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RESEARCH

# Probabilistic Transport-Induced Emissions and Health Risks for Adelaide, South Australia

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## Abstract

The research aims to assess the risks associated with the transport-induced emissions (major criteria pollutants) in Adelaide, South Australia. A stochastic emission modelling strategy was implemented for a probabilistic risk assessment of the transport system for current and future scenarios, by analysing the road specific transport system data. The simulated result suggests that NOx and $PM_{2.5}$ risks are significant at about 35% of city areas, especially along the roads with heavy vehicle concentration and higher traffic. The risk will significantly increase in 10 years if the current practice persists, demonstrating a high probability (more than 60%) of emissions above 150% of the air quality standard. The research suggests that appropriate planning is necessary to cope with the development needs for the system's future sustainability.

**Keywords** Spatial analysis · Probabilistic emission modelling · Risk analysis · Vehicular emissions · Adelaide

## 1 Introduction

Motor vehicles are mainly recognised for emissions, such as nitrogen oxides (NOx), carbon monoxide (CO), particulate matter (PM) [$PM_{2.5}$ mainly with particle size less than 2.5 µm] and volatile organic compounds (VOCs) [1–6]. Alongside the World Health Organization (WHO), several other research has identified the high concentration of these emissions as a significant risk factor for global public health [7–15]. However, as transportation is substantially important in circulating economic movement, the relationship between human health and vehicular-induced emission is getting more complex and must be regularly assessed. While a high-density monitoring system is ideal for predicting city pollution scenarios, often it is not practical due to high investment and maintenance. Therefore, emission models are becoming increasingly important for evaluating the air quality of transport networks, which allows addressing system traits that can lower the overall pollution level as well.

Emission modelling credibility is affected by many factors; vehicle fuel and travel characteristics, along with the engine technology, determine the rate of emissions from a vehicle [16–20]. Therefore, this research aimed to develop a more statistically sound and spatially varied emission modelling approach (mesoscale modelling considering city-level variability of characteristics) that can reduce the drawbacks in the commonly practised deterministic emission modelling considering average data. Alongside, instead of a one-dimensional judgement of the emission risks (risk vs pollution level), this research also aimed to implement a more coherent probabilistic risk assessment method (risk vs pollution level vs probability of pollution level) [21] for a city due to vehicular emissions. Although all emissions, including greenhouse gases and those formed secondarily from chemical reactions [22, 23], are important in evaluating the transportation system, this study concentrated only on the primary criteria pollutants [24, 25] emitted from vehicles (NOx, $PM_{2.5}$ and CO).

While estimating the emissions for a city, the transport system parameters are not constant and might vary on a daily basis. A model that does not consider the probability of the variation of these parameters can be misleading. The city-level vehicular emission inventories widely adopts the deterministic emission modelling approach, where the average parameters (traffic volume, speed, etc.) are considered without considering their probable diurnal or other

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variations [3, 4, 26, 27]. When the large number samples indicating the variations are difficult to collect, a stochastic model may incorporate the variability of the transport system parameters via generating a sufficiently large number of samples by randomising parameters using the known statistical distribution of these parameters. Stochastic modelling is widely used in many fields to handle the uncertainty of parameters [28–31]. Therefore, adopting the approach in emission modelling is an innovative strategy to obtain more statistically robust estimation. Although the new modelling approach would not reduce the uncertainty ultimately, and the assumptions made here would simplify the system to some extent, the model effectively assesses the significance of the assessed pollution level and help adapting new transport system strategies to avoid a highly probable scenario. Similar research on probabilistic emission modelling was conducted for Bangladesh [32, 33], which showcased the associated risks and mitigation strategies. A similar base model is adapted and modified to study transport-induced emissions for Adelaide city. The new model for this research considers spatial distribution of high-density road links, normal distribution of each traffic volume and their speed, adaptation of Australian risk standard, etc. The Australian ambient air quality standard for criteria pollutants [25], which matches the WHO guidelines on the effects of pollution [34], was used to assess the risk of exceeding the limit emissions and corresponding magnitude of risk. The magnitude of risks and the probability of occurrence of that emission level are considered here to assess the risk severity from generated vehicular emissions. The characteristics of Adelaide's conventional on-road transportation system were taken into account for this study to assess the risk scenario for 2020. Then, potential change in the traffic system, as well as several hypothetical transport scenarios, in the next 10 years were also evaluated in this research to predict 'what' might happen 'if' a scenario prevails in Adelaide in the future.

Adelaide, the capital city of South Australia, has a reputation for better living. As a developing city, its population is growing (population—1.33 million, growth rate—1%) [35]. Consequently, the number of vehicles is significantly increasing in Adelaide (approximately 1% per annum for all vehicles) [36]. The emissions generated from these vehicles can affect the quality of living. This research assessed the risk scenario of Adelaide and evaluated the cause-effect relationships of future scenarios. Such a relationship can indicate what policies to be implemented for the sustainability of the transport system [27, 37, 38], which might support the transport policy directions for Adelaide and other similar cities. The on-road fleet characteristics in Adelaide are diverse (engine size and technology) and utilise a variety of fuel types (petrol and diesel mainly) [36, 39] (Fig. 1). Despite having a structured public transport system [40], private vehicles provide the majority of work-related travel (approximately 60%) [41, 42]. Adelaide is an example of a growing city from a developed economy, where the pollution risks and planning directions can be evaluated due to the city's expansion and the features of its transportation system. Except for the gross inventories carried out as part of 'national inventories', not much study has been done on Australia's vehicle emission inventory [43, 44]. There has been substantial particle analysis for the Sydney region [45] only among all the cities. Reasonably, minimal research was conducted on Adelaide's vehicular emission inventory [46, 47]. Therefore, research explicitly analysing the transport system characteristics, the probability of risks for the emissions and the 'what-if' analysis depicting what might change the risk scenarios for Adelaide is important for developing a risk analysis structure and analysing the sustainability of transport systems.

## 2 Research Methods

Private vehicles (passenger vehicles and motorcycles) are the most dominant component in the vehicle fleet in Adelaide (about 80% ohe total registered vehicles). In contrast,

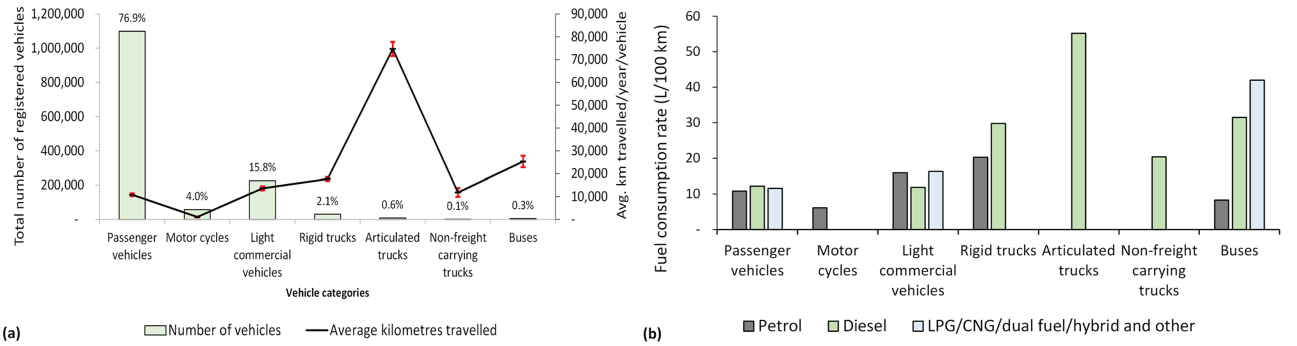

**Fig. 1** **a** Total registered number (and percentages) and average travel distance of different vehicle categories in Adelaide city. **b** Rate of fuel use by vehicles in Adelaide (data source: Australian Bureau of Statistics [ 36, 39])

on average, commercial vehicles travel more distances (around three times than private vehicles) (Fig. 1a). The fuel consumption rate in various vehicle categories (engine and fuel varied) is provided in Fig. 1b. Therefore, due to their connection to businesses, all types of vehicles may be prominent in the majority of road linkages [48]. However, the freight-carrying vehicles mainly travel interstate and might be prominent in some of the specified road links. With the increasing vehicle numbers (approximately 1% per annum) [36], many of the major/arterial roads almost reach their capacity during peak times. Therefore, assessing the pollution scenario and associated risks throughout the city is crucial to analyse the magnitude of both high- and low-risk zones. The positioning of the study area (Adelaide city) and the typical annual average daily traffic (AADT) range on its major road links at peak and off-peak hours are shown in Fig. 2.

### 2.1 Vehicular Emission Assessment: Probabilistic Estimation

The tier-2 vehicular emission inventory method developed by European Environment Agency (EEA) [1] is principally similar to the US national emission inventory guidelines [50] and was adopted by many studies [18, 32, 33, 51]. The method was used in on-road vehicular emission modelling for this study (Eq. 1):

$$\text{Emissions}, E_p(\text{g/km/day}) = \sum\nolimits_x \sum\nolimits_y \left(AADT_{xy} \times EF_{pxy}\right), \tag{1}$$

where $p$ = pollutants (e.g. NOx, PM, CO); $x$ = vehicles (e.g. private vehicles, bus, truck, articulated trucks, motorcycles, etc.); $y$ = fuels used (petrol, diesel, LPG); $AADT$ = yearly average of daily traffic and $EF_{pxy}$ = emission factor of each pollutant ($p$) corresponding to vehicle ($x$) and fuel being used ($y$) (g/km). Sixty-seven road linkages from the city's main road network were chosen as representative sample locations for the modelling. The density of the assessment nodes is shown in Fig. 3, denoting higher sampling concentrations around city and traffic corridors and lower concentrations away from the city.

