaskiewicz, 1999; Landis et al., 2001). Sufficient sidewalk width is important for the comfort of children and it would be extremely dangerous for children on a narrow sidewalk if they play on the sidewalk while they are walking.

Lighting

Dixon (1996) suggests that lighting is an important factor to increase the feeling of comfort and convenience for pedestrians. It should be provided in locations along the segment to benefit the people walking on the sidewalks. Miller et al. (2000) and Montella et al. (2020) found that the lighting is often associated with security perception as good lighting can help maintain the visibility to vehicles during the night time and can also help reduce crashes. As the weather and lighting condition might vary in different seasons during the time children are walking to/from school, lighting can help maintain the visibility of children to vehicles as well as visibility of the pavement condition to children.

Pavement condition

A good pavement should be continuous and smooth but provide enough skid resistance without cracks (Asadi-Shekari et al., 2015; Gallin, 2001). This is important for all pedestrians and in particular for children as it can help reduce the risk of injury from slip and fall during the walk to school (Sarkar, 2003).

TABLE 1 Weightings for road features in walkability based on literature.

	Mozer (1994)	Dixon (1996)	Jaskiewicz (1999)	Miller et al. (2000)	Gallin (2001)	Landis et al. (2001)	Sarkar (2003)	Carter (2007)	Jensen (2007)	Flannery et al. (2008)	Dowling et al. (2008)	Florida Department of Transportation (2013)	Asadi-Shekari et al. (2015)	Montella et al. (2020)	Weighting
Traffic speed	1	1		1		1		1	1	1		1	1	1	10
Buffer presence	1	1	1		1	1			1	1		1	1		9
Traffic volume	1					1		1	1	1	1	1		1	8
Sidewalk width	1	1			1	1	1				1	1	1		8
Pavement condition		1			1		1		1	1			1	1	7
On-street parking						1		1	1	1	1	1			6
Lighting		1		1									1	1	4
Trees		1	1						1				1		4

Trees

Dixon (1996) suggests that sidewalk users can anticipate less interaction and conflict with motor vehicles in locations where trees are planted, as trees can also act as a buffer between traffic and pedestrians to improve safety. Jaskiewicz (1999) found that the presence of trees not only provides shading to keep the atmosphere cool and comfortable for walking, but also add nice aesthetic elements to the street. Thus, the presence of trees has been found to make pedestrians generally more satisfied (Jensen, 2007); for children, the presence of trees can also be used as examples to educate them about the environment.

On-street parking

Landis et al. (2001) suggest that the presence of on-street parking can act as a barrier to improve the walkers' feeling of protection. However, this is not always true. While the buffer of parked vehicles might make some pedestrians feel safer, some pedestrians have found to be less satisfied (Jensen, 2007). On-street parking can be an obstacle reducing pedestrians' visibility to vehicles when they try to cross the road (Biswas et al., 2017; Carter, 2007). Since children are usually less visible than adults, and they may 'dart-out' without being noticed, presence of on-street parking should be avoided.

Crossings

Rothman et al. (2015) have identified that crossings have adverse effect on parents' perception of traffic safety and risk of injury. Crossing should be avoided if possible (Schwebel et al., 2012). Signalised intersections are preferred over unsignalised ones if crossings cannot be avoided (Rothman et al., 2015).

Crossing links versus walking links

Note that crossings are modelled as crossing links in a walking network as described in Section 2.3. Traffic speed and volume, sidewalk width and buffer, lighting, pavement condition, trees and on-street parking are characteristics associated with walking links, that is, they do not apply to crossing links. The effects of these characteristics that might affect an intersection, for example, the effect of lighting, will be modelled by the segment(s) leading to or egress from the crossing node(s).

2.4.2 | Weightings of walkability factors

The weightings of different factors as identified above can be determined based on judgement by the planner. It can also be determined based on surveys collecting opinion from parents and/or children.

In the present study, we apply a method as in Asadi-Shekari et al. (2015), where counts of mentioning of each criterion in the literature are used as weightings, as shown in Table 1.

2.4.3 | Assessment of walkability factors

We follow the principles of the assessment method developed in Christopoulou and Pitsiava-Latinopoulou (2012) to quantify the factors identified in Table 1. The principle behind their method is to consider *both* qualitative and quantitative qualities of a walking link before translating the assessment into a combined score. Christopoulou and Pitsiava-Latinopoulou (2012) have shown that this method has the advantage of not overestimating the scores from the quantitative assessment while at the same time reducing the likelihood of bias from considering qualitative factors only. For simplicity, we adopt a three-point system representing Bad/Medium/Good as shown in Table 2. Note that in order to standardise all optimisation objectives to be minimisation, *Good* will have a score of 0, while *Bad* will have a score of 2, and a *Medium* score of 1 in the middle.

2.5 | Mathematical model of the route performance criteria

2.5.1 | Objective 1—To minimise walking time

Walking links

We assume a constant speed to be applied to all walking links. The typical walking speed for 5-year old school children has been found to be about 1.29 m/s (Pinheiro et al., 2014). Based on an average speed, we can obtain the walking time to traverse a walking link by Equation (1),

$$t_a^w = \frac{l_a^w}{\bar{v}^w}, \tag{1}$$

where, t_a^w is the time to traverse a walking link a; l_a^w is the length of the walking link a; and $\bar{v}^w$ is the average walking speed of children.

Crossing links

The time to cross through an intersection is dependent on the intersection arrangement. Generally it consists of two components, that is, waiting time and time to walk through the intersection. An intersection might consist of more than one crossing link. We represent the crossing time for each link in the form of Equation (2),

$$t_b^x = \frac{l_b^x}{\bar{v}^w} + \bar{t}_b^w, \tag{2}$$

where, t_b^x is the time to traverse a crossing link b; l_b^x is the length of the crossing link b; and $\bar{v}^w$ is the average walking speed of children; $\bar{t}_b^w$ is the average waiting time at the start of crossing link b.

Total walking time for a route

The total walking time along a route equals to the sum of time to traverse all walki links a and crossing links b along the route,

$$t^r = \sum_{a \in r} t_a^w + \sum_{b \in r} t_b^x, \tag{3}$$

where, t^r is the total walking time for a route r.

2.5.2 | Objective 2—To minimise pollutant dose

To estimate the pollutant dose on any walking or crossing links, we apply the approach in Dirks et al. (2012), based on the average pollutant concentration along a link, the time spent to traverse the link, and the breathing rate of children during the walk,

$$d_a^y = C_a^y \times t_a \times \bar{\beta}_a, \tag{4}$$

where, d_a^y is the relative dose of pollutant y along walking link a; C_a^y is the concentration of pollutant y along walking link a; t_a is the travel time on link a; and $\bar{\beta}_a$ is the average walking breathing rate along link a.

The same principle applies to crossing links,

$$d_b^y = C_b^y \times t_b \times \bar{\beta}_b, \tag{5}$$

where, d_a^y is the relative dose of pollutant y along crossing link b; C_a^y is the concentration of pollutant y along walking link b; t_b is the travel time on link b; and $\bar{\beta}_b$ is the average walking breathing rate along link b.

The total dose for each route, r, will be the summation of doses on all the walking and crossing links along the route,

$$d_r^y = \sum_{a \in r} d_a^y + \sum_{b \in r} d_b^y. \tag{6}$$

2.5.3 | Objective 3—To maximise walkability

As explained in Section 2.4.3, in order to standardise all three objectives to be minimisation, we use a three-point scale of 0/1/2, corresponding to Good/Medium/Bad, to assess the score of each attribute on each link.

Walking links

By applying the weighting α^i of each attribute i, as summarised in Table 1, we can determine the walkability score of each walking link,

$$w_a = \sum_i \alpha^i s_a^i, \tag{7}$$

where, w_a is the walkability score of walking link a; α^i is the weighting of attribute i; and s_a^i is the score of link a in terms of attribute i.

Crossing links

Crossing links can be scored according to the crossing type based on the judgement of the planner. The scores can vary with a worse score for an unsignalised intersection as compared with a signalised one. As crossings are to be avoided along a route, crossing links are to be scored the same as a *bad* walking link in this paper.

The overall walkability score along a given route r is given by:

$$w_r = \sum_{a \in r} l_a^w w_a + \sum_{b \in r} l_b^x w_b, \tag{8}$$

TABLE 2 Three-point marking system for walkability factors.

