Urban Pathways

UNIVERSITY OF HELSINKI

MODELLING AIR QUALITY TO SUPPORT THE DECISION-MAKING OF URBAN LEADERS IN KIGALI, KATHMANDU AND QUITO


©Kigali City

Wuppertal Institut

UN-HABITAT
FOR A BETTER URBAN FUTURE

UN environment programme

Author: University of Helsinki

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The Urban Pathways project helps delivering on the Paris Agreement and the NDCs in the context of the New Urban Agenda and the Sustainable Development Goals. It has established a facility in close cooperation with other organisations and networks active in this area to support national and local governments to develop action plans and concrete implementation measures to boost low-carbon urban development. This builds on UN-Habitat's role as "a focal point on sustainable urbanisation and human settlements including in the implementation and follow-up and review of the New Urban Agenda". The project develops national action plans and local implementation concepts in key emerging economies with a high mitigation potential. The local implementation concepts are being developed into bankable projects, focusing on the access to urban basic services to create a direct link between climate change mitigation and sustainable development goals.

Project concept

The project follows a structured approach to boost Low Carbon Plans for urban mobility, energy and waste management services that deliver on the Paris Agreement and the New Urban Agenda. The project works on concrete steps towards a maximum impact with regards to the contribution of urban basic services (mobility, energy and waste management) in cities to global climate change mitigation efforts and sustainable and inclusive urban development. This project makes an active contribution to achieve global climate change targets to a 1.5°C stabilisation pathway by unlocking the global emission reduction potential of urban energy, transport and resource sectors. The project will contribute to a direct emission reduction in the pilot and outreach countries, which will trigger a longer term emission reduction with the aim to replicate this regionally and globally to make a substantial contribution to the overall emission reduction potential.

Project aims

This project implements integrated urban services solutions as proposed in the New Urban Agenda providing access to jobs and public services in urban areas, contributing to equality and social coherence and deliver on the Paris Agreement and the Sustainable Development Goals.This is the first dedicated implementation action oriented project, led by UN-Habitat to deliver on inclusive, low-carbon urban services. Securing sustainability and multiplier effect, the project aims to leverage domestic and international funding for the implementation projects that will follow from this initiative

Urban Pathways Project and Replication Cities

BACKGROUND

With support from the Urban Pathways project, the University of Helsinki (UH) was supporting cities in modelling Air Quality through the collection air quality data and carrying out the air quality measurements, as well as by providing the open-code MegaSense platform to be used for air quality monitoring services for 3 cities: Kigali, Kathmandu and Quito, using the UH MegaSense data platform.

UH was also responsible for coordinating the Decision Support Modeling by updating the open-code MegaSense data platform by adding a Decision Support Systems (DSS) feedback loop to understand exposure to air pollution and related health impacts in any city and other works of the project.

Setting up the city DSS computational environment

The open-code MegaSense platform is configured to support the University of Helsinki's multi-functional air portable air quality monitors and provide the Decision Support System. During the project the MegaSense data platform was used as a cloud service with open APIs and open data storage with access to third parties. The MegaSense data platform reactively received data from Open Seneca and from city reference air quality monitoring stations, geo-spatial applications (Open Street Maps); and weather information from Finnish Meteorological Institute (FMI) SILAM.

Air Quality Measurements as data points

Open Seneca provided a network of light-weight portable low-cost air quality monitors to measure PM2.5, its relevant air quality conditions and identify emission hotspots at a scale of 1m resolution. Open Seneca distributed their own low-cost air-quality monitors to local stakeholders using cycles and motorcycles to measure air quality at roadsides. Open Seneca uploaded their PM2.5 datapoints and the geo-locations to the MegaSense platform. In the absence of receiving air quality data points that included NO_x, CO and CO_2, the University of Helsinki simulated air quality measurements created by traffic emissions in the three cities to create the air quality model and data needed for the Decision Support System. Due to the complexities required and the limited time project frame, the integration with the Open Seneca data to the DSS models for a selected city will occur in 2022.