While there are several variables that might affect emissions, the stochastic modelling developed handled the fluctuations in traffic volumes (AADT in Eq. 1) and the relationship between fuel usage and vehicle speed. However, as the availability of such data is limited for Adelaide city, Monte-Carlo simulation method was implemented in this study, where a large number of data were generated randomly within the probable range of traffic volume and vehicle speed. While the actual distribution of traffic was absent, it was considered normally distributed in this study. The assumption might be logical considering the traffic distribution over the peak and off-peak hours and variations for different days of the week. The emission model was formulated accordingly for the randomly generated data using Eq. 2, by writing a computer program (using computer programming

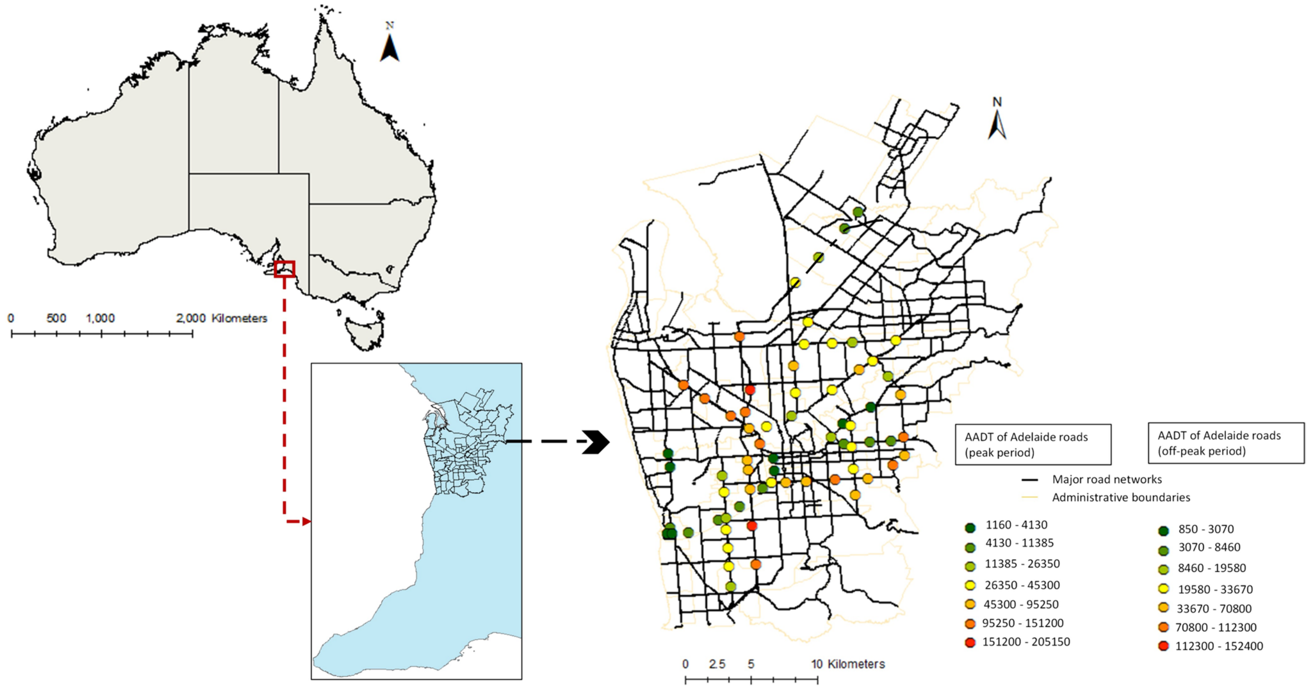

**Fig. 2** The main road networks in Adelaide and the AADT at different road links of Adelaide city [data source: Department of Infrastructure and Transport of South Australia; road network map [49], AADT data [48]]

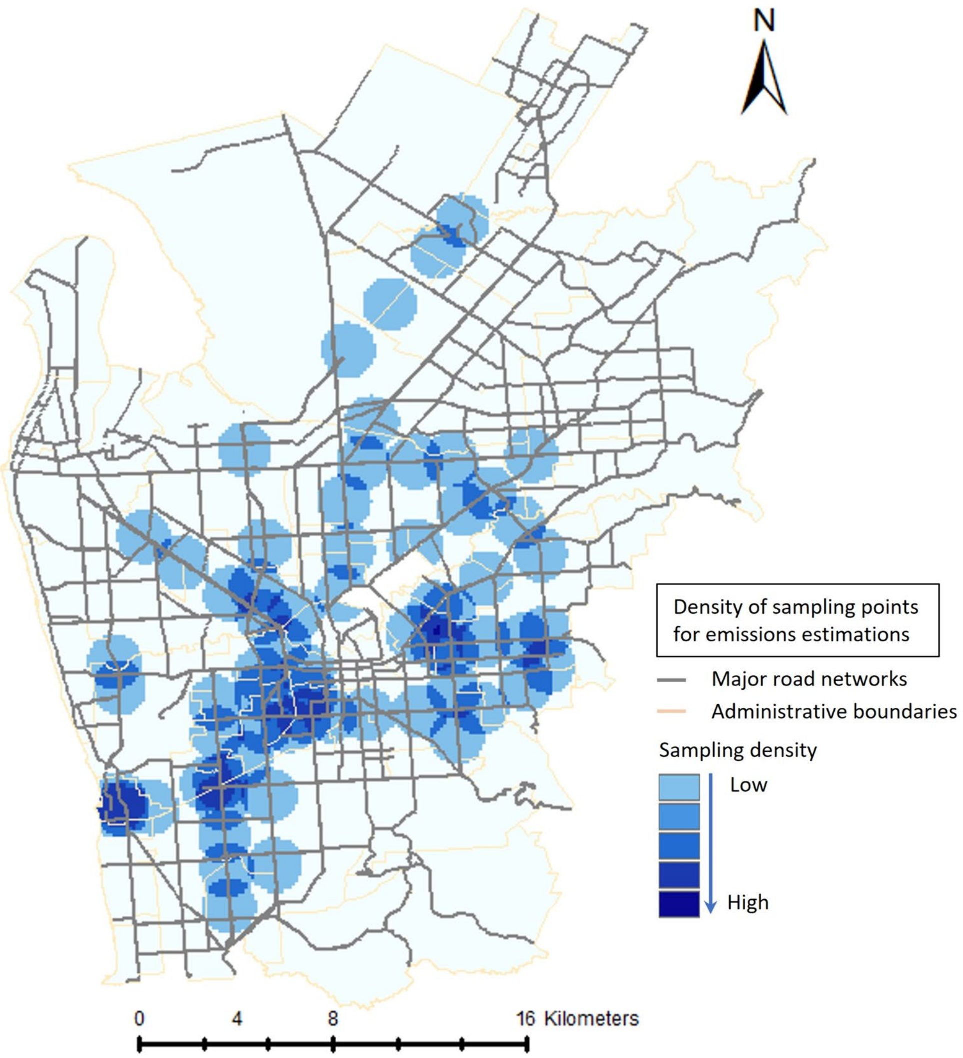

**Fig. 3** The density of sample locations designating representative road linkages for emission estimation in Adelaide

language vb.net) that can generate random samples within the specified range and handle all the road links simultaneously. The model, probability density function, is expressed mathematically as:

$$f(z) = \frac{e^{\frac{-(z-\mu)^2}{2\sigma^2}}}{\sigma\sqrt{2\pi}}, \tag{2}$$

where $z$ = emissions; $\mu$ = mean of emissions and $\sigma$ = standard deviation of emissions.

The authors implemented the same strategy previously for a different city, which showed the substantiality of considering the emission probability [32, 33]. Iqbal et al. [32] produced stable findings with 20,000 randomly generated samples (conservative value),the same randomisation strategy was used in this study. The developed code thus simulated about 14 million data at a time and generated road link-specific outputs. Figure 5 provides a schematic layout of the probabilistic assessment technique, outlining the inputs and presumptions used.

- The traffic volume range (highest and lowest) was required for the randomisation of data. Therefore, link-specific AADT data was first obtained from the government records [48]. The total AADT was then segmented according to vehicle categories (Table 1) based on the government statistical data [36] on the type of vehicles and their fuel consumption. Few assumptions while doing the segmentation include:
  - Eighty percent of passenger cars were considered using gasoline, while 10% using diesel and 10% using LPG (liquid petroleum gas). Out of the gasoline passenger cars, 40% with engine capacity more than 2000 cc (cm3), while rest are equally distributed in 2 groups.
  - Light commercial vehicles operated in diesel.
  - All diesel passenger cars had an engine capacity of more than 2000 cc.
  - Ninety-five percent of the buses operate in diesel, and the rest in LPG.

**Table 1** Tailpipe emission factors (EF) (mg/g of fuel consumed) for key pollutants tailored for Adelaide city, Australia, considering the specific vehicle standards (Euro 3/Euro 4) for the city, and the % of AADT considered for each category of vehicles

| | **Emission factors (mg/g of fuel consumed)** | | | | | | **% AADT in each category of vehicles** |
|---|---|---|---|---|---|---|---|
| | **NOx** | **$PM_{2.5}$** | **CO** | **NOx** | **$PM_{2.5}$** | **CO** | |
| | **Euro 3** | | | **Euro 4** | | | |
| **Gasoline** | | | | | | | |
| Passenger car | | | | | | | |
| < 1400 cc | 1.75 | 0.02 | 38.21 | 1.11 | 0.02 | 12.68 | 17.29 |
| 1400–2000 cc | 1.48 | 0.02 | 29.70 | 0.94 | 0.02 | 9.97 | 17.29 |
| > 2000 | 1.06 | 0.01 | 18.37 | 0.67 | 0.01 | 6.38 | 27.67 |
| Light commercial vehicles | 1.29 | 0.01 | 50.50 | 0.64 | 0.01 | 20.10 | – |
| MC-2 (> 50 cc) | 7.78 | 0.27 | 75.83 | 0.78 | 1.78 | 75.83 | – |
| MC-4 (> 50 cc) | 5.39 | 0.10 | 84.17 | 5.39 | 0.10 | 84.17 | 3.83 |
| **Diesel** | | | | | | | |
| Passenger car | | | | | | | |
| < 2000 cc | 14.18 | 0.75 | 1.76 | 10.93 | 0.62 | 1.76 | – |
| > 2000 cc | 10.68 | 0.56 | 1.33 | 8.23 | 0.47 | 1.33 | 7.68 |
| Light commercial vehicles | 11.57 | 0.88 | 5.31 | 9.34 | 0.46 | 4.21 | 16.04 |
| HDV truck (> = 7.5 t) | 21.04 | 0.45 | 4.67 | 13.12 | 0.08 | 0.38 | 0.68 |
| HDV bus | 25.63 | 0.57 | 7.30 | 14.81 | 0.13 | 0.61 | 0.29 |
| HDV truck (7.5–16 t) | 27.74 | 0.57 | 6.27 | 17.10 | 0.10 | 0.46 | 2.18 |
| **LPG** | | | | | | | |
| Passenger car | 2.02 | 0.00 | 38.95 | 1.11 | 0.00 | 18.25 | 6.92 |
| Light commercial vehicles | 1.15 | 0.00 | 22.20 | 0.63 | 0.00 | 10.40 | – |
| HDV bus | 18.02 | 0.02 | 1.80 | 18.02 | 0.02 | 1.80 | 0.13 |