Factors	Mark standard 2	1	0
Pavement	Bad	Medium with slight misfits	Good
Trees	Do not exist	Existence decreases free movement	Suitable existence
Lighting	Dark	Light with some dark spots	Adequate
Buffer	Do not exist	Partly provided	Fully covered
Traffic speed	> 60 kph	Between 30 kph and 60 kph	⩽30 kph
Traffic volume	Congestion	Continuous flow	Easy change of lane
Sidewalk width	< 1.5 m	Between 1.5 m and 2.05 m	⩾2.20 m
On-street parking	Intolerable	Suitable existence	Rare existence

where, l_a^w is the length of walking link a; l_b^x is the length of crossing link b; w_a is the walkability score of walking link a; and w_b is the walkability score of crossing link b.

2.6 | Multi-objective route choice model

We adopt a multi-objective shortest path method based on the three objectives formulated in Section 2.5. Note that mathematically the three objectives have been standardised to minimisation as follows. They are all additive along the links forming a route.

1. To minimise walking time, Equation (3)
2. To minimise pollutant dose, Equation (6)
3. To minimise (un)walkability, Equation (8)

The presence of multiple objectives implies that rather than a single optimal route, there is a set of so-called efficient routes. A route is efficient, if there is no other route that is at least as good in all of the three objective functions, but strictly better in at least one of them.

The multi-objective shortest path-problem of finding all efficient paths from an origin to a destination is a well-known extension of the standard shortest path problem in Operations Research literature, with added complexity. This problem is formulated on a network of nodes and arcs, where each arc (or link) has a tail node, a head node and a value for each of the objective functions. Given an origin node s and a destination node t, an $s-t$ path is a sequence of arcs and nodes such that that the tail of the first arc is s and the head of the last arc is t, and such that the head node of each arc is the tail node of the subsequent one. An $s-t$ path p is called efficient if there is no other $s-t$ path p' such that the objective vector of p' is component --wise smaller than or equal to that of p with at least one strict inequality. It is known that in the worst case, the number of efficient paths can be exponential in the number of nodes even for just two objectives. For further information see Raith and Ehrgott (2009) and references therein. Despite such negative theoretical results, applications of the multi-objective shortest path problem in transport, for example, Wang et al. (2018), show that, in practice, the number of efficient paths is reasonably small, even in huge networks (Müller-Hannemann & Weihe, 2006) and that it can be solved quickly when the objectives are additive, as in our model. In the bi-objective case, label setting and label correcting algorithms perform well, as experiments by Raith and Ehrgott (2009) have shown. The same paper also gives an overview of other solution techniques. We employed the three-objective label correcting algorithm, which is a straightforward extension of the standard label correcting algorithm of Bellman (1958) for the single objective shortest path problem.

3 | A CASE STUDY

3.1 | Study area—Shipley Church of England Primary School

A school located in the City of Bradford in West Yorkshire, England, has been chosen as our study area for applying our multi-objective WSB route optimisation model. Bradford is one of the eight cities in the UK where Clean Air Zones (CAZ) have been planned (Bradford Council, 2021), with targeted action to be taken to improve air quality. The main objective of CAZ is to discourage the use of older, more polluting vehicles from entering the zone by setting a charge for entering. Extensive studies have been conducted by the Council to target improvement of air quality by 2022 in the area, including around Shipley Church of England (CE) Primary School, which has been selected as our case study. This school seems to be typical in terms of the UK, at least as far as modal split for school travel is concerned. As mentioned in Section 1.2, 66% of primary school pupils are walking to school supervised or unsupervised, whereas 31% are driven in private vehicles in Bradford. This leaves only 3% for all other modes.

We started with an informal interview of one of the parents who kindly also organised a site visit with us in the area. What has been highlighted as the main issue around Shipley CE Primary is that it is located on the A6038 Otley Road, which is a very busy arterial route connecting Airedale and Wharfedale to Bradford City Centre and beyond to the Strategic Road Network. What has made it worse is that the school entrance on Otley Road is not far from an

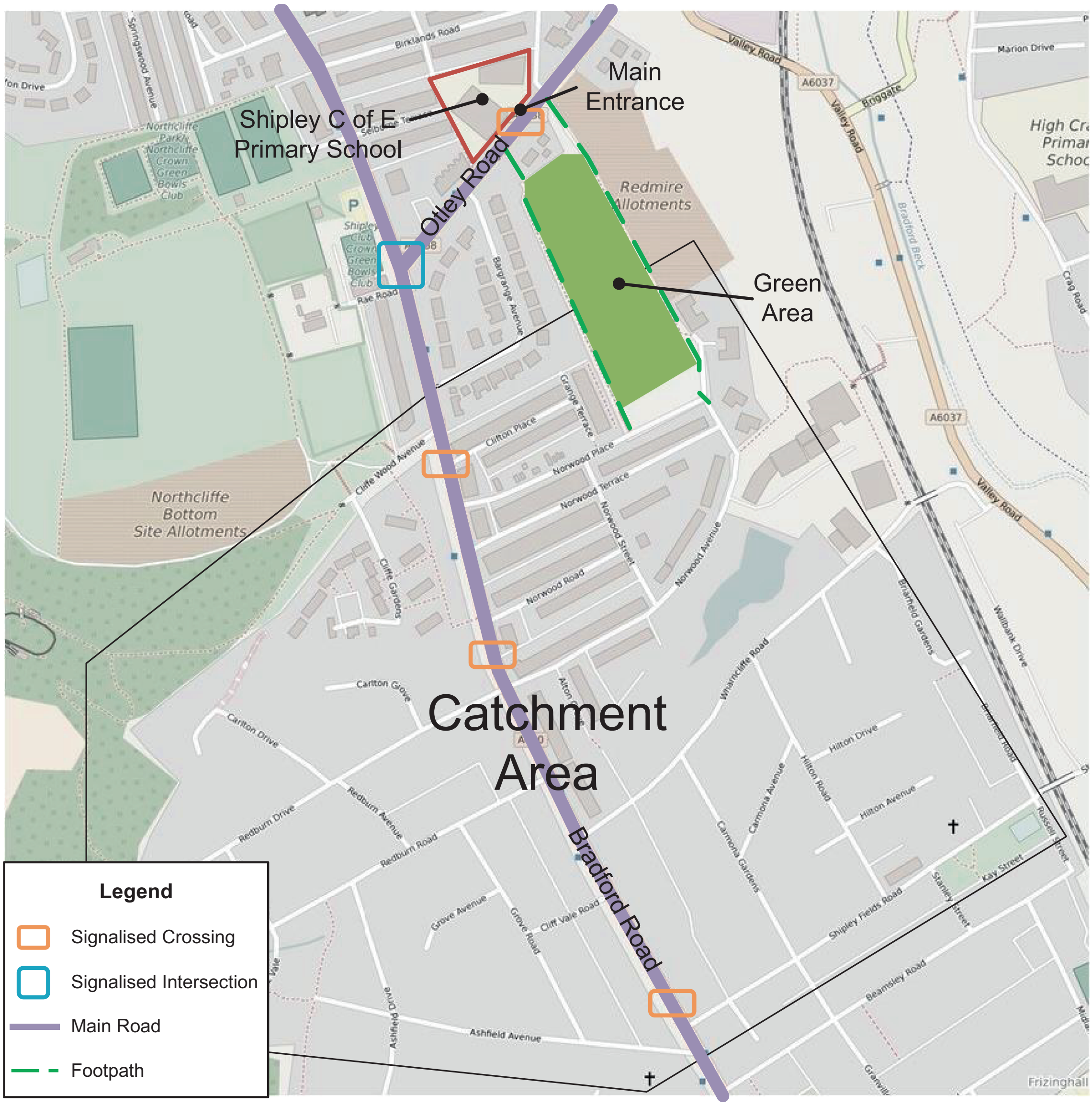


FIGURE 2 Overview of study area—Shipley Church of England Primary School.

intersection with another busy road, Bradford Road, as shown in Figure 2, where there is very limited space on the traffic island at the signalised crossing. The traffic accident statistics from CrashMap (2018) have shown that the section from this intersection to another crossing near the school entrance is one of the highest risk spots within the south catchment area of the school.

We anticipate that the introduction of WSB will not only have a very high potential as an aid to help alleviate both the traffic congestion and safety issues identified, but also ensuring that children can benefit from better air quality during their walk to school. We foresee that applying our model for this school will be insightful and valuable.