Air Quality Measurement for city-wide representation

In the work, the University of Helsinki applied two well-known open-coded software models. Traffic emissions are modelled using the Simulator of Urban Mobility (SUMO)[1]. The SUMO model uses the global data source of Open Street Map (OSM) to generate traffic patterns in space and time. OSM coverage is global, so this method is applicable to any city. The chemical transport model SILAM[2] is used to simulate urban air quality spatially distributed across the city.

Air Quality Measurements from Traffic Simulations

For the three cities, the University of Helsinki redesigned, recompiled, and executed SUMO traffic simulation application on University's computational infrastructure to generate daily city-wide air quality measurements for the three cities under study. "Simulation of Urban MObility" (SUMO) is an open source, portable, microscopic, and continuous traffic simulation package designed to handle large city networks. It allows for intermodal simulation including pedestrians and comes with a large set of tools for scenario creation. It is mainly developed by employees of the Institute of Transportation Systems at the German Aerospace Center. SUMO is licensed under the EPL 2.0.

The University of Helsinki created SUMO network files for the three cities on top of OSM. University of Helsinki used scripts to convert the OSM into SUMO network files to describe traffic-related part of a map, the roads, and intersections the simulated vehicles run along or across. At a coarse scale, a SUMO network is a directed graph. Nodes, named "junctions" in SUMO-context, represent intersections, and "edges" roads or streets. The SUMO network contains the following information: every street (edge) as a collection of lanes, including the position, shape and speed limit of every lane, traffic light logic referenced by junctions, including their right of way regulation, connections between lanes at junctions (nodes).

University of Helsinki defined each motorized trip consisting of the starting and the ending edge and the departure time. Each simulated vehicles produced pollutants PM_x, NO_x, CO and

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[1] https://www.eclipse.org/sumo/

[2] https://silam.fmi.fi

CO_2 accumulated during the routes throughout the city. The emissions of the pollutants were affected by many features, the type of car engine (EURO 3-5), route length, the speed, idling at junctions, traffic lights and in traffic jams. For each city University of Helsinki therefore created digital traffic networks and executed millions of trips between sources (starting points in the city) and sinks (destination points driven to in the city):

- Quito simulated traffic network with 887,038 edges and 1,6 million trips producing daily traffic emission inventory
- Kigali simulated traffic network with 173,851 edges and 2,1 million trips
- Kathmandu simulated traffic network with 397,400 edges and 1,2 million

At the end of each model run, spatial (locations) and temporal (hourly, daily) pollutants emitted by the simulated vehicles were written to a specially configured output files readable by the FMI SILAM model. Each simulation and scenario described in this report took up to 6 hours to execute.

Air Quality Measurements and FMI SILAM (Atmospheric dispersion model)

The SUMO configured traffic emission inventories of the three cities were dispatched to Finnish Meteorological Institute (FMI) computational center and as an input file for an air quality model called SILAM. FMI SILAM (System for Integrated modeLling of Atmospheric composition) is an atmospheric dispersion model. Atmospheric dispersion modeling provides a mathematical simulation of the dispersion of traffic and global air pollutants in the ambient atmosphere. The dispersion model estimates the downwind ambient concentration of air pollutants emitted from the SUMO vehicular traffic. SILAM is the dominant type of model used in air quality policy making. They are most useful for showing pollutants that are dispersed over large distances and how they may react in the atmosphere.

University of Helsinki chose the SILAM to model the three cities, as it a global-to-meso-scale dispersion model developed for atmospheric composition, air quality, and emergency decision support applications, as well as for inverse dispersion problem solution used by the European Union. The model incorporates both Eulerian and Lagrangian transport routines, 8 chemicophysical transformation modules (basic acid chemistry and secondary aerosol formation, ozone formation in the troposphere and the stratosphere, radioactive decay, aerosol dynamics in the air, pollen transformations), 3-and 4-dimensional variational data assimilation modules. Each SUMO model run producing one month of hourly simulations takes 4 days to execute on a supercomputer.

Air Pollution spatial distribution and temporal concentration simulated for three cities

The spatial and temporal distribution of air quality measurements at the city scale are sufficiently represented by combining daily SUMO traffic emissions with the SILAM air quality model producing hourly model forecasts. In the next sections, it is demonstrated how city-wide air pollution can be remotely modeled with very sparse data input for the three case study cities. For each city, common traffic scenarios are modelled daily; air quality dispersion models are executed using traffic patterns and course open meteorological data; and decision-support system inferring recommendations for the city stakeholders to consider.