EF calculated based on EEA methodology [1], % AADT calculated based on Australian Bureau of Statistics vehicle data [36]

*MC* motorcycle (4 stroke), *HDV* heavy-duty vehicles, *LPG* liquid petroleum gas, *cc* engine size, $cm^3$ *t*, engine size, tonne

- Peak and off-peak traffic percentages for the Sydney metropolitan region [52] were considered in this study, as Adelaide's diurnal traffic variation data was not available. Sydney has the most comprehensive data available publicly and it was assumed that the vehicle percentages in peak and off-peak time follow the similar pattern at all Australian capital cities.
- For each randomly generated traffic number, vehicle speed was also randomised within the vehicles' speed range for peak and off-peak hours. The vehicle speed profile was obtained from the government travel speed record at different road links in Adelaide [53]. Although the randomised vehicles' speed profile might differ from the probable vehicle speed for the fleet running on the road, the low variation of speed profile (within the peak and off-peak times) would not affect the estimation significantly and is thus considered legitimate. A typical vehicle speed profile at the modelling nodes is provided in Fig. 4, which also shows an interpolated distribution of vehicle speed profile based on the nodes' data. Although the interpolation result does not accurately portray the speed profiles for all the roads (for instance, locations with no data node), it shows a general distribution profile along the city. Lower speed is generally observed around the city centre and along the roads with high volume of traffic. The effect of idling and queuing of the vehicles in the intersections is incorporated within the typical speed profiles.
- The probabilistic emission at a road network is obtained from an average of 20,000 random samples' result.

The emission factors (EF in Eq. 1) are dependent primarily on the vehicles' fuel type, engine technology and the amount of fuel being consumed. Therefore, vehicle category-specific emission factors for key pollutants were developed using typical vehicle technologies in Adelaide (Table 1). The emission factors prepared are fuel consumption dependent; therefore, vehicles' speed-dependent fuel consumption, provided by the European Environment Agency [1, 51], was incorporated for the total emission estimation considering the speed profiles for the roads (Fig. 4). The other scale factors that determine the emission factors (viz., start pattern, environmental condition, AC usage in the vehicles) were not incorporated into this research.

The emission factors also depend on the vehicle technology, which is indicated by the vehicle emission standard followed in the vehicles. As per the Australian standards,

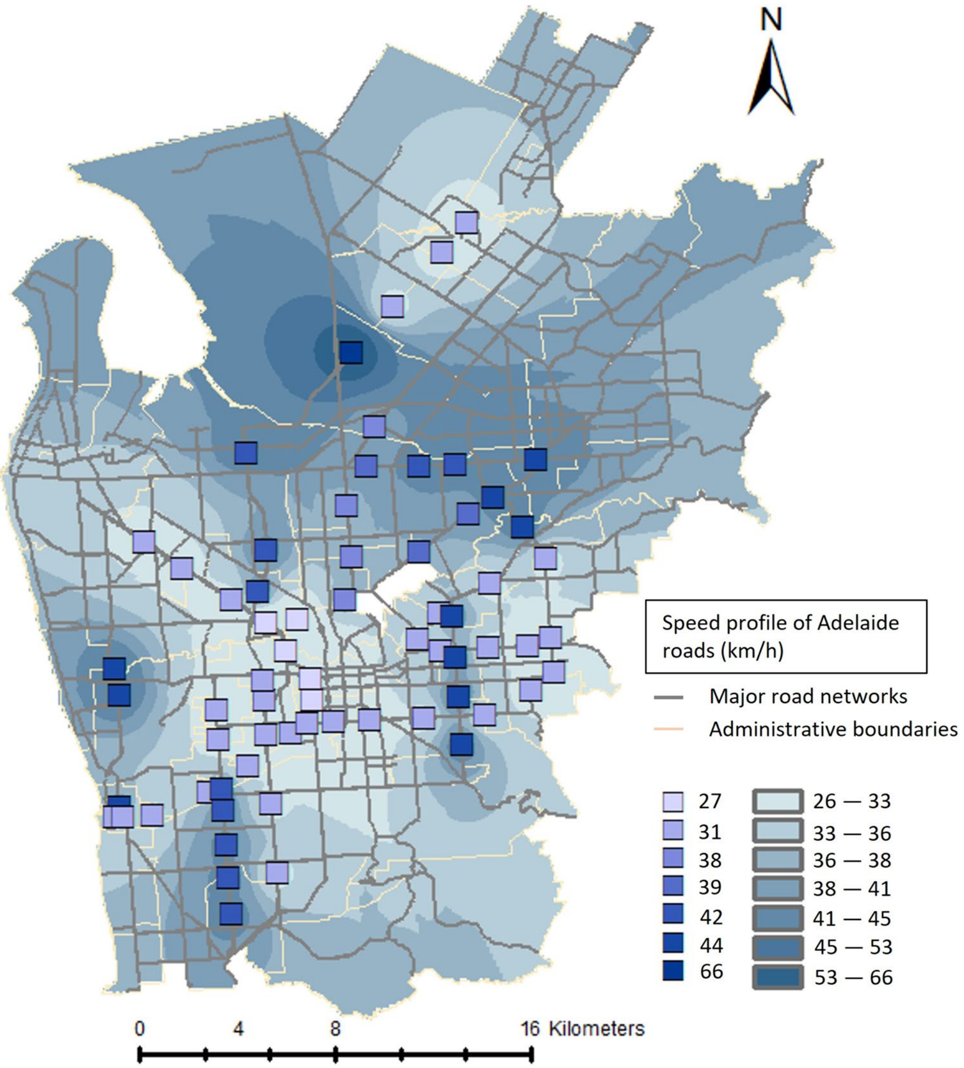

**Fig. 4** Vehicle speed profile (average) at the modelling nodes (road links) and the interpolated distribution of speed in Adelaide (based on the nodes) [note: data provided by the Department of Infrastructure and Transport of South Australia [53]]

gasoline, light diesel and LPG vehicles manufactured after November 2016 must comply with Euro 5 emission standards, while the vehicles manufactured after 2010 must comply with Euro 4 standards [54]. As the relatively older vehicles can still operate (manufactured before 2007), thus vehicles with Euro 3 standards are also present on the road. Although, the quality of fuel (viz., sulphur content) varies depending on different available fuel categories in Australia,for instance, octane 98, 95, 95 and ethanol are petrol of different qualities with sulphur content ranging from 10 to 150 ppm [55]. But, as Australia follows the Euro emission standards for the vehicular emission standards, therefore, the fuel quality parameters were not considered separately for this research. For Adelaide, this research assumed that 95% of these vehicles following Euro 4 emission standards, while the rest are following Euro 3 standards. The heavy-duty diesel vehicles manufactured after November 2011 needs to comply with Euro 5 standards, while vehicle manufactured after 2003 up to 2008 might follow Euro 3 emission standards [54]. Therefore, in this research, it was assumed that 60% of the heavy-duty diesel vehicles were following Euro 3 standards, while the rest following Euro 4 standards. No portion of the vehicles was considered following Euro 5 emission standards (although some vehicles are following that) to be more conservative about the emissions generated by the vehicles.

## 2.2 Estimating On-road Pollutant Concentrations

Assuming no further transformation of emissions, the US EPA recommended line source dispersion model, CALINE4 [56], was considered in assessing on-road concentrations in the road links resulted from emissions (estimated earlier).

The modelling was done for the dry season (December only) to get a higher concentration scenario due to lower deposition [57], allowing a worst-case scenario. The wet season is expected to have more wet deposition and thus was not considered in this research. The meteorological parameters that govern pollution dispersion (wind speed and direction, atmospheric stability, mixing height, ambient temperature) were obtained from the Bureau of Meteorology of Australia [58, 59].

Background emission concentration due to other sources and long-range transport [60] determines the ambient concentration of pollutants. However, to forecast the emission concentration solely from vehicles, the model did not include any background concentration.

The model was run for all the 67-road links considering the emissions generated by the probabilistic emission modelling. The other road links, where the data were not available, were not incorporated in the CALINE4 simulation. Based on the concentrations obtained at the road links, the approximate emissions equate to the threshold (standard) emission level was assessed for further analysis. The approximation was made because of the probable variability of emissions for generating a concentration despite the same meteorological condition, which might be affected by the orientation of the roads (dispersion due to wind direction effects) and road width.

Model design considerations:

- No deposition of the pollutants; velocity = 0.
- Suburban aerodynamic roughness coefficients for the roads outside the central business district.
- Eight-hour simulation period was considered for each transport scenario for predicting the worst-case concentration for peak and off-peak periods.
- All road links are at grade, no tunnels.
- Concentration was estimated for 1.8 m receptor height.
- Chemical transformation of the pollutants was ignored for the simulation.

## 2.3 Probability of Emission Exceedance: Evaluating the Risk of Emissions

The research assessed the probability of exceeding the standard emission concentrations for the concerned pollutants being generated on the road. The CALINE4 model assessed the threshold emission level that equates to the standard emission concentrations on the road. Thus, the probability of emission exceedance was obtained from the cumulative distribution of emissions (Eq. 2). The schematic diagram assessing the emission exceedance probability is outlined in Fig. 5.

## 2.4 Probabilistic Risk Analysis

With the higher emission exceedance on the road, the level of risks for the emissions increases. In this research, a risk matrix [61, 62] was generated (Table 2) based on the level of exceedance (magnitude of risk) and the probability of that exceedance. For some roads, the exceedance can be higher, while the probability of that exceedance might be low. In such a case, the probability of the risk reduces. A similar risk matrix was used by the authors in their earlier research on Dhaka city, which was adopted in this research [32].

