Impact of traffic control measures in reducing pollutant dose by shifting from car commuting to walking to school

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Abstract

Traffic-related air pollution, especially emissions from car traffic significantly contributes to 73% of urban air pollution worldwide. Children are significantly exposed to this pollution while commuting between home and school. To reduce air pollution concentrations around school area many traffic management strategies have been investigated. This study employs a traffic (Newell's car following rule) and an emission model (PHEM) to assess the trade-off between pollutant concentration under different traffic control measures and changes in total pollutant dose resulting from an increase in the number of children driven to school. The experiment was conducted based on a primary school situated along a busy street, where increasing traffic volume leading to congestion is a major concern. The results indicate that reducing the number of children driven to school, implementing speed reductions, and optimising traffic signals significantly contribute to concentration reductions, thereby reducing the exposure dose for school-going children. The analysis emphasises the importance of holistic strategies aimed at modifying travel patterns around school areas to effectively mitigate emissions from vehicular traffic.

1 Introduction

Due to the rapid urbanisation and economic growth, urban air pollution is one of the most challenging and concerning issues for governments worldwide [1]. The World Health Organisation (WHO) lists air pollution as one of the greatest environmental health risks and calls for immediate actions to attain safe air quality for citizens. Exposure to air pollution is linked to premature deaths, health impacts, and welfare losses [2]. Children, one of the most vulnerable groups, face heightened susceptibility to the harmful effect of air pollution, evident in the WHO's report of 7 million premature deaths of which 600,000 are children [3, 4]. Children's exposure to higher concentrations than adults is a major health concern because of their developing immune system, breathing rates, physical growth pattern, and different metabolic capacities [5, 6, 7, 8]. Exposure to air pollution also has a significant impact on children's cognitive development, contributing to the progression of neurological disorders, autism, and learning deficiencies, with potential ramifications across the entire life course [9, 10, 11]. Hence, mitigating children's exposure to air pollution emerges as a critical objective for public health.

Traffic-related air pollution, especially emissions from car traffic, significantly contributes to 73% of urban air pollution [12]. Children are significantly exposed to this pollution while commuting between home and school, particularly by walking during peak pollution periods [13, 14]. Despite the short travel time between home and school, children receive a substantial portion of their daily pollutant dose while walking due to increased breathing rates and enhanced physical activity [15]. Rivas et al[16] estimated that children

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spent 6% of their time commuting but received 20% of their daily black carbon dose. On the contrary, active commuting to school is regarded as a sustainable transportation mode, advocated to promote physical activity [17, 18], support cognitive development [19], enhance social interaction[20, 21], develop healthy habits [22, 23], and mitigate ambient pollution in the vicinity of school [24, 25]. However, global statistics indicate a substantial rise in the modal share of children being driven to school over the past two to three decades both in developed and developing countries [26]. Paradoxically, opting to drive exacerbates traffic conditions and environmental pollution around schools, dissuading parents from allowing their children to walk. To break this cycle, reducing the number of children driven to school and ensuring lower pollution levels along home to school routes are crucial. A study by Mölter and Lindley [27] highlighted that the relative decrease in pollution exposure on low-pollution routes tends to surpass the relative increase in route length. A decrease in traffic around the school area not only fosters a safer and more appealing walking environment but also enhances children's physical well-being, ultimately contributing to ensuring sustainable mobility.

To reduce air pollution concentrations on busy urban roads or around points of interest (e.g., schools, hospitals) many traffic management strategies have been investigated. These endeavours typically concentrate on the advancement and implementation of innovative vehicle and fuel technologies, as well as the regulation and optimisation of traffic and travel activities [28]. A study by [29] empirically proved that changing the hypothetical speed limit outside the school from 30 km/h to 50 km/h could result in a 3% reduction in NO_2 concentration and a 2% reduction in PM_{10}. Additionally, a transition in the vehicle fleet from diesel to petrol vehicles was found to decrease these pollutants by 4% and 3%, respectively. Nevertheless, augmenting traffic speed in the vicinity of schools may elevate the likelihood of traffic accidents. However, these findings prompt the question of how the observed reduction or increase in pollution levels will influence the health of school-going children, whether they are driven or walking to school. This study employs a traffic and an emission model to analyse the interplay of mode choice (being driven or walking to school), the environmental conditions (air quality), and the impact on children's health (dose) under various traffic management scenarios. These scenarios include alterations in speed limits, modifications in traffic signal, and adjustments to non-school traffic volume.