CASE STUDY 1 QUITO, ECUADOR: CITY DECISION SUPPORT SYSTEM

Air Pollution and Climate Change

Quito is the capital of Ecuador, situated in the Andean region at 2,800 altitude meters with 2.7 million inhabitants. Quito is the most polluted city in Ecuador due to the number of cars contributing to air pollution and mountain range structure that impedes airflow needed to reduce contamination. The high altitude makes combustion in the vehicles very inefficient and creates major pollution episodes that regularly exceeds the WHO air quality guidelines for PM2.5, PM_{10}, O_3, and SO_2. Buses and taxis are the main sources of traffic noise and pollution.

According to the city's Environmental Department, transportation generates the greatest amount of CO_2 emissions (56%) in the city (2,902,402 tons of CO_2 per year) (2016), and its operation affects both urban environmental conditions and the health of Quito residents. For this reason the city has invested in mobility alternatives that contribute to reducing the carbon footprint and improving environmental quality, while coping with the possible effects of climate change and other natural hazards. The major example being the Quito Metro line that that contribute to sustainable development and build resilience towards the year 2040.

Quito traffic network

The city of Quito is about 40 km long and 5 km at its widest, most of the important avenues of the city extend from north to south. The two main motorways go from the northern part of the city to the southern on the eastern hills that border the city, and on the western side of the city on the Pichincha volcano. The number of cars and traffic flow has been increasing statistics show 213,932 vehicles entered the city in 2016 and 2017, 227,187 vehicles in 2017 representing a 6.19% increase in traffic flow. Higher traffic density has increased the commute time to between 1 to 2.5 hours for travelling between work and home.

To estimate the daily traffic emission inventory and the traffic carbon footprint needed for air quality modelling, we extracted the digital map of Quito from Open Street Networks and created a traffic network of 887038 edges (lanes) and nodes - connections between lanes at junctions. The Quito traffic network included the position, shape and default speed limit of every lane, traffic light logic referenced by junctions, junctions, including their right of way regulation. The default vehicle type was chosen (emission class, max speed (70km), acceleration and deacceleration rates) and defined the routes (see below). For the first simulation, 1,6 million trips on the road network were ran for one day. Figure 1.1 shows the vehicles, coloured yellow used to simulate traffic behavioiur.

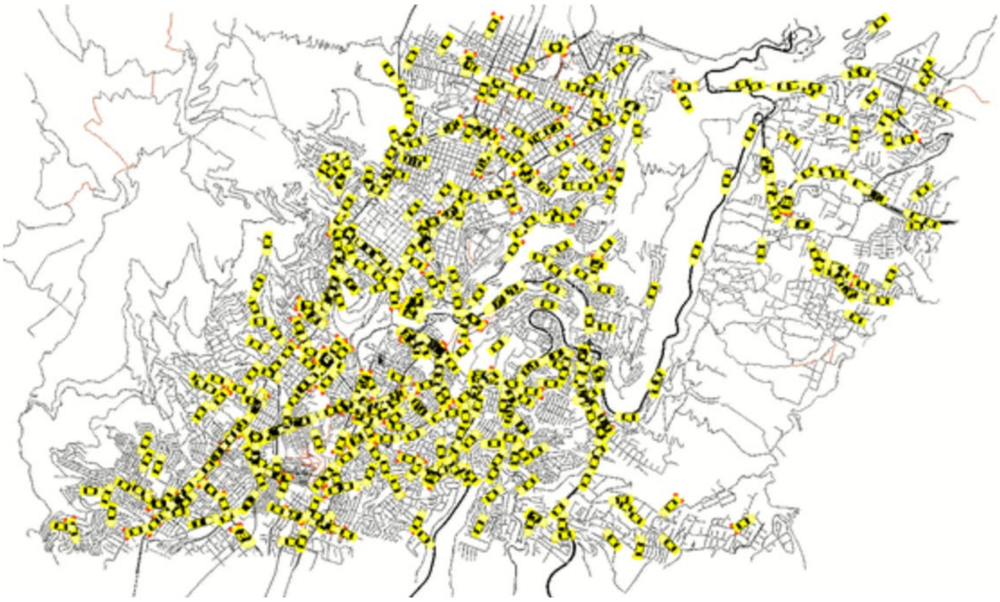


Fig 1.1. Quito simulated traffic network with 887038 edges and 1,6 million trips producing daily traffic emission inventory and CO_2 footprint