The national ambient air quality standard (yearly average) for Australia for NOx, $PM_{2.5}$ and CO are 0.03 ppm, 8 µg/m$^3$ and 9 ppm, respectively [25], considered for setting the magnitude of risk severity.

- Severe-magnitude rank = 4: concentration > 200% of annual standard level.
- Critical-magnitude rank = 3: concentration > 150% of the annual standard level.
- Marginal-magnitude rank = 2: concentration at annual standard level.
- Negligible-magnitude rank = 1: concentration below the annual standard.

While probability scale varies depending on the assessor, an approach practised in project management [61, 63] was adopted in this research. The product of probability and severity was used to formulate the risk index, which was categorised into five indices based on the results: extreme, acute, major, moderate and minor.

### 2.4.1 Risk scenario analysis

For conducting the risk analysis of Adelaide's future transport system scenarios, the vehicle growth rate for the last 10 years (2010–2020) was assessed. The same trend was utilised to project vehicle numbers for the next 10 years, i.e. up to 2030 (Fig. 6). The rates of growth for different vehicles are different, and therefore the vehicle-specific rates were considered for the projection instead of considering the flat rate of increase of the total number of vehicles.

Three scenarios were assessed for the future risk assessment: (a) the business as usual (BAU) scenario for 2030 with the current vehicle growth trend and Euro standard, (b) the BAU vehicle growth with all the vehicles using Euro 4 emission standards and (c) modified transport system with 50% less private vehicles, 50% less diesel light vehicles and a 10% increase of buses for supporting the mobility. The 'what-if' analysis with these three scenarios was conducted to understand what might change the risk scenarios in the future. The scenarios were developed hypothetically without considering all the determining factors, for example the latent demand for private vehicles due to public transport services or the improvement of road networks. The scenarios considered the growth as present and what might happen if that growth is reduced or altered. Again, how the scenarios will be achieved is not the scope of this research. As mentioned, it is a hypothetical assessment of the 'what-if' scenarios.

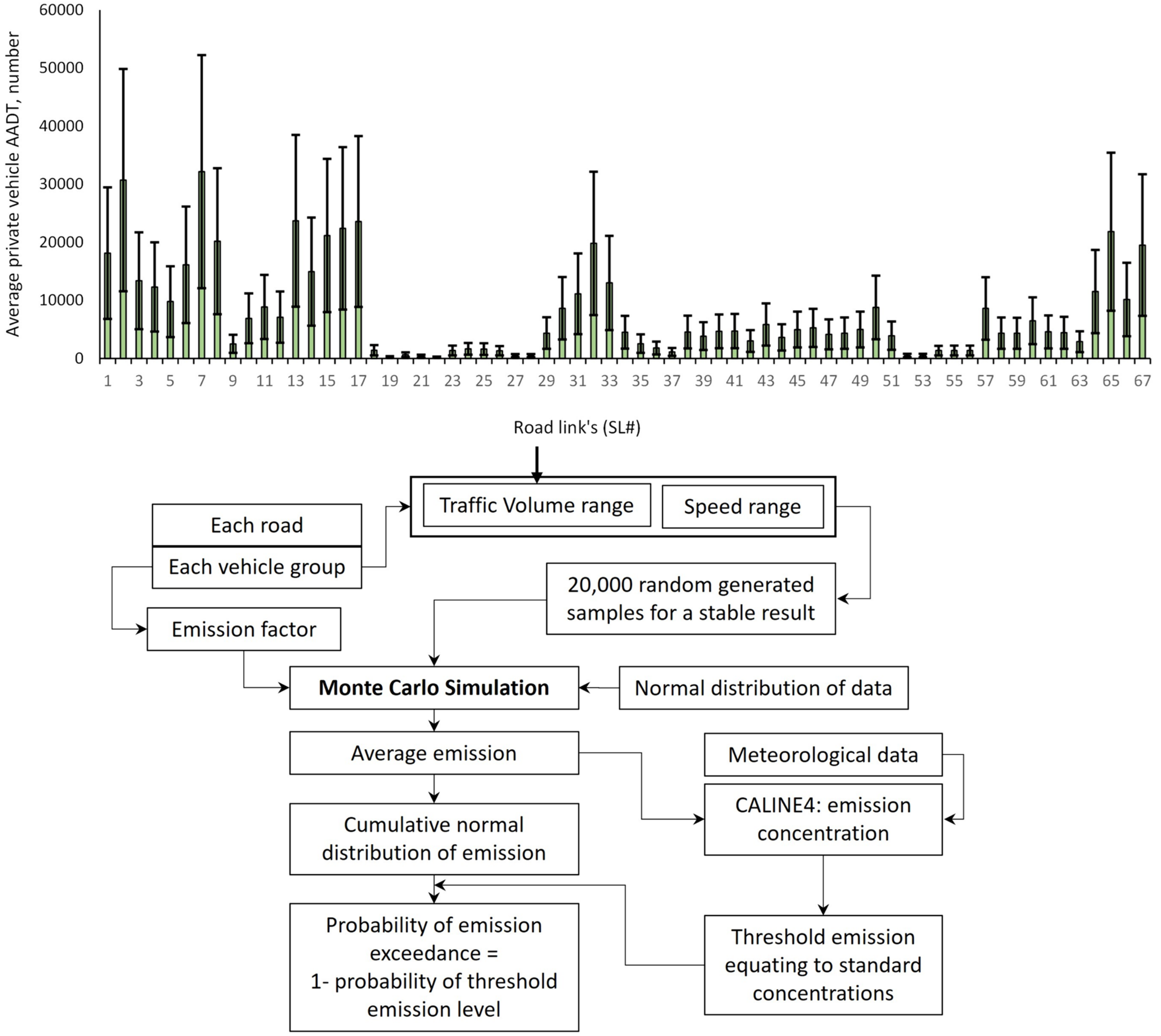

**Fig. 5** Schematic diagram of the probabilistic emission exceedance (vehicular) above the standards for Adelaide [private vehicle's data obtained from the South Australia Government [48],supporting data provided in the Appendix, Table 3]

**Table 2** Risk analysis matrix: [risk magnitude × probability of emission exceedance]

| Probability | Severity | | | |
|---|---|---|---|---|
| | **[4] severe** | **[3] critical** | **[2] marginal** | **[1] negligible** |
| **[5] strong (≥ 80%)** | Extreme (5) | Acute (4) | Major (3) | Minor (1) |
| **[4] high (≥ 60– < 80%)** | Acute (4) | Major (3) | Modest (2) | Minor (1) |
| **[3] medium (≥ 40– < 60%)** | Major (3) | Modest (2) | Modest (2) | Minor (1) |
| **[2] low (≥ 10– < 40%)** | Modest (2) | Modest (2) | Minor (1) | Minor (1) |
| **[1] improbable (< 10%)** | Minor (1) | Minor (1) | Minor (1) | Minor (1) |

RM = 20 [extreme, RI = 5]; RM ≥ 15 [acute, RI = 4]; RM ≥ 10 [major, RI = 3]; RM ≥ 6 [modest, RI = 2]; RM < 6 [minor, RI = 1]

*RM* risk matrix, *RI* risk index

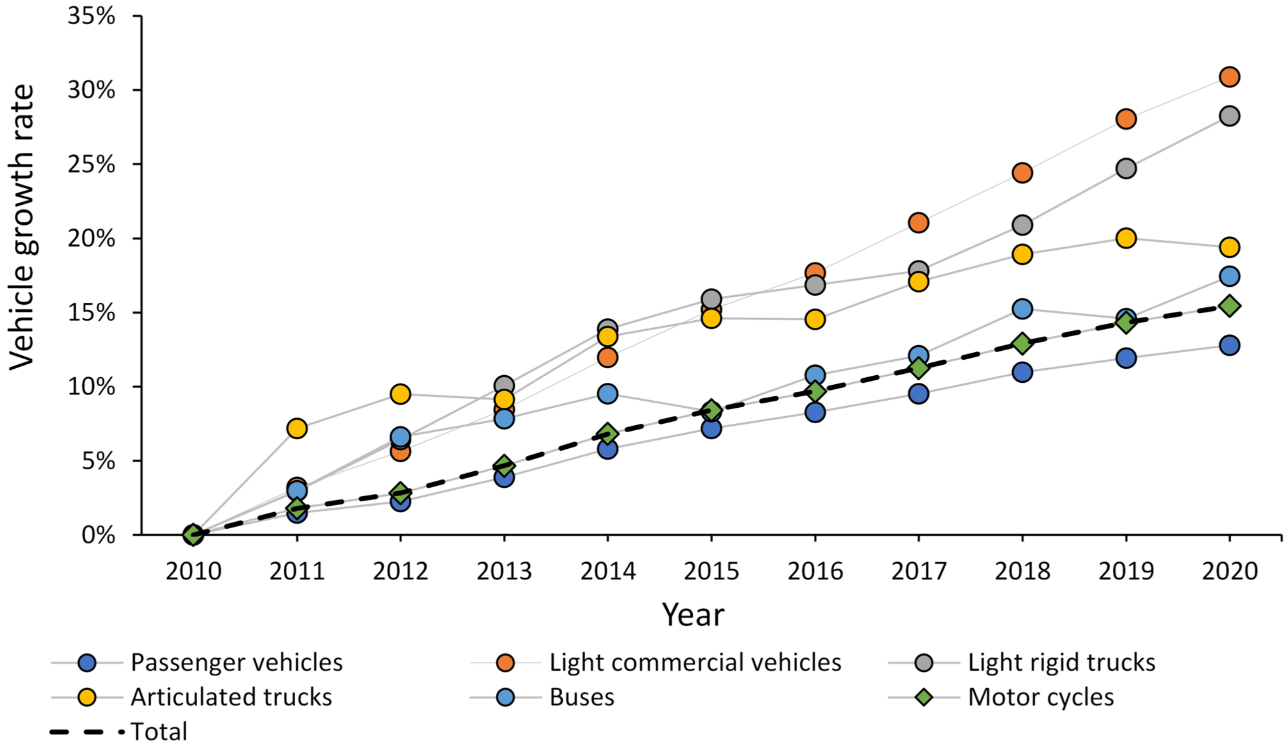

**Fig. 6** Vehicle growth trend (%) in Adelaide from the year 2010 to 2020, indicating vehicle specific increase and the growth of the total number of vehicles (solid line)