2 Study area and data

For simulation purposes, the Shipley C.E. Primary School located in the Bradford District, United Kingdom, was chosen. This selection was done based on its strategic positioning along Otley Road, a thoroughfare characterised by the higher vehicular flow that crosses the neighbourhood and interfaces with Bradford Road (Figure 1). Additionally, the school does not have a school bus provision. As a result, children living in the catchment area must rely on either cars or walking to school due to limited public transport coverage and a lack of facilities for cycling to school. Notably, the traffic data used in this study is conveniently accessible on the official website of the Department for Transport [30]. To do the simulation, the traffic network and pertinent signal data for Otley Road were extracted from OpenStreetMap. The existing speed limit for Otley Road is 30 mph. The traffic simulation encompassed the time frame from 7:00 AM to 9:00 AM. Notably, the influx of school-related traffic commenced between 8:30 AM and 9:00 AM, aligning with the scheduled opening time of the school gate from 8:45 AM to 9:00 AM. Furthermore, considering the school's current capacity, set at 220 children, the simulation was constrained to encompass a maximum of 220 school cars. This assumption is grounded in the premise that each child is transported to school by an individual car.

3 Methodology

3.1 Traffic flow model

In this study, we implemented Newell's car following model in Eclipse SUMO by modifying the default Krauss' model. According to Newell's model, trajectory of the following vehicle will be influenced by the leading vehicle. If in each segment i of the link there are k number of vehicles at time t and the k^{th} vehicle is following the $(k-1)^{\text{th}}$ vehicle, the spacing headway Δx_k between follower (k^{th} vehicle) and leader ($(k-1)^{\text{th}}$