Traffic Assignment Zones

To estimate the spatial-temporal distribution of traffic emission inventory University of Helsinki routed the daily traffic flow through Quito using Traffic Assignment Zones. These are areas where participants (drivers and passengers) depart (zone of origin) or arrive (zone of destination). It was assumed that vehicles would depart from Cumbaya, Lloa, Conocoto,La Mena, San Juan, Guangacalle, Nayon and Itchimbia (from a random starting points) and travel to Centro Histórico, La Magdalena, La Libertad, La Floresta” and Iñaquito (stopping at sinks - random edges) during the morning rush hour, and return from the CBD during the evening rush hour (the behaviour is reversed). The traffic assignment zones are shown in Fig 1.2 and number of trips in Table 1.1.

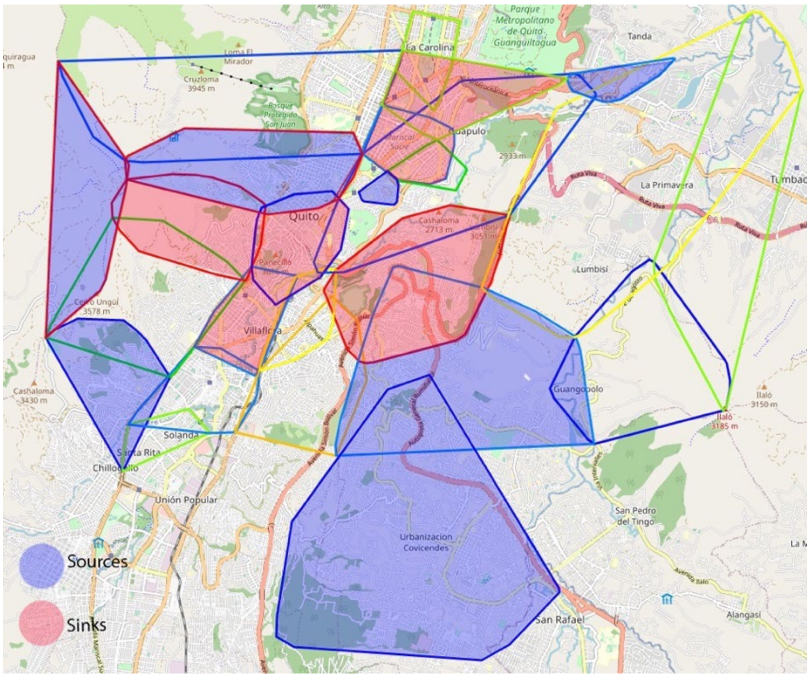


Fig 1.2. Traffic Assignment Zones Morning traffic flow from departing (source) to arriving flow (sink) 08:00 - 12:00. The afternoon traffic flow is the reverse.

Routing	**Sources**	**Sinks**	**Parameters**
	Leave Zone	Arrive Zone	Trips
08:00-12:00	Cumbaya, Lloa, Conocoto,La Mena, San Juan, Guangacalle, Nayon and Itchimbia	Centro Histórico, La Magdalena, La Libertad, La Floresta" and Iñaquito	400000
12:00-16:00	Cumbaya ,Lloa ,Conocoto, La Mena, San Juan, Guangacalle , Nayon and Itchimbia	Centro Histórico, La Magdalena, La Libertad , La Floresta" and Iñaquito	100000
16:00-20:00	Centro Histórico, La Magdalena, La Libertad, La Floresta, and Iñaquito	Cumbaya, Lloa, Conocoto, La Mena, San Juan, Guangacalle, Nayon, and Itchimbia	400000

The traffic emission inventory were applied to the FMI SILAM atmospheric dispersion model using high-resolution meteorological data for 10th October 2021. The output in terms of $PM_{2.5}$ spatial distribution for air pollution at 09:00 and 11:00 are shown in Figure 1.3. In the Figure the road network is clearly identifiable and there is higher $PM_{2.5}$ at the CBD.