## 3 Results and Discussions

The modelling approach adopted in this research generated the mean emissions from 20,000 randomly generated data for each road link, and the concentrations corresponding to that emissions are portrayed in Fig. 7. The emission concentrations of NOx, $PM_{2.5}$ and CO were estimated for 67 road links of Adelaide city for 2020, and their spatial distribution was mapped using ArcGIS 10.8. The inverse distance weighted (IDW) interpolation was used, where the values of known points explicitly assume to predict the value for unknown points. The spatial analysis thus

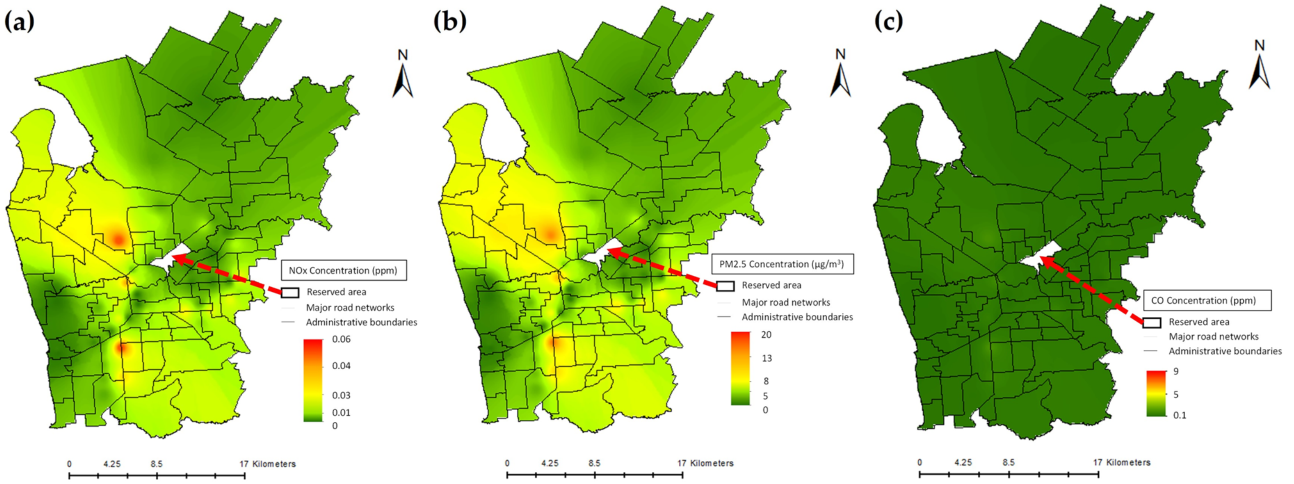

**Fig. 7** Spatial distribution of on-road vehicular average emission concentrations [**a** NOx, **b** $PM_{2.5}$, **c** CO] during peak time for dry season in Adelaide in 2020

provided an approximate assessment of the air quality hot spots of the city from the vehicular emissions.

Figure 7 reveals the spatial distribution of monthly average (for dry season only) emission concentration across Adelaide city during the peak time for the year 2020. The peak time represents when the vehicle movements are higher, typically during morning and late afternoon-evening. As the daily traffic data were not collected specifically for this research, the peak time slots are not specified here; instead, it is a general representation of the traffic movement situation. The process of peak-time traffic calculation is specified in the methods section.

However, as revealed in Fig. 7, the NOx concentration is at and above the standard level (0.03 ppm) at the central, north-western and south-eastern portions of the city, which is nearly 50% of the total city coverage. The central part is the CBD (central business district), while the north-western portion is the corridor for the port. The south and south-eastern portion is the zone for several schools, an old-established residential and commercial zone and the inter-state travel corridor. The significant hotspots are related to high commercial and freight vehicles along with the dominance of private vehicles. As per the city setting, the concentration is logically higher where the traffic movement is higher (Fig. 1 reveals that). Other parts of the city, while not at the state of concern, but are approaching there with the city's continued development. The results are consistent with research findings on vehicular emission profiles obtained in other cities, demonstrating the correlation of NOx and $PM_{2.5}$ emissions with vehicle population [64, 65], engine technology, heavy vehicles population and the fuels being used [3].

The $PM_{2.5}$ concentration also follows the same pattern of emission hotspots. The only difference is slightly more areas of the city meet the standard emission level for $PM_{2.5}$ than that of NOx, and the hotspots are more dispersed. So, it is indicative of higher health exposure for $PM_{2.5}$ but more intense exposure to NOx and demands concern that can reduce the exposure. The CO concentration during the peak period is relatively at the safer state in the city. As the vehicles were considered to be following Euro 3 or Euro 4 standards, the emission generated from incomplete combustion was relatively lower, making the distribution well mixed irrespective of the roads. However, this can be different in the field as many old vehicles are running on the road. The off-peak concentrations of the pollutants were relatively low in the city and were below the standards throughout; therefore, they were not mapped separately here in this paper.

Considering the vehicles are normally distributed, the emission modelling generated the normal and cumulative distributions of NOx and $PM_{2.5}$ emissions for each road link of Adelaide (67 road links in total) for 2020 (Fig. 8). The distribution of CO was not presented because of insignificance, as indicated in Fig. 7c. Because of the normal distribution, the mean emissions would have a higher probability (Fig. 8a, c). The cumulative normal distribution shows the probability of obtaining a specific emission level. Figure 8b and d indicate the probability of occurrence for the threshold emission levels linking the air quality standards, suggesting that more than 30% of the roads are prone to a higher probability of emission exceedance. As stated in the methodology section, this probability of emission exceedance is important while assessing the risks generated by the emissions portrayed earlier.

The modelling results are important to be validated with other relevant information or research. But there is minimal research conducted on the vehicular emission for Adelaide (and even for Australia), especially the mesoscale spatial distribution of emissions. Therefore, the modelling result cannot be compared straightway. However, the Environment Protection Authority of South Australia (SA EPA) has gaseous pollutant monitoring setup, which covers continuous NOx monitoring data for Adelaide CBD for the year 2020 (Fig. 9a) [66]. The monitoring data for the summer months was considered here for comparison as the modelling was done for the summer months. The result shows a wide variation in monitoring data, which might have fluctuated due to the variability of the source and meteorological conditions. As the specific location in Adelaide CBD for the monitoring

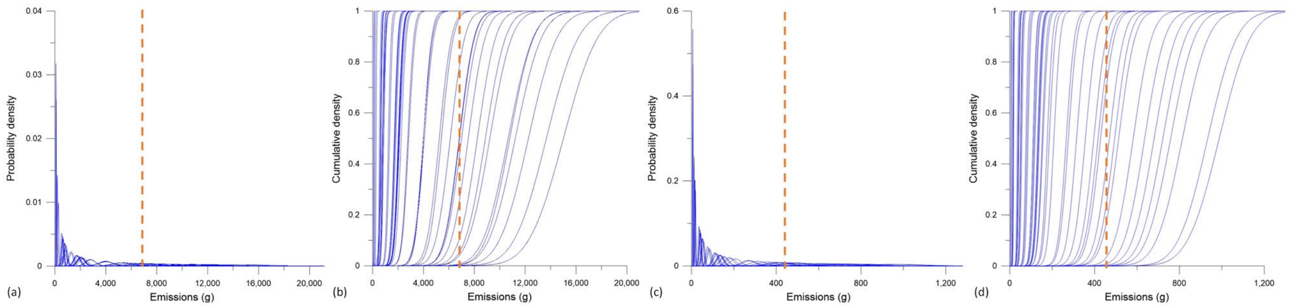

**Fig. 8** Normally distributed and the cumulative distribution of vehicular emissions (**a**, **b** NOx, **c**, **d** $PM_{2.5}$) at 67 road links in Adelaide for 2020. The reference dashed lines indicate the threshold emission level (g/km/h) relating to ambient air quality standard

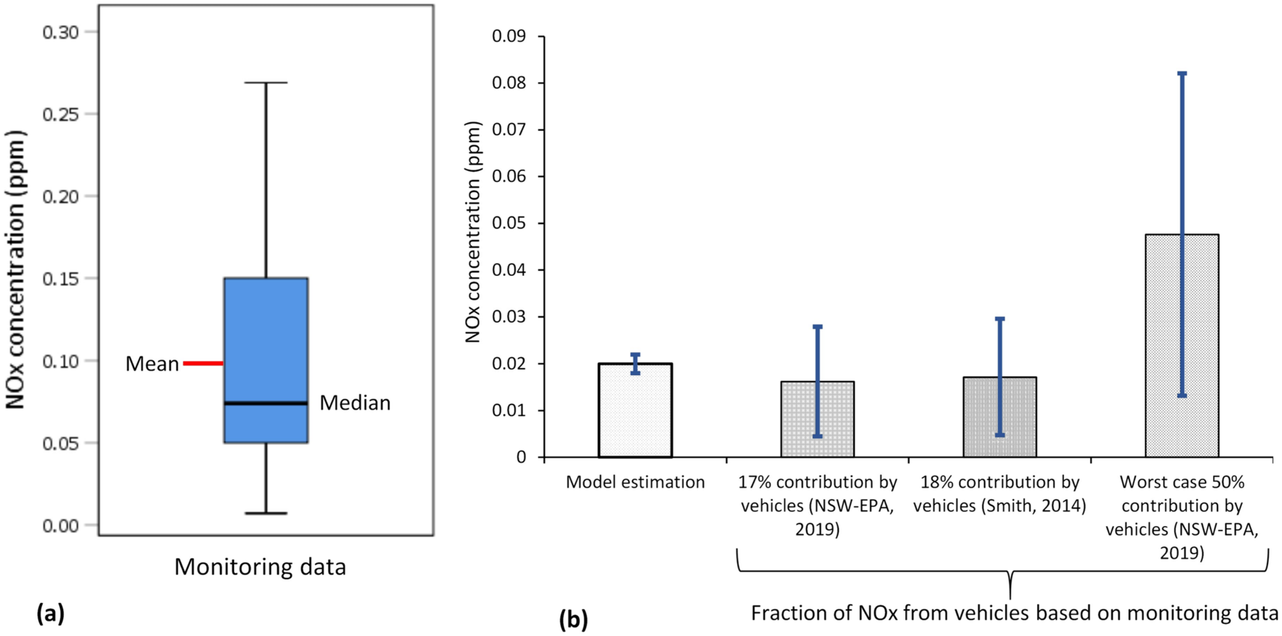

**Fig. 9** Comparison of model result with monitoring data of 2020 for Adelaide city; **a** variations of monitored NOx concentration (all sources) for summer season, **b** comparison between modelling result (this study) and monitoring results scaled for vehicular emissions only

is not specified, the modelling result for the centre of Adelaide CBD was considered for comparison. Again, as the monitoring data includes the concentration contributed from all the sources, the data was scaled down to predict the contribution from vehicles. Smith [44] indicated that about 18% of the NOx in Australia is contributed by vehicles supported by NSW-EPA [43], stating that about 17% is contributed by on-road vehicles in greater metropolitan regions. NSW-EPA [43] specified the contribution as about 50% in the dense city. Comparing the scaled monitored concentration distributions with the modelling result (Fig. 9b) shows that the modelling result is underestimated if the highest range of monitored data is considered, but is close to the mean of characteristic scenarios of monitoring data. Considering the variability of monitoring data and the modelling result fitting into that range, the modelling estimation was considered legitimate. It indicates that the risk assessed by this modelling might be lower, and thus the predicted risks need to be considered seriously for the sustainability of the system.