Houses within walking distance surrounding the school can be split into two main areas, the North and the South; while the area to the West is a green area with few houses and the area to the East is an industrial area. In this study, we focus on the south catchment area as shown in Figure 2, which has been chosen after consultation with parents who lived there and have expressed their concern on the factors that we are considering. All walking paths originated from this catchment area would require crossing the busy roads around the main entrance to the school, as highlighted in Section 3.2.1. Assuming the maximum distance children would prefer to walk is 1.6 km, the walking time for the catchment area identified would be within a maximum time of about 20 min.

3.2 | The walking network

3.2.1 | Walking links

Busy roads

As highlighted above, all walking trips from this area to the school will need to cross Otley Road. Bradford Road is a main road cutting this

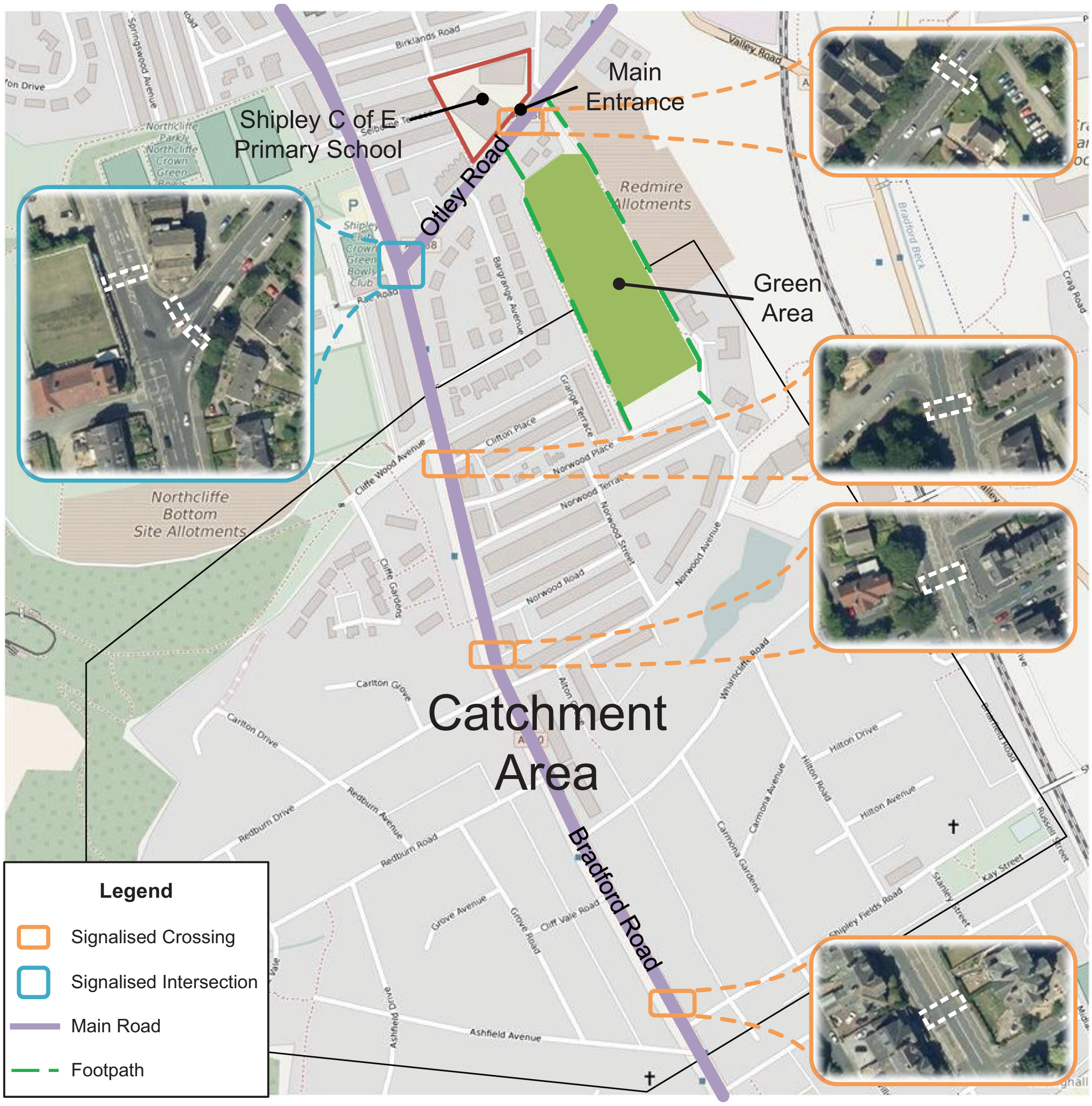


FIGURE 3 Crossing links in the study area.

area into the two subareas. Trips from the subarea on the west of Bradford Road will need to cross Bradford Road as well as Otley Road. These two arterial roads carry the busiest traffic in our study area. Traffic flow and speed might vary in the two directions on each road; and the air quality on different sides of the same road might be different. Both roads have more than one signalised crossing facility. It is important to be able to choose which side of the road to walk along and where to cross the road. We, therefore, have created two walking links on each side of the two main roads, that is, Bradford Road and Otley Road.

Residential streets

On the other hand, the residential streets within each subarea are relatively quiet with only localised traffic. One walking link would be sufficient to represent walking on either side of the residential streets.

Footpaths

There are some footpaths which might not be obvious in the OpenStreetMap (OpenStreetMap, 2021). Some are connected to the residential streets and some are present in a green area within the subarea on the east side of Bradford Road. They have been identified during our site visit and modelled with walking links in our model.

3.2.2 | Crossing links

Signalised single crossings

There are three signalised single pedestrian crossings along Bradford Road and one on Otley Road very close to the entrance to the school. Each of these four crossings, as shown in Figure 3, is modelled as one crossing link.