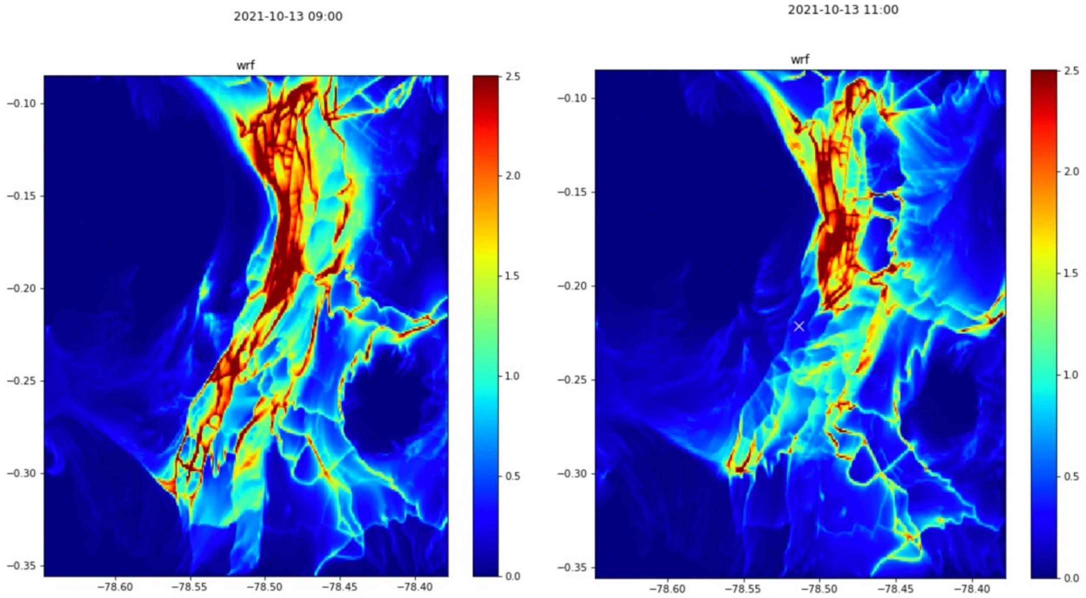
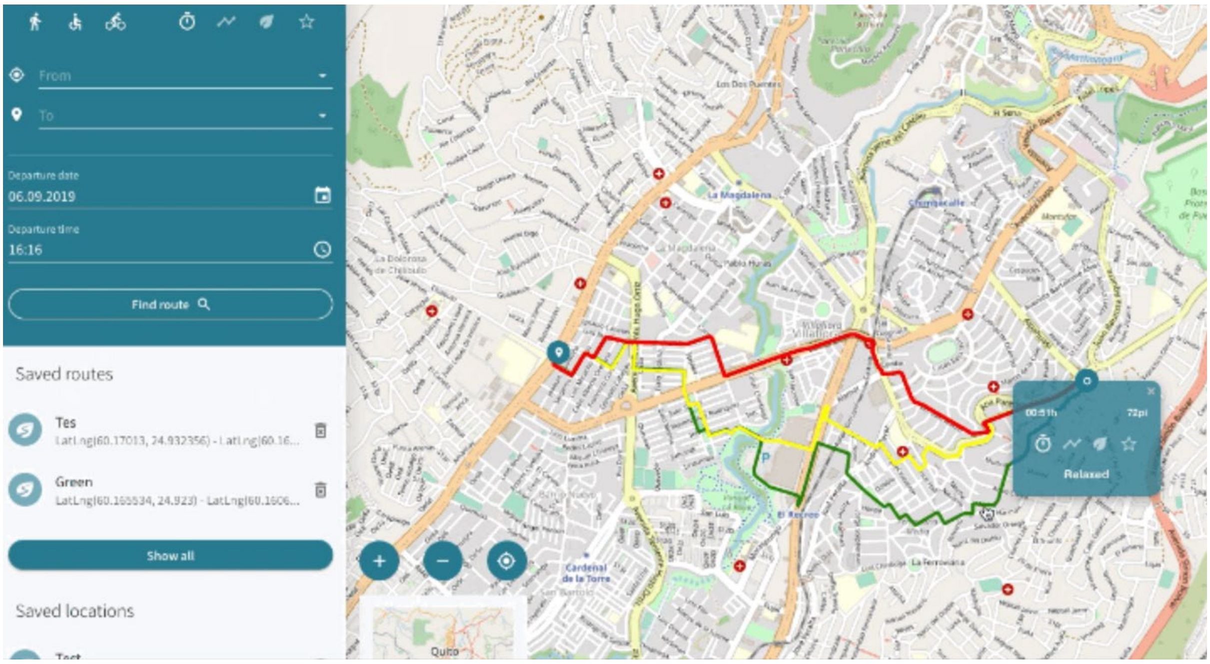