As mentioned earlier, the concentration map stipulated earlier might not portray the real risk of those concentrations. The magnitude of risk and the probability of those concentrations are also important for assessing the risk. The method for assessing the risk is discussed earlier in the methods section. Based on that, the risk map prepared for Adelaide is shown in Fig. 10 for NOx and $PM_{2.5}$. As the CO concentration was found within the city limit, the risk for that was not evident due to the vehicular emissions only. The CO risk scenario might change if the background concentration from other sources is considered, but that is out of scope for this research. The risk map shows a similar pattern as the concentration map, with a difference in the extent of zones falling under risk. The concentration map showed a wider range of areas meeting the emission standards and indicating that about half of the city area approaches the threat. But the risk index might have omitted some of the risks when considered the probability of that emission.

However, in case of NOx risk, the southern region and north-western region near the central part are susceptible to major risk, with some evident extreme and acute risk hot spots. The north-western and south-eastern zones showing a moderate risk are also important as they are susceptible to the threat of being a major risk. Some areas are under moderate risk zone and have critical emission levels and will develop major or acute risks within few years if the current transport system persists. For $PM_{2.5}$, the higher risks are evident to a wider extent, detecting more extreme and acute risk hotspots in the eastern and north-western sides. The north-western side, a zone of movement between the industries located there and the port, shows higher risk correlating with the higher presence of heavy vehicles in that part of the city. The eastern and southern sides are the interstate travel corridors and experience a relatively higher number of heavy vehicles, which might lead to higher $PM_{2.5}$ risk.

As shown in Table 1, diesel vehicles are the higher contributors of NOx and $PM_{2.5}$, and a significant number of passenger vehicles, light commercial vehicles, rigid/articulated trucks and buses are running on diesel. Moreover, the

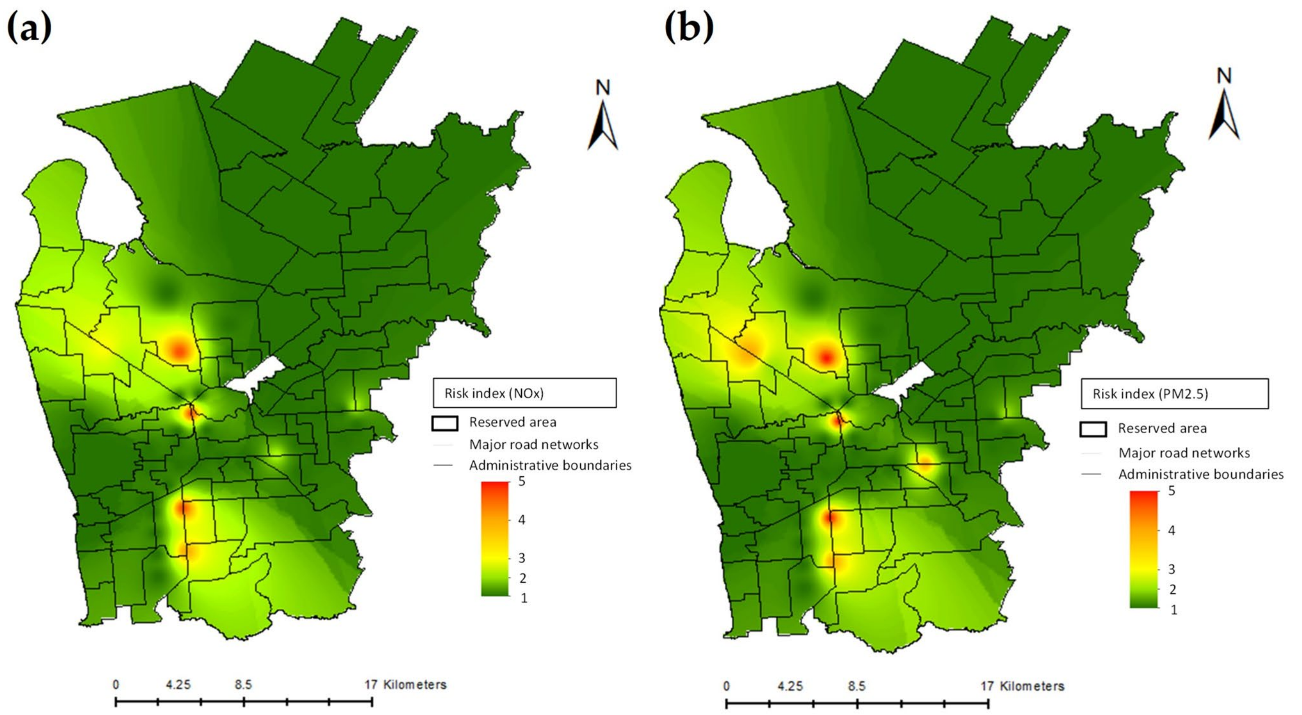

**Fig. 10** Spatial distribution of emission risks [**a** NOx, **b** $PM_{2.5}$] during peak time in Adelaide in 2020; note: risk index 5 = extreme, 4 = acute, 3 = major, 2 = moderate and 1 = minor

vehicle emission standard followed in diesel vehicles is also relatively lenient (Euro 3). These factors and the huge number of private vehicles might work as a background reason for the risks evident in Adelaide city. If the same trend continues, the situation will worsen, and more areas would fall under major risks. Figure 11 shows a projected emission risk scenario for Adelaide for the year 2030, considering the same trend of vehicle growth (1% per year) and the current vehicle emission standard, without applying any traffic management scheme that reduces the movement of private vehicles. The major change predicted in the risk is that, instead of having some risk hot spots, a wider area of the currently exposed zones will be under acute risk. Alongside, more hot spots will be developed in other parts of the city.

While the risks of vehicular emissions are evident for a 10-year prediction considering the same level of growth and practice, the research intended to assess what might happen if the transport system parameters change. The Australian government's vehicular emission policy specifies to adopt Euro 5 emission standards for the vehicles manufactured from 2016 and Euro 4 for the vehicles from 2010. Therefore, a scenario was tested (Fig. 12) to see what happens in 2030 if all the vehicles use at least Euro 4 emission standards while keeping all the other parameters as same (scenario (b) specified under Sect. 2.4.1).

The results of the scenario testing show that risk intensity would reduce significantly when the vehicles will be using Euro 4 emission standards. The risk scenario would be better than the current 2020 state in such a case. However, there would still be zones with major risks, and even acute and extreme risks, which is still public health concern. But, without implementing aggressive policies or modifying the transport characteristics, and implementing the current policies, the predicted risk scenario is acceptable for the time being. But as the city is expanding and vehicle demand increases proportionately, implementing just the emission standards might not be a sustainable option for minimising the health risks. Therefore, this research tested another scenario where the transport system characteristics were modified hypothetically to see what might happen (Fig. 13). This is also a 2030 scenario considering 50% less private vehicle usage than predicted, 50% less diesel light vehicles and a 10% increase of buses supporting mobility (scenario (c) specified in Sect. 2.4.1).

The results of this scenario testing (Fig. 13) reveal that the risk intensity would be minimised completely when the control is imposed on vehicle growth and fuel usage pattern in the vehicles. This signifies the importance of supporting work-related mobility (at least) with public transport instead of private vehicles currently dominant in Adelaide. Although many factors can influence the system's performance and generate emissions, the result portrayed here indicates the importance of adopting appropriate management strategies for long-term efficiency.