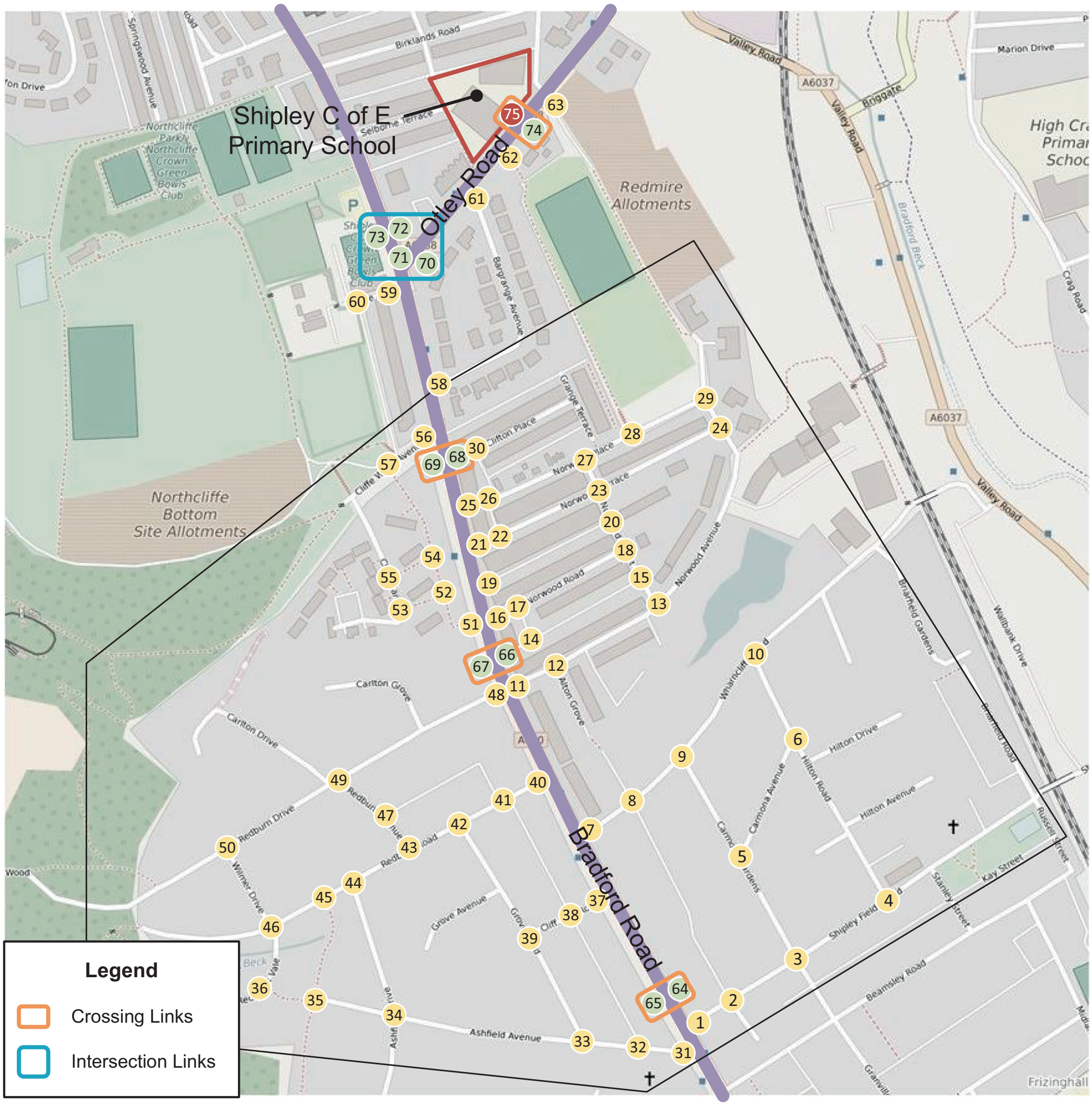


FIGURE 4 Walking network for the study area of Shipley CE Primary School.

Signalised intersection

As mentioned earlier, there is an intersection between Bradford Road and Otley Road. As shown in Figure 3, there are three crossing links at this intersection: one single crossing on Bradford road and a two-part crossing on Otley Road at this intersection with a small traffic island in the middle.

3.2.3 | Final walking network

The complete walking network consisting of all walking and crossing links. All walking and crossing nodes are illustrated in Figure 4, where crossing nodes corresponding to the crossings and intersections identified in Figure 3 are highlighted. Walking links have been created to connect the walking nodes to represent the possible paths. Walking nodes and links are depicted side-by-side in Figure 5.

3.3 | Assessment of the three objectives

3.3.1 | Walking time assessment

Link walking time

Walking time on each walking/crossing link is determined based on a measurement of the link length on OpenStreetMap divided by a constant children walking speed of 1.29 m/s as measured by Pinheiro et al. (2014), as shown in Equations (1) and (2).

Average waiting time at crossings

All seven modelled crossing links in our study area are signalised. We adopt the same method as in Ehrgott et al. (2012) where the average waiting time $(\bar{t}_b^w)$ is estimated by,

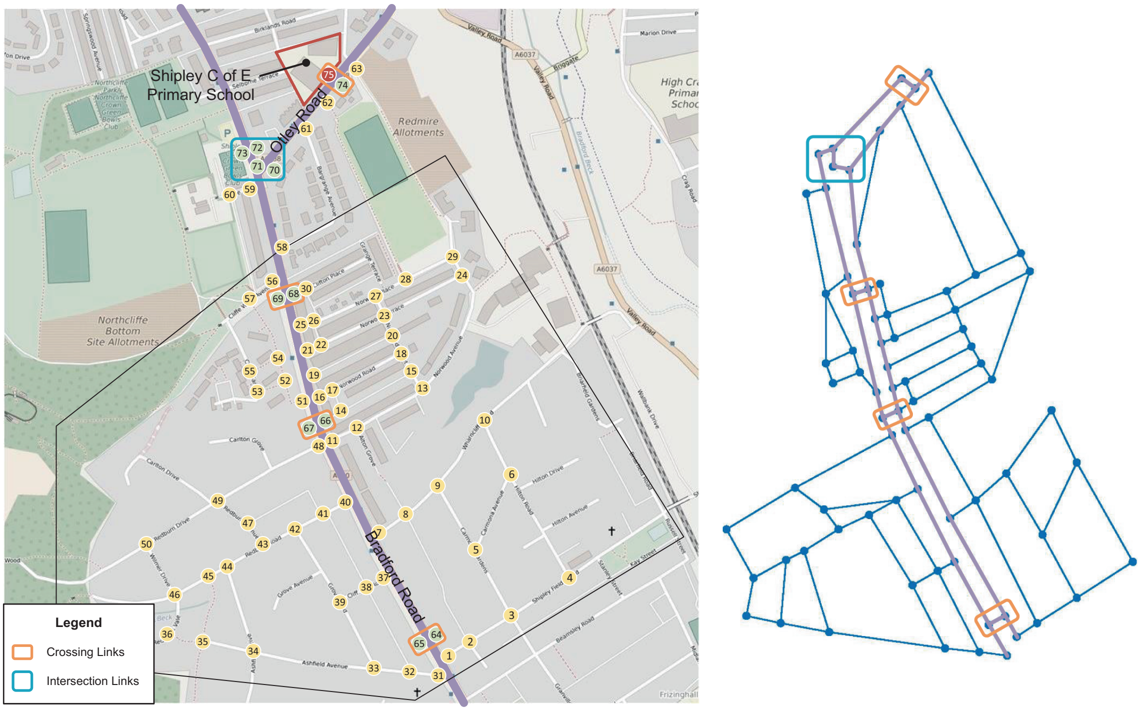
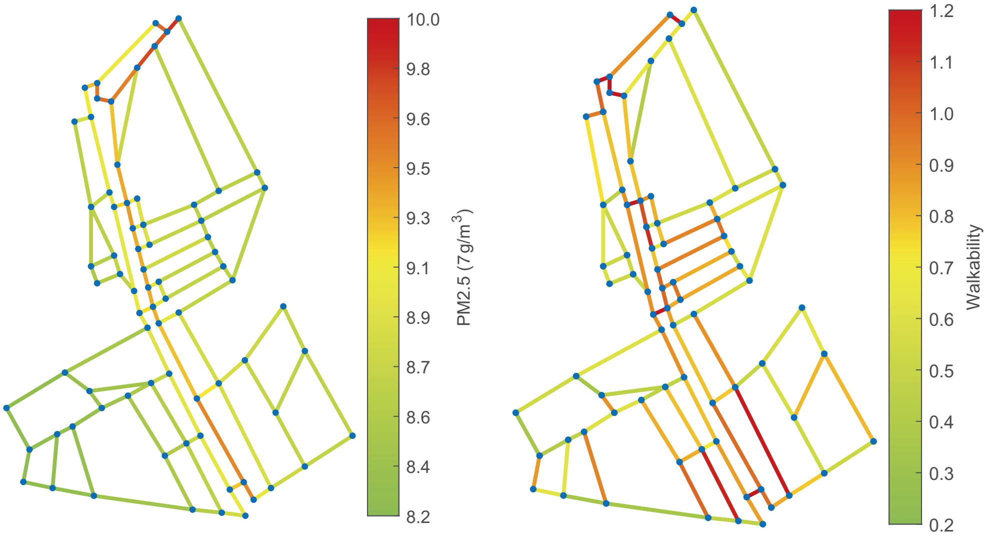


FIGURE 5 Walking nodes and links in the walking network.



(a) Heatmap of PM2.5 Concentration

(b) Heatmap of Walkability Assessment

FIGURE 6 Heatmaps of modelling parameters.

$$\bar{t}_b^w = \frac{R_t^2}{2S_t}, \tag{9}$$

where, S_t is the signal cycle time and R_t is the red time for pedestrians at the signal.

3.3.2 | Pollutant dose assessment

We have modelled two kinds of pollutants in our study, NO_2 and $PM_{2.5}$, based on calibrated modelled datasets provided by Bradford Council for 2018 on a 1 m × 1 m-grid. If a link is longer than its cross section with a grid, we determine the average concentration proportionally, based on the lengths of the cross sections. In this way, we were able to determine the estimated dose on each side of the busy roads and on each crossing links based on very detailed air quality information provided by the Council by applying Equations (4) and (5). The breathing rate for walking is assumed to be 36 L/min, which is estimated by Scalco et al. (2019) based on a study conducted in Brazil, where children were asked to continuously increase their walking speed while their maximum ventilation capacity was measured.