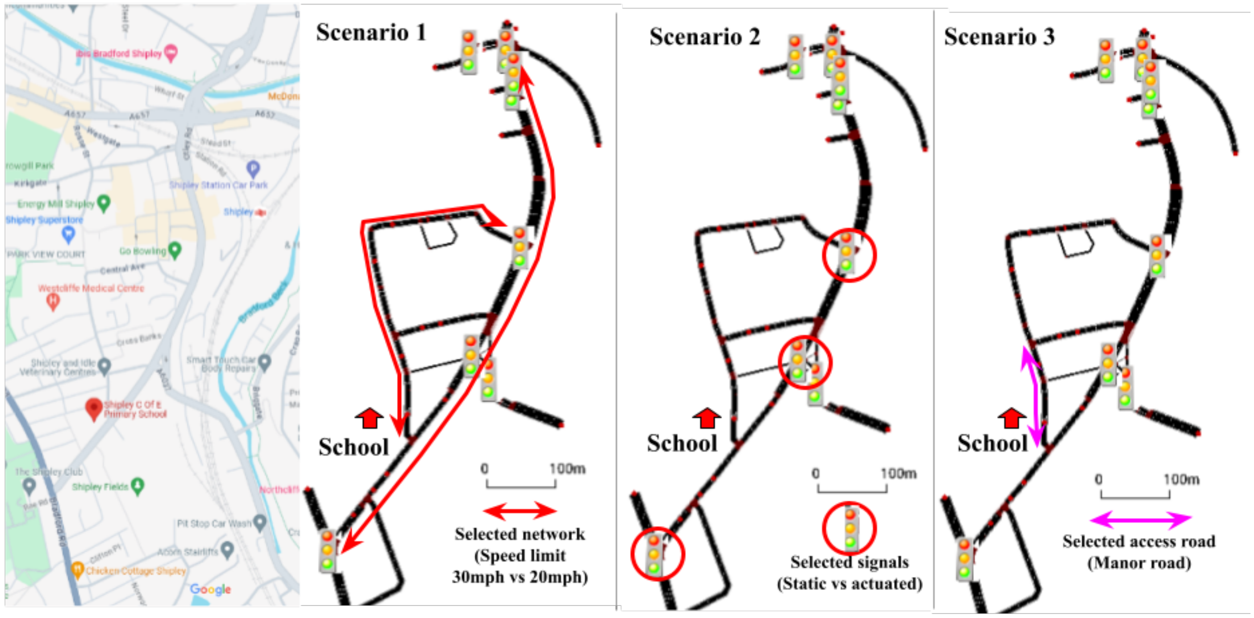

Figure 1: Study location map

vehicle) can be assumed to be linearly correlated with speed v:

$$\Delta x_k(t) = \tau_k v_k(t) + \delta_k \quad (1)$$

Here, τ_k is the time taken by the follower to adjust its speed after observing leader's action δ_k is the minimum safety spacing the follower wants to maintain at speed 0. In this study, τ_k and δ_k were assumed to be constant for each driver but vary from drive to driver. The desired speed was specified as minimum speed of the two speed setting:

$$v_{desire}(t + \tau_k) = min(V_{max}, v_k(t) + a_k(t)\tau_{k,t}) \quad (2)$$

$$x_k(t + \Delta t) = x_k(t) + v_{desire}(t + \Delta t) \times \Delta t \quad (3)$$

3.2 Emission modelling

Emissions within the simulation were computed employing the Eclipse SUMO PHEMlight emission model. PHEMlight relies on data files containing the parameters pertinent to the modelled emission classes. The model itself was formulated through the utilisation of characteristic emission curves, delineating the emission quantity [g/h] in relation to the actual engine power of the vehicle. These curves were generated through PHEM, utilising representative dynamic real-world driving cycles. Consequently, the emission and fuel consumption outputs for a vehicle during each simulation step were derived by calculating the power requisite for the vehicle.

$$P_e = (P_{rolling\ resistance} + P_{air\ resistance} + P_{acceleration} + P_{road\ gradient})/\eta_{gearbox} \quad (4)$$

Here, $P_{rolling\ resistance} = (m_{Vehicle} + m_{Load)} \times g \times (Fr_0 + Fr_1 * v + Fr_4 + v^4) \times v$
$P_{air\ resistance} = (Cd \times A \times \rho/2) \times v^3$
$P_{acceleration} = (m_{Vehicle} + m_{Rot} + m_{Load)} \times a \times v$
$P_{road\ gradient} = (m_{Vehicle} + m_{Load}) \times Gradient \times 0.01 \times v$

$\eta_{gearbox} = 0.95 \times$ *(average efficiency)*

To compute the power demand, the emission factors are selected from the PHEM database, and the coefficients are determined based on the type of vehicle and engine used by the vehicles (Euro-4 passenger car with petrol and diesel engine). In our simulation, we considered a mix of 50% petrol and 50% diesel car for both school and non-school car.

3.3 Modelling air pollution dose from traffic flow model

The concentration C of pollutant per volume (g/m^3) generated by the entire vehicle fleet according to Dirks et al. (2002, 2003) [31, 32]is:

$$C = \frac{\text{(Total emission by fleet)}}{u\Delta Z} + C_B \tag{5}$$

here, u is the wind speed in m/s. and was assumed to be the average morning wind speed, ΔZ is the box height[1] in m. It was assumed that at the steady state traffic flow u and ΔZ were constant. Additionally, we made the assumption that all background concentration (C_B) values are zero, signifying that all pollutants originate exclusively from the road itself. This assumption is particularly relevant for a school situated within a residential area. We also assumed that that the concentration remains the same, whether an individual is traveling by car or walking.