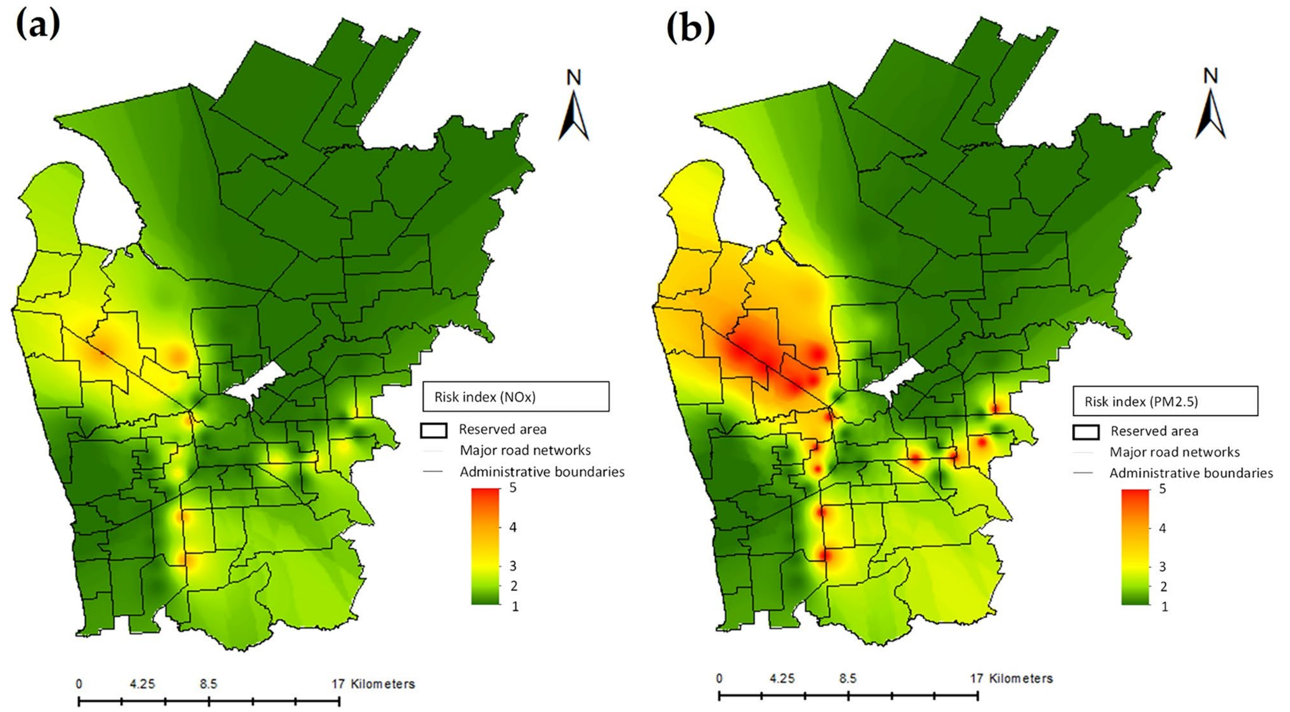

**Fig. 11** Spatial distribution of projected emission risks [**a** NOx, **b** $PM_{2.5}$] during peak time in Adelaide in 2030; note: risk index 5 = extreme, 4 = acute, 3 = major, 2 = moderate and 1 = minor

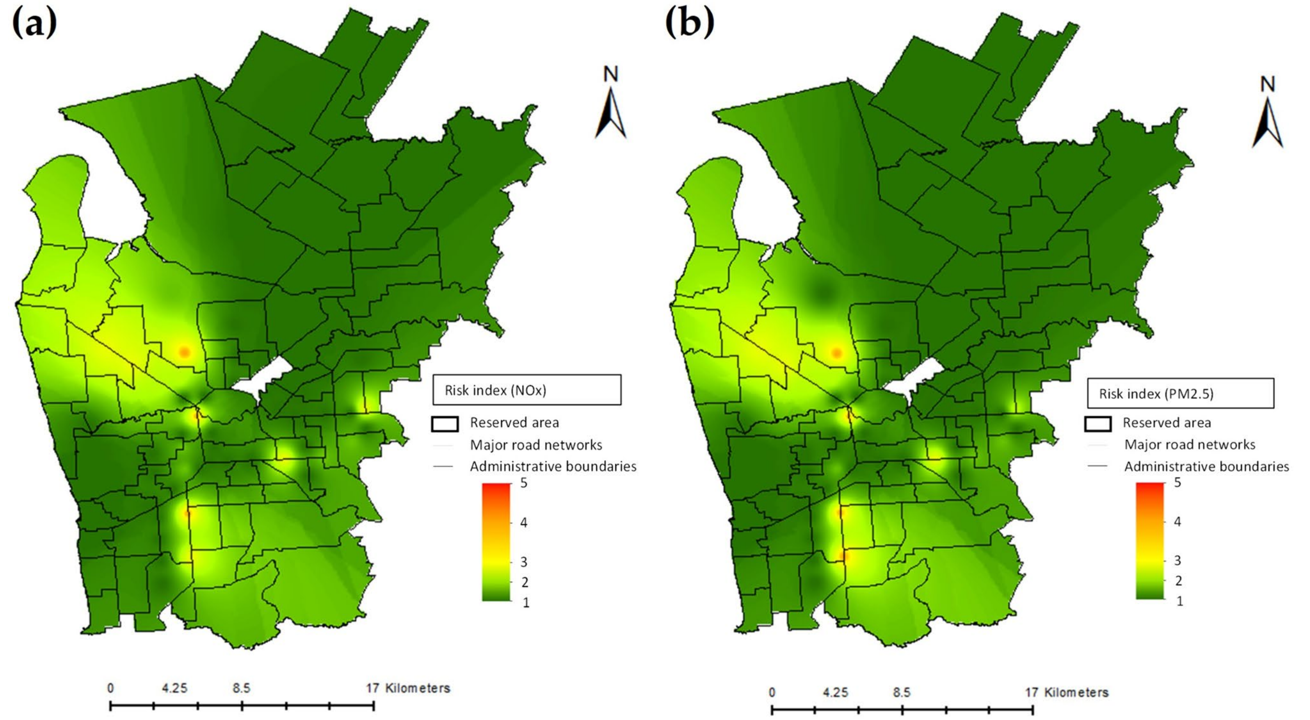

**Fig. 12** Spatial distribution of projected emission risks [**a** NOx, **b** PM2.5] during peak time in Adelaide in 2030 for a modified scenario—BAU vehicle growth predicted for 2030 with all vehicles adopting Euro 4 emission standards; note: risk index 5 = extreme, 4 = acute, 3 = major, 2 = moderate and 1 = minor

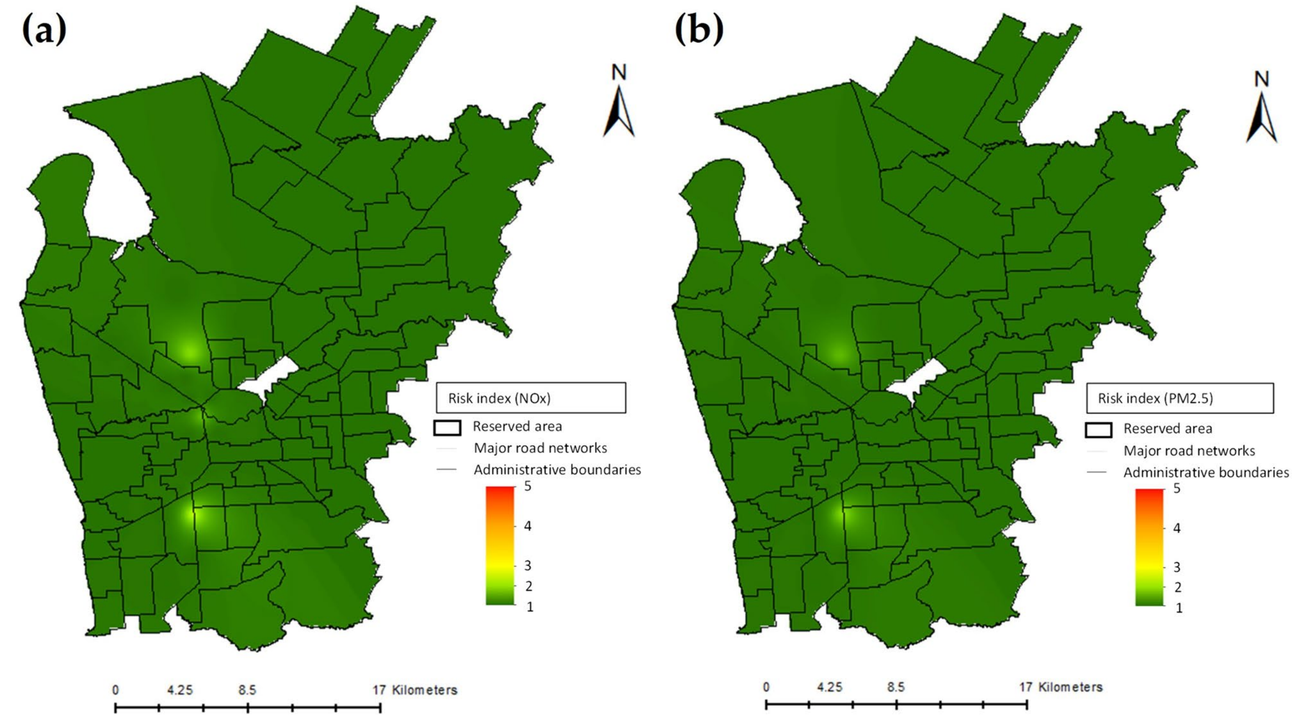

**Fig. 13** Spatial distribution of projected emission risks [**a** NOx, **b** PM2.5] during peak time in Adelaide in 2030 for a modified scenario—modified transport system with 50% less private vehicles, 50% less diesel light vehicles and a 10% increase of buses for supporting the mobility; note: risk index 5 = extreme, 4 = acute, 3 = major, 2 = moderate and 1 = minor

As mentioned earlier, how the scenarios would be achieved is a different concern and is not within the scope of this research. The assessment is conducted to evaluate what would happen to risk scenarios if such modifications are done. However, these hypothetical assessments indicate that, while the current vehicle emission standard policy can handle the risks for the near future, the increased vehicle number might still concern Adelaide. Therefore, a well-developed transport planning is required to be tested for its emission risks for the city's sustainability.

## 4 Conclusions

The results show that the pollutant concentration for NOx and $PM_{2.5}$ for 2020 reaches (and exceeds) the national standard level in more than 50% of Adelaide city roads; it might be significantly worse in 2030, increasing the intensities of emissions. The increased risk intensity might result from the rapid growth of vehicles and traffic conjunction in the city and commercially important areas that mainly dominate the traffic flow. The risks are particularly significant during the peak periods of the day. CO concentration is not substantial as it remains within the standard level. The Australian government's policies on maintaining vehicle emission standards for newly introduced vehicles might improve the scenario in 10 years, but not sufficient to control the risk if the current growth of private vehicles continues. The introduction of the electric/hybrid vehicles might change the emission scenarios significantly from vehicles, although the emission from other sources would increase. Therefore, policies to control vehicle growth without compromising the mobility of the people are important, which can be achieved by improving the public transport system. The hypothetical scenario assessment indicates better sustainability in such a case, along with controlling the use of diesel vehicles.

The research provides a stochastic modelling approach to reduce the uncertainty of deterministic estimation (considering the average) and demonstrates how the developed method can be applied to transport planning. Although it does not reduce the uncertainty ultimately, city-level emission modelling would be more refined by considering a higher number of randomised samples. This approach is particularly significant in assessing the probability of getting a threshold emission level (as the assessment considered a large number of samples); the magnitude and probability together would provide a more comprehensive evaluation of the risks.