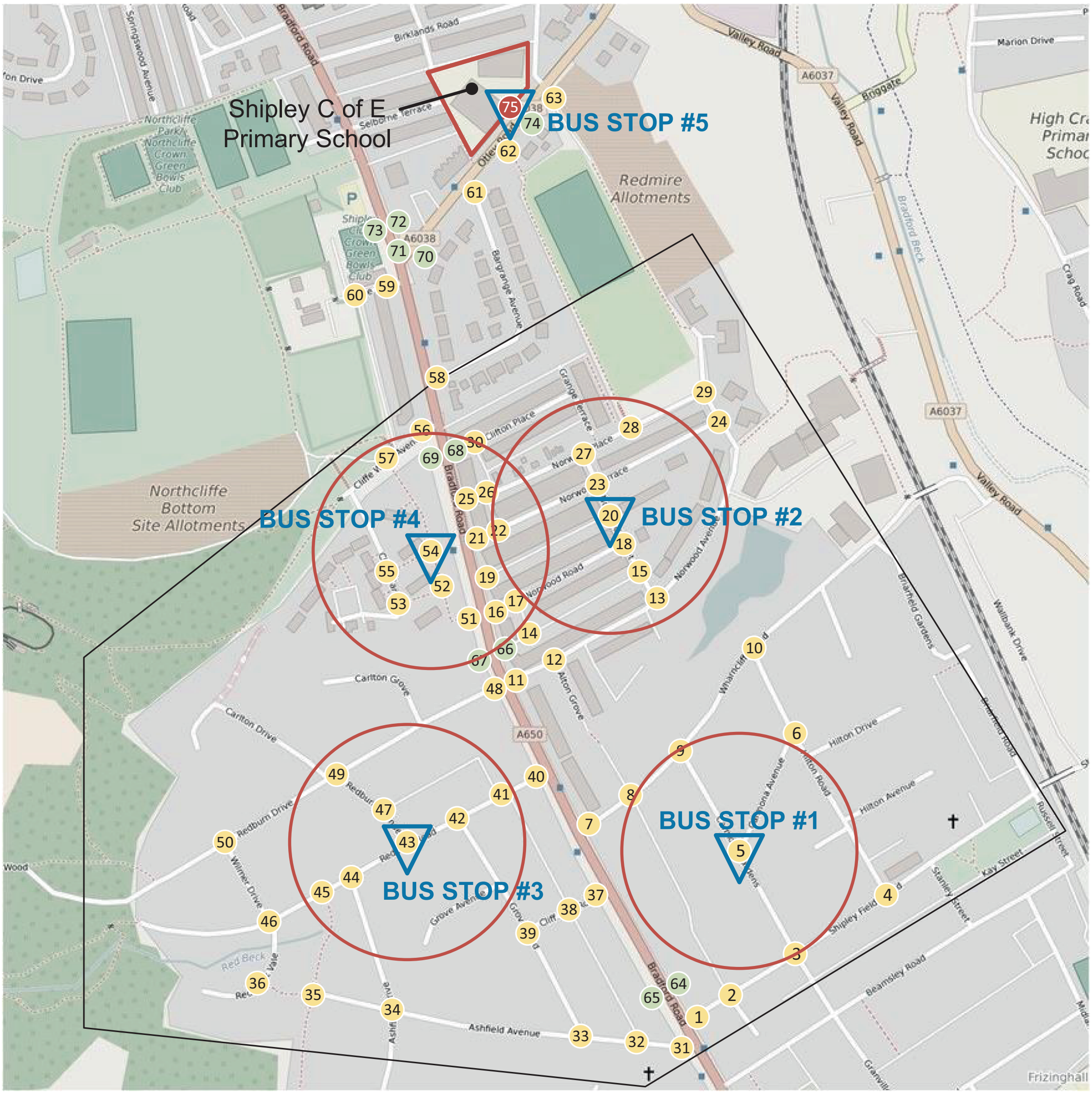


FIGURE 7 Location of bus stop #1–#4 and Shipley CE Primary at bus stop #5.

In this paper, for illustration purposes, we present only the results obtained based on modelled $PM_{2.5}$ concentration provided by the Bradford Council. The heatmap of average $PM_{2.5}$ concentration along the walking links is depicted in Figure 6a.

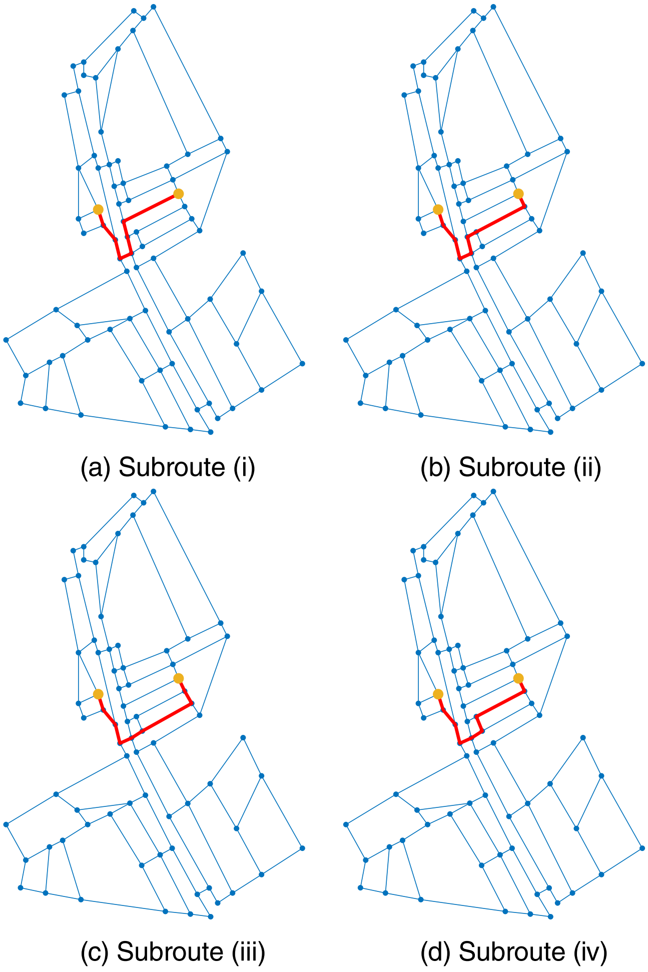
3.3.3 | Walkability assessment

Site visits were conducted to collect information on walkability assessment. The walkability assessment method as described in Section 2.4.3 is applied to determine a score for each walking link for each attribute in Table 2. Measurements required for the assessment are measured on OpenStreetMap and/or observed on site during the site visits. Equation (7) is then applied to obtain the score for each walking link. All crossing links are signalised in this case and they are all classified as Bad with a link score of 2 for each crossing link. The results of the walkability assessment are visualised in Figure 6b, depicting the link performance of each link on a heat map scale.

4 | WSB ROUTING OPTIMISATION

4.1 | WSB with 'bus stops'

There are generally two kinds of WSBs. One operates door-to-door to pick up children along the route and the WSB will reach the school together. Another kind of WSB requires parents to walk their children to the nearest 'Bus Stop'. In this case, the 'driver' of the WSB will start from a 'Bus Stop' at the start of a route, walking from one stop to another to pick up children from each stop, with the final stop at the school. Both Bolkhanian and Reyers (2019) and Tresoldi et al. (2021) have looked at the first type, that is, door-to-door then to



(a) Subroute (i) (b) Subroute (ii)

(c) Subroute (iii) (d) Subroute (iv)

FIGURE 8 Efficient routes for {#4–#2}.

school. This paper will be the first to look at the optimisation for the second type, with WSB routes operating bus-stop-to-bus-stop with the final stop at the school.

As highlighted earlier, there is a busy road, Bradford Road, which naturally divides the catchment area into two subareas. Residents on the west side will have to cross Bradford Road in order to get to the school. To maximise the catchment area for WSB, we have located a total of five bus stops to cover the study area, two (Bus Stop #1 & #2) on the east side of Bradford road, two on the west side (Bus Stop #3 & #4), and the final stop (Bus Stop #5) at the destination, Shipley CE Primary School. As shown in Figure 7, with a radius of 100 m around each bus stop, the four bus stops prior to the final stop will cover most of the residents within the catchment area, with a maximum walking time of about 1–2 min from their door to the nearest bus stop. Note that from this point onwards, bus stops will be denoted as '#*n*' for simplicity.

4.2 | Selecting bus stops and sequencing

As explained earlier, before applying our model, we will need to select the stops and their sequencing. There are many possible combinations and sequencing of bus stops that can be considered. We define a WSB Line as a combination of stops in a predetermined sequence. For simplicity a WSB Line will be referred to as Line from this point onwards. Geographically, both #1 and #3 can be a natural starting point for a WSB line, with #5 as the destination. For example,

TABLE 3 Performance of each subroute for {#4–#2}.