3.4 Dose analysis

The air pollution dose D a person experiences is the product of the concentration to which they are exposed, the travel time and the breathing rate (minute ventilation).

$$D = C \times t \times \beta \tag{6}$$

Here, t is the travel time in minutes and β is the breathing rate. Now, we formulated the simulation to estimate the air pollution dose for children driven by car and children walking to school.

$$n_t = n_w + n_d \tag{7}$$

Here, n_t is 220 (current school capacity). $n_w$is the number of children walking to school and n_d is the number of children driven to school. We assumed that all children will either be driven to school or walk to school and the total number of children is equal to the school capacity. Dose for all children walking to school given total traffic flow f_t (vehicle/hour) is this:

$$D_w = \sum_{i=1}^{n} C(f_t, \theta) \times t_{w,i}(l) \times \beta_w \tag{8}$$

Also, dose for all children driven to school given total traffic flow f_t is this:

$$D_d = \sum_{i=1}^{n} C(f_t, \theta(f_t)) \times t_{d,i}(l, \theta(f_t)) \times \beta_d \tag{9}$$

Here, l is the distance and θ is the vector of other factors (e.g., velocity, acceleration, waiting time at the signal) at traffic flow f_t affecting the concentration of pollutant.

4 Results and discussion

In this study, we assessed the trade-off between pollutant concentration under different traffic control measures and changes in total pollutant dose resulting from an increase in the number of children driven to

[1]The box model proposed by Hanna et al., 1982 [33] assumes a constant emission rate along a road, with pollutants being uniformly mixed within a two-dimensional box of height ΔZ

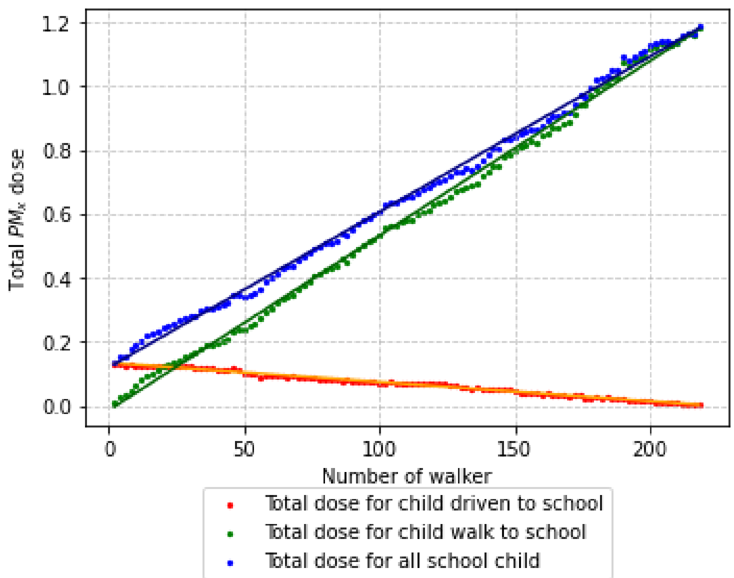

Figure 2: Experimental simulation at existing condition

school, simultaneously a decrease in the number of children walking to school. Three different traffic control strategies were evaluated to estimate the total dose (PM_x) for children walking to school and driven to school under the circumstance of existing traffic flow. Figure 2 shows the experimental results under existing traffic conditions (30 mph speed, static traffic signals, flow across access road), illustrating how a decrease in the number of children driven to school leads to an increase in the number of walkers. Figure 3 shows the changes in concentration of pollutant before and after imposing new traffic control measures. Given that the background traffic flow, representing the current hourly flow, remains constant throughout the experiment investigating the impact of increased school car on PM_x concentration, the level observed when there is no school car. Figure 4 shows the summary of simulation results. In the left column, the figures represent the total dose for children who are driven to school, while in the right column, the figures represent the total dose for children walking to school.

Results indicate that as the number of walkers increases, the total dose for children who are driven to school is likely to decrease (Figure 2 and Figure 4). However, there is a rising trend in the total dose for walkers, despite a decrease in school- traffic around the school area. Encouraging children who are typically driven to school to walk could help reduce the total dose inhaled during the car journey. But, the simulation results underscore the significant contribution of total dose to walking children from other factors, including the location of the school and non-school-related traffic.