The research was conducted based on available gross secondary data, which might have compromised the accuracy of modelling results. Therefore, more detailed and specified data on the system might produce more comprehensive outcomes. Future research can focus on specifying the transport system characteristics for Adelaide for a more detailed mesoscale emission modelling. The research considered a normal distribution of system parameters, which might be different in real-time, leaving the future scope. There is a scope for further research assessing the influence of land use on vehicle movement and fleet characteristics. The influence of future technological improvements, viz., increased use of electric vehicles and driverless cars, might influence the emission scenarios and be assessed in future research. Future transport planning strategies, including the latent demand for car travel, demand further research attention as that might influence the system's performance. Even though the research simplified many aspects while assessing the risk scenarios and predicting the future, it developed a structure that can be implemented with the more detailed system parameters. Emission modelling with a stochastic approach would handle many uncertainties (vehicle number, speed, fuel use pattern, etc.) and assess the sustainability of transport systems more effectively.

## Appendix

**Table 3** Road link specific traffic data (passenger vehicle) for 67 road links of Adelaide [data source: private vehicle data obtained from the traffic volume data provided by South Australia Government [48],the maximum and minimum range of vehicles were estimated based on data provided by Roads and Maritime Services Sydney [52]]

| SL# | Road link | Max | Min | Average | STDEV |
|---|---|---|---|---|---|
| 1 | SOUTH RD–TONSLEY BLVD TO DAWS RD | 26,131 | 10,132 | 18,132 | 11,313 |
| 2 | SOUTH RD–DAWS RD TO CROSS RD | 44,253 | 17,160 | 30,707 | 19,158 |
| 3 | SOUTH RD–ANZAC HWY TO RICHMOND RD | 19,259 | 7468 | 13,364 | 8337 |
| 4 | SOUTH RD–RICHMOND RD TO SIR DONALD BRADMAN DR | 17,725 | 6873 | 12,299 | 7674 |
| 5 | SOUTH RD–SIR DONALD BRADMAN DR TO HENLEY BEACH ROAD | 14,084 | 5461 | 9773 | 6097 |
| 6 | SOUTH RD–PORT RD TO TORRENS RD | 23,218 | 9003 | 16,111 | 10,052 |
| 7 | SOUTH RD–TORRENS RD TO REGENCY RD | 46,346 | 17,971 | 32,159 | 20,064 |
| 8 | SOUTH RD–GRAND JCT RD TO PORT RIVER EXPY | 29,092 | 11,281 | 20,187 | 12,594 |
| 9 | MAIN NORTH RD–ROBE TERRACE TO NOTTAGE TERRACE | 3606 | 1398 | 2502 | 1561 |
| 10 | MAIN NORTH RD–NOTTAGE TERRACE TO REGENCY RD | 9944 | 3856 | 6900 | 4305 |
| 11 | MAIN NORTH RD–REGENCY RD TO GRAND JCT RD | 12,770 | 4952 | 8861 | 5528 |
| 12 | MAIN NORTH RD–GRAND JCT RD TO MONTAGUE RD | 10,238 | 3970 | 7104 | 4432 |
| 13 | PORT RD–NORTH TERRACE TO ADAM ST | 34,155 | 13,244 | 23,700 | 14,786 |
| 14 | PORT RD–ADAM ST TO SOUTH RD | 21,519 | 8344 | 14,932 | 9316 |
| 15 | PORT RD–SOUTH RD TO EAST AVE | 30,507 | 11,829 | 21,168 | 13,207 |
| 16 | PORT RD–EAST AVE TO WOODVILLE RD | 32,288 | 12,520 | 22,404 | 13,978 |
| 17 | PORT RD–WOODVILLE RD TO OLD PORT RD | 33,993 | 13,181 | 23,587 | 14,716 |
| 18 | TAPLEYS HILL RD–ANZAC HWY TO SIR DONALD BRADMAN DR | 2014 | 781 | 1398 | 872 |
| 19 | TAPLEYS HILL RD–SIR DONALD BRADMAN DR TO HENLEY BEACH ROAD | 363 | 141 | 252 | 157 |
| 20 | TAPLEYS HILL RD–HENLEY BEACH RD TO GRANGE RD | 934 | 362 | 648 | 404 |
| 21 | ANZAC HWY–COLLEY TCE TO GORDON ST | 577 | 224 | 401 | 250 |
| 22 | ANZAC HWY–GORDON ST TO BRIGHTON RD | 263 | 102 | 183 | 114 |
| 23 | ANZAC HWY–BRIGHTON RD TO MORPHETT RD | 1943 | 754 | 1349 | 841 |
| 24 | ANZAC HWY–MORPHETT RD TO MARION RD | 2368 | 918 | 1643 | 1025 |
| 25 | ANZAC HWY–MARION RD TO SOUTH RD | 2300 | 892 | 1596 | 996 |
| 26 | ANZAC HWY–SOUTH RD TO RICHMOND RD | 1889 | 733 | 1311 | 817 |
| 27 | WEST TCE–NORHT TCE TO GROTE ST | 687 | 266 | 477 | 298 |
| 28 | WEST TCE–GROTE ST TO PORT RD | 681 | 264 | 473 | 295 |

**Table 3** (continued)

| SL# | Road link | Max | Min | Average | STDEV |
|---|---|---|---|---|---|
| 29 | GREEN HILL RD–ANZAC HWY TO GOODWOOD RD | 6274 | 2433 | 4354 | 2716 |
| 30 | GREEN HILL RD–GOODWOOD RD TO PEACOCK RD | 12,434 | 4822 | 8628 | 5382 |
| 31 | GREEN HILL RD–PEACOCK RD TO GLEN OSMOND RD | 16,046 | 6222 | 11,134 | 6947 |
| 32 | GREEN HILL RD–GLEN OSMOND RD TO PORTRUSH RD | 28,541 | 11,067 | 19,804 | 12,356 |
| 33 | GREEN HILL RD–PORTRUSH RD TO GLYNBURN RD | 18,725 | 7261 | 12,993 | 8106 |
| 34 | SALISBURY HWY–PORT RIVER EXPY TO ELDER SMITH RD | 6494 | 2518 | 4506 | 2811 |
| 35 | SALISBURY HWY–ELDER SMITH RD TO KINGS RD | 3666 | 1421 | 2544 | 1587 |
| 36 | SALISBURY HWY–KINGS RD TO WATERLOO CORNER RD | 2572 | 997 | 1785 | 1114 |
| 37 | SALISBURY HWY–WATERLOO CORNER RD TO COMMERCIAL RD | 1610 | 624 | 1117 | 697 |
| 38 | MARION RD–OAKLAND RD TO FINNISS ST | 6533 | 2533 | 4533 | 2828 |
| 39 | MARION RD–FINNISS ST TO STURT RD | 5519 | 2140 | 3830 | 2389 |
| 40 | MARION RD–OAKLAND RD TO BRAY ST | 6706 | 2600 | 4653 | 2903 |
| 41 | MARION RD–BRAYS ST TO CROSS RD | 6786 | 2631 | 4709 | 2938 |
| 42 | MARION RD–CROSS RD TO MOORINGE AVE | 4330 | 1679 | 3005 | 1875 |
| 43 | MARION RD–MOORINGE AVE TO RICHMOND RD | 8380 | 3249 | 5815 | 3628 |
| 44 | MARION RD–RICHMOND RD TO SIR DONALD BRADMAN DR | 5204 | 2018 | 3611 | 2253 |
| 45 | PARK TCE–TORRENS RD TO ADAM ST | 7140 | 2769 | 4955 | 3091 |
| 46 | BRIENS RD TO FOSTERS RD | 7590 | 2943 | 5267 | 3286 |
| 47 | FOSTERS RD TO SUDHOLZ RD | 5954 | 2309 | 4132 | 2577 |
| 48 | NOTTAGE TERRAE TO HAMPSTEAD RD | 6241 | 2420 | 4331 | 2702 |
| 49 | HAMPSTEAD RD TO OG RD | 7162 | 2777 | 4970 | 3101 |
| 50 | OG RD TO SUDHOLZ RD | 12,672 | 4914 | 8793 | 5486 |
| 51 | FULLATORN RD TO NELSON ST | 5648 | 2190 | 3919 | 2445 |
| 52 | NELSON ST TO PORTRUSH RD | 710 | 275 | 493 | 308 |
| 53 | PORTRUSH RD TO GLYUNBURN RD | 722 | 280 | 501 | 313 |
| 54 | PAYNEHAM RD TO PORTRUSH RD | 1939 | 752 | 1346 | 839 |
| 55 | PORTRUSH RD TO GLYNBURN RD | 1944 | 754 | 1349 | 841 |
| 56 | GLYNBURN RD TO ST BERNARDS RD | 1944 | 754 | 1349 | 841 |
| 57 | GLEN OSMOND RD TO GREENHILL RD | 12,389 | 4804 | 8597 | 5363 |
| 58 | GREENHILL RD TO KENSINGTON RD | 6239 | 2419 | 4329 | 2701 |
| 59 | KENSINGTON RD TO MAGILL RD | 6233 | 2417 | 4325 | 2698 |
| 60 | MAGILL RD TO PAYNEHAM RD | 9334 | 3619 | 6477 | 4041 |
| 61 | GRAND JCT RD TO NORTH EAST RD | 6590 | 2555 | 4573 | 2853 |
| 62 | NORH EAST RD TO GAMEAU RD | 6362 | 2467 | 4415 | 2754 |
| 63 | GAMEAU RD TO LOWER NORTH EAST RD | 4147 | 1608 | 2878 | 1795 |
| 64 | GORGE RD TO MONTACUTE RD | 16,580 | 6429 | 11,505 | 7178 |
| 65 | MONTACUTE RD TO MAGILL RD | 31,453 | 12,196 | 21,825 | 13,617 |
| 66 | MAGILL RD TO KENSINGTON RD | 14,615 | 5667 | 10,141 | 6327 |
| 67 | KENSINGTON RD TO HEATHERBANK TERRACE | 28,130 | 10,907 | 19,519 | 12,179 |

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## Declarations

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**Competing Interest** The authors declare no competing interests.

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