Subroute	Walkability	Time (s)	Dose (μg)	Comments
(i)	287.20	256.94	1.417	Best time
(ii)	270.37	258.53	1.414	
(iii)	260.75	262.31	1.424	Best walkability
(iv)	268.86	259.54	1.413	Best dose

TABLE 4 Performance of each subroute for {#4–#5}.

Subroute	Walkability	Time (s)	Dose (μg)	Comments
(v)	378.50	384.53	2.188	Best time
(vi)	393.27	387.70	2.182	Best dose
(vii)	292.20	434.09	2.426	Best walkability

- Line #1 – #2 – #5
- Line #1 – #2 – #4 – #5
- Line #1 – #3 – #4 – #5
- Line #3 – #4 – #5
- Line #3 – #2 – #5
- Line #3 – #4 – #2 – #5

For illustration purposes, we choose three sequences of stops, Line A, B & C, as described below, to demonstrate how our route optimisation model can be applied to generate *efficient* routes for WSB.

Line A {#1-#2- #5} Line A would be a natural routing sequence for trips generated from the vicinity of #1 & #2, as both stops are located on the east side of Bradford Road.

Line B {#3-#4-#5} Line B would be another natural routing sequence for trips generated from the vicinity of #3 & #4, as both stops are located on the west side of Bradford Road.

Line C {#3-#4-#2-#5}Line C is an extended version of Line B, with #2 added as an additional stop to increase the catchment for the route.

4.3 | Optimising the routing between stops

Once a sequence of bus stops has been determined, the optimisation will begin with each pair within the sequence. In this case, Line A will be decomposed into two pairs of origin–destination (OD): {#1–#2} and {#2–#5}. Line B will be decomposed into two OD pairs: {#3–#4} and {#4–#5}. Line C will be decomposed into three OD pairs: {#3–#4}, {#4–#2} and {#2–#5}. Now altogether, we have five OD pairs, that is, {#1–#2}, {#2–#5}, {#3–#4}, {#4–#5} & {#4–#2}, for which we need to

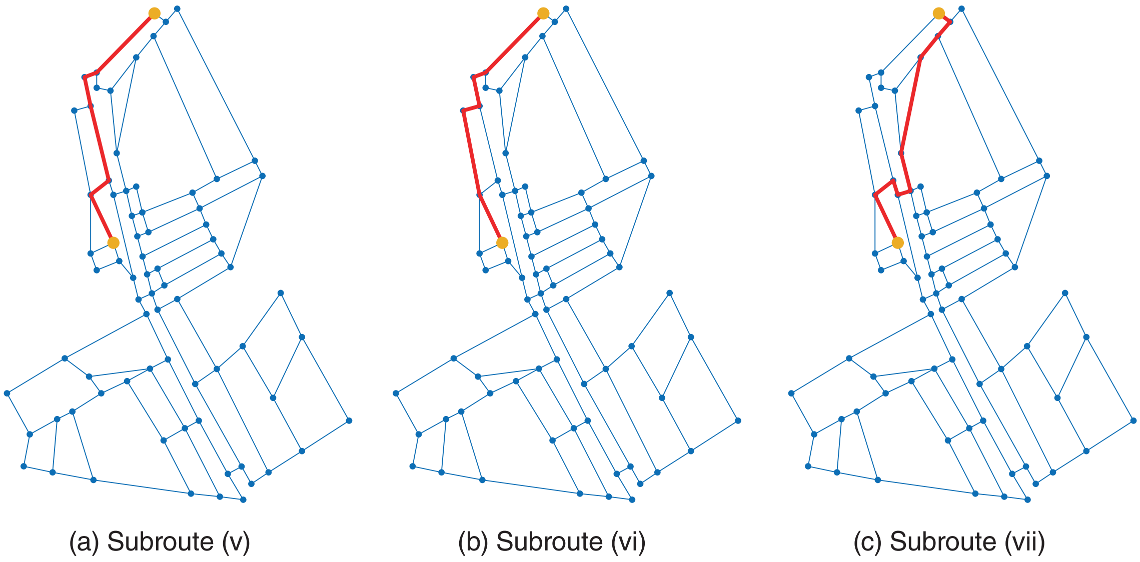

(a) Subroute (v) (b) Subroute (vi) (c) Subroute (vii)

FIGURE 9 Efficient routes for {#4–#5}.

apply the three-objective optimisation method that we have developed to find all the *efficient* routes between them. The meaning of a route being *efficient* is that we cannot improve the performance of the route in terms of any one of the three objectives without sacrificing another objective.

Let us look at {#4–#2} of Line C as an example. For this OD pair, there are four *efficient* routes as shown in Figure 8a–d. All four routes will start from #4 following the same links to get to the same crossing on Bradford Road. After the crossing, they will follow different links to #2. The performance of each subroute in terms of the three objectives are depicted in Table 3. Note that Subroute (i) has the shortest time of 257 s, while Subroute (iii) has the longest time of 262 s but the best performance in terms of walkability, and Subroute (iv) has the has the lowest dose.

Now let us look at what happens if the WSB does not go from #4 to #2 on Line C, but will go to the school directly, that is, {#4–#5} on Line B. For this OD pair, there are three *efficient* subroutes as shown in Table 4. Subroute (v) & (vi), as shown in Figure 9a,b, will cross Bradford Road nearer to the school so that they will not need to cross Otley Road. Subroute (vii), as shown in Figure 9c, will cross Bradford Road first to walk on the other side of the road but they will need to cross Otley Road near to the entrance of the school. The performance of the three subroutes is as shown in Table 4. The three choices are very interesting here as each of them performs the best in terms of one of the three objectives. Subroute (v) achieves the best time by staying along the main road most of the time; Subroute (vi) stays off the main road for a bit longer to reduce the dose to the lowest among the three; and Subroute (vii) has the best walkability among the three by using the off-road links on the east side of Bradford Road.

4.4 | The efficient WSB lines

By combining the efficient subroutes under Line A, B, and C, we obtain a set of potentially efficient routes. From this set, we determine the final set of efficient WSB routes for each line. The resulting WSB routes are as shown in Figures 10–12. The performance of the efficient WSB routes is summarised in Table 5. The efficient route options for each line and their performance are visualised in Figures 10–12.

As shown in Figure 10 and Table 5, Line A {#1–#2–#5} has only one efficient route. Finding only one efficient route in a network might be unusual mathematically, but this route is in fact a natural efficient route in this case. It goes through the green area where pollutant dose is the lowest and walkability would be the best. At the same time, it cuts through the area along a footpath with the shortest distance.

On the other hand, Line B {#3–#4–#5}, as shown in Figure 11 and Table 5, involves tradeoffs between all three objectives. As described earlier, the main tradeoffs are related to the subroutes for {#4–#5} where decisions of where to cross and whether to stay off or along the main road will affect the performance of the route in terms of the three criteria.

Line C {#3–#4–#2–#5}, as shown in Figure 12 and Table 5, is tested as an extension of Line B by adding #2 to increase the catchment. There are also four different efficient routes, due to the different characteristics of subroutes for {#4–#2}. By comparing and contrasting the results for different lines, for example, the efficient routes for Line C and Line B, we will be able to determine what might be the smallest additional time required to increase the catchment of a route with one additional stop, and at the same time, maintain low pollutant dose and high walkability. In this particular case, the best time for Line B {#3–#4–#5} is 662 s (11 min) (Option B1); by including #2 to form Line C {#3–#4–#2–#5}, the best time will be increased to 865 s (14.5 min) (Option C1). This means that an additional 203 s (3.5 min) would enable the pupils living around #2 to join the WSB to walk to school together with other pupils living around #3, #4 & #5. If the planner would like to improve the dose, Option C4 would be the best, while Option C3 would be the best in terms of walkability. As