4.1 High speed vs. low speed

The empirical evidence indicates that traffic-related emissions are significantly influenced by the speed limit allowed on roads. A strict speed limit has been advocated to mitigate exposure and health effects for individuals residing near roads [34]. This study employs a combined traffic and emission model to estimate the concentration of PM_x in the vicinity of a school under various speed limit conditions. The comparison involves testing the existing speed limit ($30mph$) against a reduced speed limit ($20mph$). Results demonstrate that, under current traffic flow conditions at the reduced speed limit, the PM_x concentration around the school area decreases by 4% to 8% (Figure 3). However, an observable increase in concentration is also noted as the number of children driven to school increases. This suggests a contribution of emissions from both non-school and school traffic passing by the school located along a busy road. Moreover, with the implementation of the reduced speed limit, the total pollutant dose for children driven to school increases due to the extended travel time required to complete the school trip. This prolonged exposure leads to a higher pollutant dose through inhalation. The pollutant dose for children driven to school exhibits a

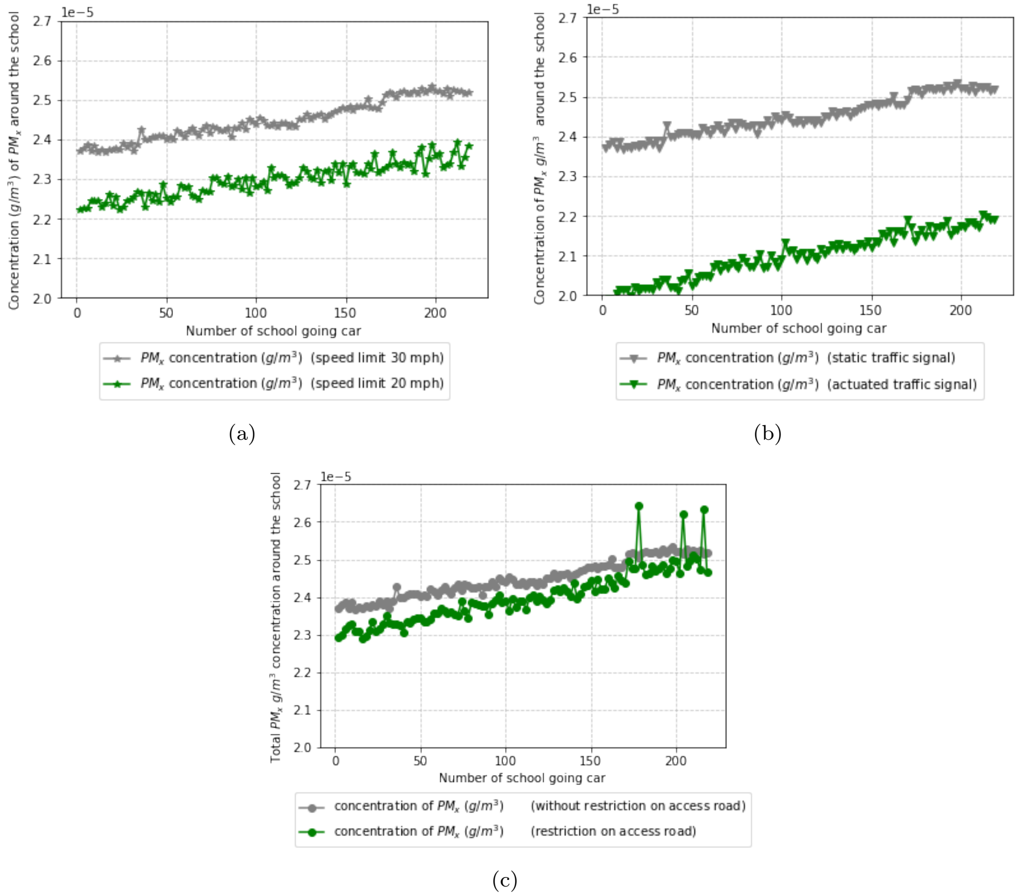

Figure 3: Contribution of school going cars on the concentration of PM_x at (a) different speed limits (30 mph vs 20 mph), (b) different traffic signal type (static vs actuated), (c) access road closure for non-school traffic.

decreasing trend, coinciding with an increase in the number of children walking to school. As speed limit restrictions are imposed, the pollutant dose for children walking to school decreases as more children opt for this mode (walking) of transportation (approximately 10%) (Figure 4). Additionally, this decrease in the total pollutant dose coincides with a significant reduction in school-related traffic around the school area.