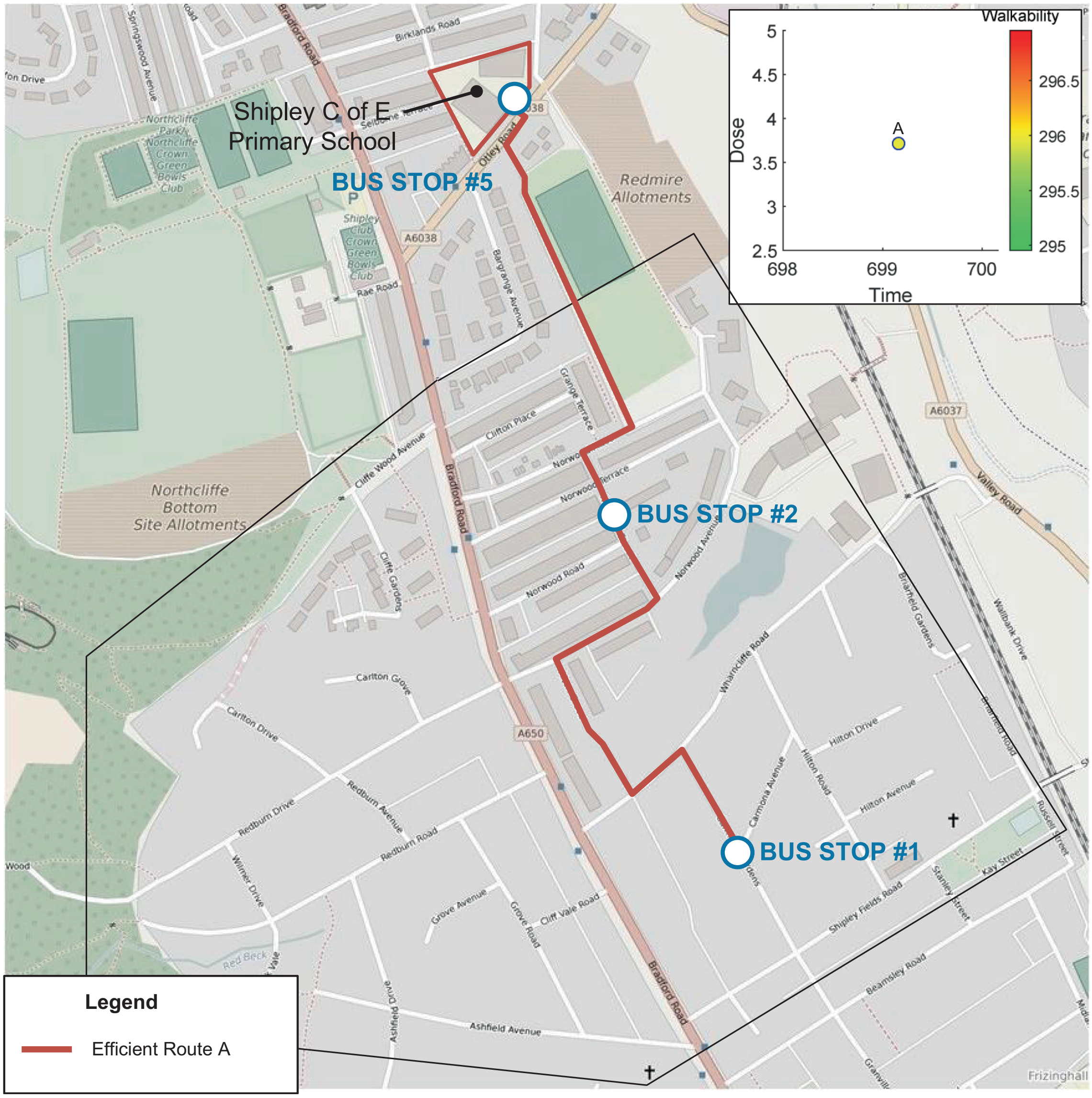


FIGURE 10 Efficient route for WSB Line A {#1–#2–#5}.

compared with Option C1, Option C4 can offer improvement of dose, while Option C3 can offer improvement of walkability, each at the expense of a different marginal increase in time.

5 | CONCLUSIONS AND SUGGESTION FOR FURTHER RESEARCH

We propose a new multi-objective route optimisation model to generate efficient routes for WSB to serve a predefined sequence of 'bus stops'. We consider three objectives, namely, time, pollutant dose and walkability, specifically designed to address the most important factors vital to the success and sustainability of WSB programmes, including time, environment, air quality, safety and comfort. Time was the only factor that had been considered in the WSB routing problem in the literature. In addition to time, minimising pollutant dose will enable health benefits from physical exercise to be achieved along the route. Walkability covers the needs of both parents and children in terms of their views on safety and comfort. Our goal is to help WSB planners to provide WSB services on a combination of *efficient* routes so that all children within the catchment area of a school can enjoy walking to school together, gaining the best health benefits that can be offered as well as having the most enjoyable experience.

Our walking network model provides a new method to model pedestrian movements within the catchment area of a school. Walking movements on different sides of the road and crossing movements at intersections and crossings are represented with specific links and nodes. This enables the assessment of the pollutant dose at a route level, taking into account the influence of localised air quality.

The application of multi-objective routing optimisation enables the trade-offs of different objectives among the efficient routes

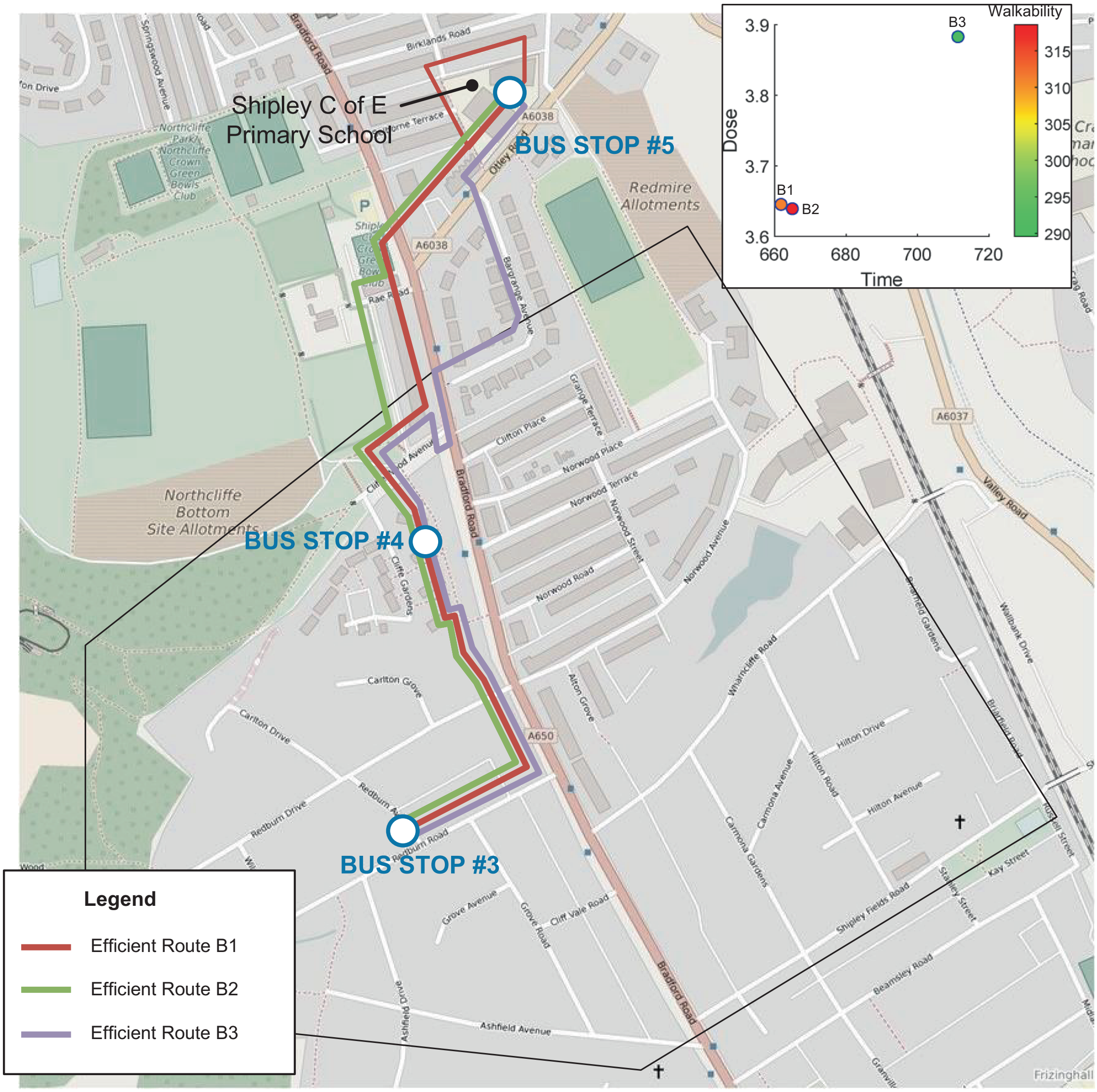


FIGURE 11 Efficient routes for WSB Line B {#3–#4–#5}.

generated. This will help the planner to select a set of WSB lines to be offered, covering the catchment area and utilising the resources available. For each line, a planner can also select one or more than one efficient route(s), based on trade-offs of their performances in terms of the three different criteria. With a case study in Bradford in the UK, we demonstrate how our optimisation model can be applied to generate efficient WSB routes to cover a specified catchment area of a selected school located on a busy road. We further demonstrate, for instance, how to assess the marginal time increase for an additional 'Bus stop'. Once the sequence of 'Bus stops' have been decided, further trade-offs can be made for improvement in dose or walkability by considering the marginal time increase required, which can be determined by comparing the performance in terms of the three objectives within the set of efficient routes identified.

The presence of trade-offs within the set of efficient solutions also means that a selected route is usually not optimal with respect to more than one objective. In our case study, we identified eight efficient routes for the three lines. For these routes, walking time varies between 661.77 and 869.99 s, pollutant dose between 3.64 and 4.660 μg, and unwalkability between 260.87 and 318.57. Hence rather than focusing on a true minimal walking time, we obtain walking times in an interval. Nevertheless, for some lines, it is possible that a single route is best for all objectives. This was the case for line A in the case study, indicating that this single route is indeed good for all aspects considered.

The empowerment of WSB schemes and their longevity ultimately depend on the children's enjoyment and their parents' satisfaction. By offering WSBs on the selected efficient routes, modal shift from being driven to walking to school can be most effectively facilitated, satisfying the needs of both children's and parents'. Hayes et al. (2022) propose a multicriteria decision analysis method to identify targeted development areas for WSB schemes. The model developed in this paper is a tool for the next vital step to initiate a virtuous walking-and-chauffeuring-to-school circle in the targeted areas.

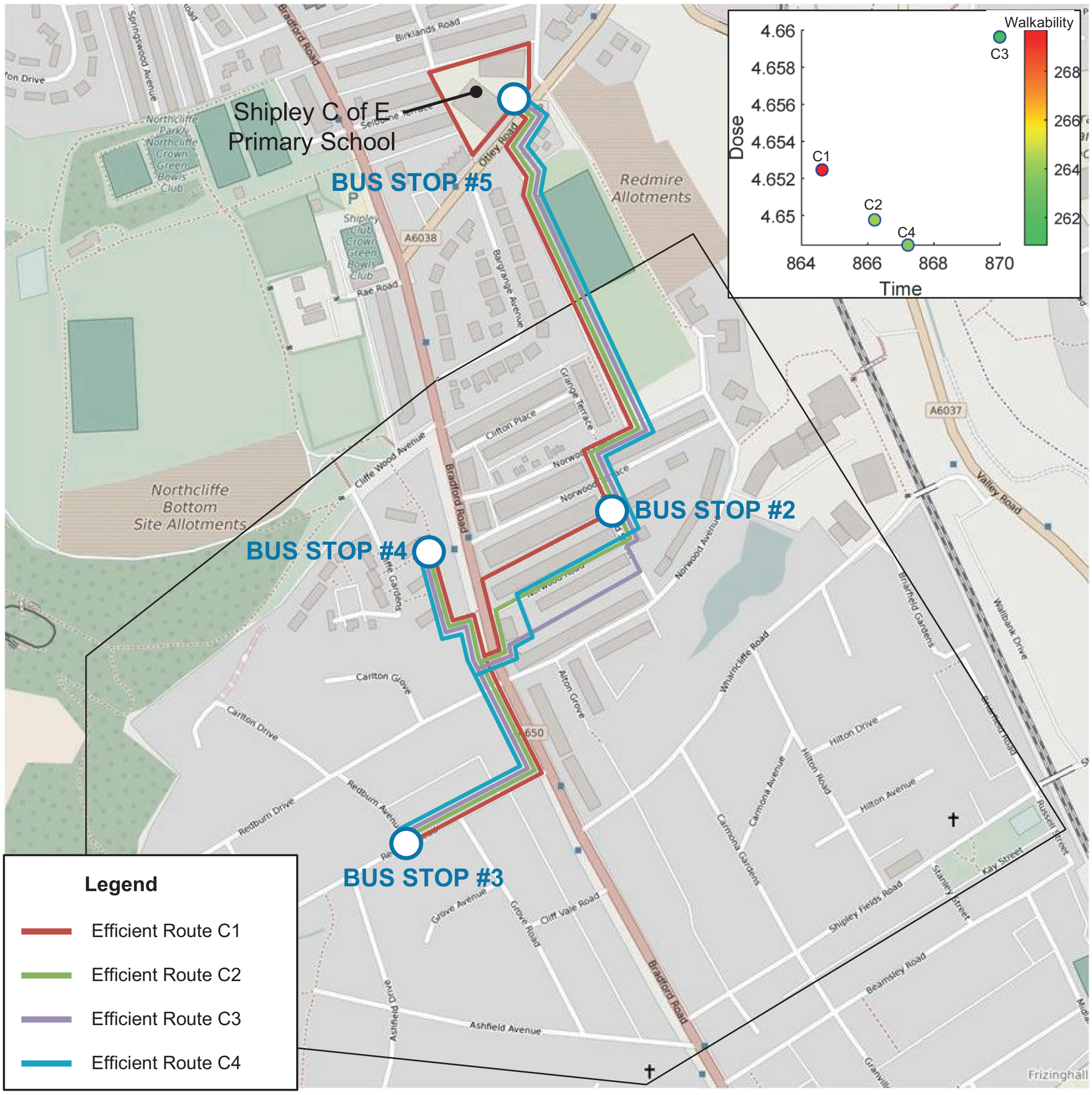


FIGURE 12 Efficient routes for WSB Line C {#3–#4–#2–#5}.

TABLE 5 Performance table for WSB Line A, B and C.

Efficient route option	Walkability	Time (s)	Dose (μg)	Comments
A	295.96	699.00	3.710	Best walkability, time and dose
B1	311.19	661.77	3.645	Best time
B2	318.57	664.93	3.639	Best dose
B3	289.58	711.32	3.883	Best walkability
C1	269.69	864.62	4.652	Best time
C2	264.07	866.21	4.650	
C3	260.87	869.99	4.660	Best walkability
C4	263.57	867.22	4.648	Best dose

It is important to note the limitations and data requirement of the proposed model. The proposed model essentially needs good quality data to support route-based assessment. For example, good air quality data is required to enable meaningful assessment of pollutant dose. In this study, we have had access to modelled air quality data at 1 m × 1 m grid level from the Bradford Council, which supports our analysis really well. On walkability assessment, the selection of factors in this paper has been conducted based on a comprehensive literature review, from which we have also adopted the weightings of the walkability factors. Depending on the country and location of the school, parents and children might have difference preferences. Planners might wish to adjust the selection of the walkability factors and the weightings to reflect their preferences.

Finally, this paper focuses on the multi-objective optimisation of WSB routing for a WSB line with predetermined sequence of 'Bus stops'. A WSB system with bus stops can help to increase the accessibility of WSB, ensuring that WSB will be accessible to all the residents in the catchment area. Our focus is on the WSB routing problem in this paper. We apply our multi-objective optimisation model to optimise the WSB routes to cover selected stops in a predetermined sequence. Further research topics include optimisation of both location and sequencing of 'Bus stops'. The location of bus stops is in itself an optimisation problem. They need to ensure that every home of a child participating in the WSB scheme in the catchment area is within a short walk (1–2 min in this study) of a WSB stop, and that the stop locations are suitable for groups of children to gather in terms of effects on health and walkability. Moreover, the scheduling of the WSB scheme in terms of the assignment of bus drivers to the WSBs offers further applications of optimisation tools to ensure an efficient operation of the scheme. These topics will be investigated in further research.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are provided by the City of Bradford Metropolitan District Council. Restrictions apply to the availability of these data, which were used under license for this study. The author(s) do not have the permission of City of Bradford Metropolitan District Council to provide the data.

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