4.2 Static vs. actuated traffic signal

The impact of traffic signal control on vehicular emission is well-established, as it affects different parameters such as vehicle waiting time at signals, acceleration and deceleration, queue length, and manoeuvrability. In this study, we investigated how signal control may influence the pollutant dose for school-going children. The chosen school, situated along a busy street, has its traffic movement regulated by four major signals. We examined the contribution of these signals to emissions under both static [2] and actuated traffic signal [3] conditions.

The results indicated that actuated signals significantly reduced the PM_x concentration around the school (approximately 12% to 17%) (Figure 3). Through optimised traffic signal control based on time gaps, even with an increase in school-related traffic, the total emissions from non-school traffic are lower compared to situations where signals are static. Similar to the concentration findings, the total PM_x dose is substantially lower under actuated traffic signal conditions for both children driven to school and those walking (Figure

[2] Fixed phase duration

[3] Phase prolongation based on time gaps between vehicles

4). The optimised signals lead to reduced travel time and exposure for children driven to school. Also for those walking, the concentration is substantially smaller due to reduced delay at the signal, resulting in a reduced pollutant dose for children walking to school.

4.3 Road closure for non-school traffic

A widely used approach to mitigate emissions and concentration resulting from vehicular traffic involves alterations in traffic flow patterns. Studies have demonstrated a noteworthy reduction in emissions linked to the decrease in traffic volume achieved through the closure of roads to vehicular traffic [35]. In this particular investigation, we sought to assess the impact of restricting vehicular traffic along the access road (Manor Road).

In the selected context (Otley road and Shipley primary school), our findings indicate that closing access roads for non-school traffic results in a decrease in emissions and concentration. However, with the increase in school traffic around the school area also leads to an increased concentration, aligning with our hypothesis. But, the decrease in concentration does not result in a significant reduction in the total dose for school children, whether they are driven to school or walking. This phenomenon arises due to prolonged queues on Otley Road resulting from the altered routes taken by other non-school traffic. Given the school's location along a busy street, restricting access roads did not yield a substantial reduction in pollutant dose for both children walking and those driven to school exhibited an increase in dose inhalation even after the imposed restrictions on the school street. This outcome suggests that, to effectively decrease pollutant exposure for school children attending institutions situated along busy streets, traffic calming strategies should be implemented not only on access roads but also on the main thoroughfares contributing significantly to vehicular movement.

5 Conclusion

In this study, we utilised micro-simulation (flow simulator linked to emission model) to elucidate the impact of different traffic control strategies adopted around the school area. The aim of these strategies specifically focused on the reduction of traffic-related air pollution and the consequent PM_x dose for school-going children, whether walking or driving to school. In contrast to prior research by Tang et al. [29], which indicated a reduction in emissions with higher speed limits, our investigation reveals that a strict speed limit is associated with emission reduction, albeit leading to an overall increase in the total dose for school-going children. Additionally, our study illustrates that road closure, often linked with reduced pollutant dose, leads to an increased total dose for both walkers and children driven to school. This outcome arises from the formation of longer queues along the main road, resulting from restrictions on the access road. Significantly, the presence of a traffic signal in front of the school emerges as a crucial factor in diminishing pollutant concentration and dose. The comprehensive analysis underscores the necessity of holistic strategies aimed at altering travel patterns around school areas to effectively mitigate emissions from vehicular traffic. Moreover, this study conducted its investigation in the context of a school situated along a busy road, accounting for the contribution of non-school traffic to the total dose estimation. However, future research is imperative, particularly around schools located in cul-de-sacs, to explicitly assess similar effects concerning school traffic arising from children being driven to school. For this experiment, we only considered children who were driven to school or walked. However, including cars driven by staff members would be an interesting addition for future research.

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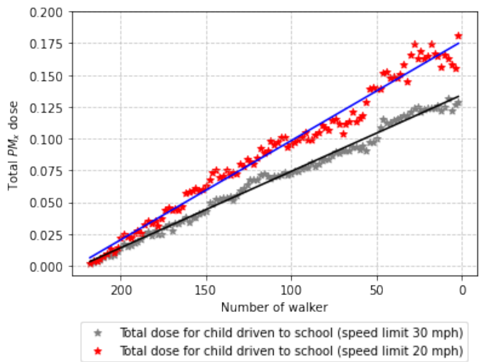
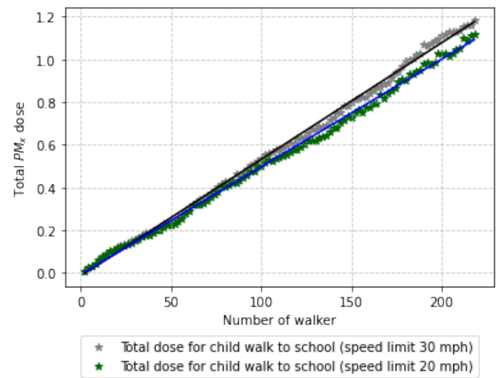


(a)



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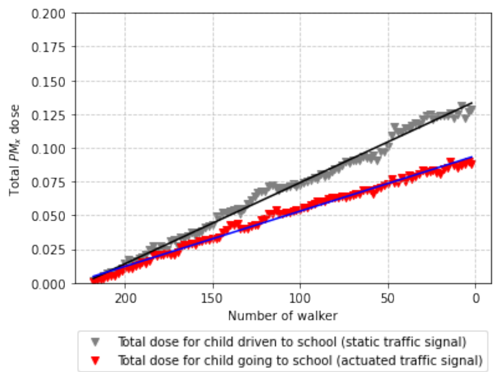

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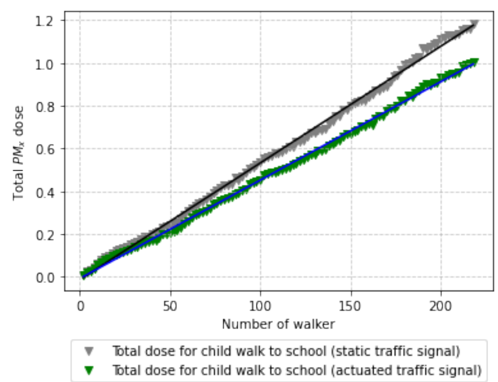

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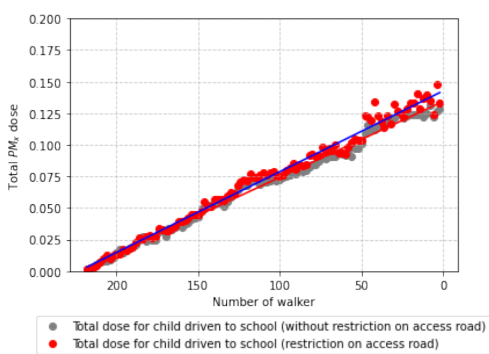

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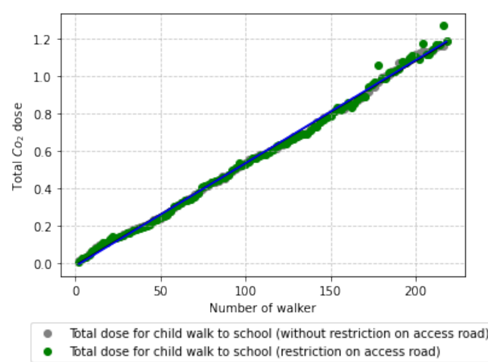

(f)

Figure 4: Total dose of PM_x at (a and b) different speed limits (30 mph vs 20 mph), (c and d) different traffic signal type (static vs actuated), (e and f) access road closure for non-school traffic

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