Fig 1.3. FMI SILAM **spatial distribution of** Quito based simulated traffic network and high-resolution meteorological data for 09:00 and 11:00 for 13rh October 2020. The contribution of traffic air pollution with the valley of Quito is clearly seen.

Citizen Clean Air Routing for Quito

To provide citizens of Quito a green path solution, a Clean Air Routing (CAR) algorithm was applied to build a health-optimal route recommendation system between the origin and the destination in Quito based on the FMI SILAM model using meteorological data for 2019 (Fig 1.4). Healthy green navigation paths are achieved by overlaying air pollution data ($PM_{2.5}$ concentration data), with the road network graph obtained through OpenStreetMaps. To find the most suitable walking and cycling routes via the least cost path routing algorithm, the CAR software applies (edge) cost calculation principles to different travel modes and street types adopted and simplified from the OpenTripPlanner. A least cost path routing method was implemented where all cost attributes are pre-calculated and assigned to edges during the start-up of the application, i.e., prior to solving the least cost path problem with Dijkstra's algorithm. The air pollution exposure-adjusted edge costs were calculated from edge-level base costs and environmental exposure data using the environmental impedance function. The outcome is the Clean Air Routing navigation that help's citizens in Quito reduce their overall $PM_{2.5}$ exposure by offering a healthier alternative route which may be slightly longer than the shortest path in some cases.



Departure date
06.09.2019

Departure time
16:16

Saved routes

Tes
LatLng(60.17013, 24.932356) - LatLng(60.16...

Green
LatLng(60.165534, 24.923) - LatLng(60.1606...

Saved locations

Fig 1.4. MetaTavu clean air routing application for Quito based on the modelled spatial distribution of $PM_{2.5}$ based on simulated traffic inventory and meteorological conditions of Sept 2019. The red route is the fastest navigation. The green route is the healthiest navigation. The yellow route is the most convenient navigation.

Traffic Network Behaviour

The road network in Quito has an elongated shape which heavily constraints the alternatives to travel from one place to another. According to the average traffic flow per edge (street) from the traffic simulations (Fig 1.5) over the day. One can see that some major lanes support 1900 per hour and 300 vehicles per km. Most lanes support less than a 1000 vehicles per hour and 200-300 vehicles per km. With many lanes congested at 500 vehicles an hour and with densities of 100-400 vehicles per km implying traffic congestion and high emission rates.

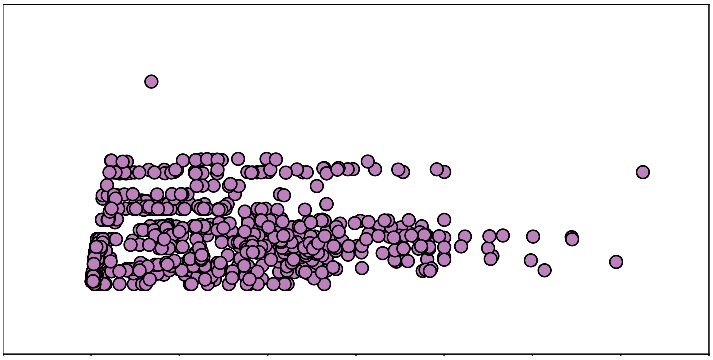


Fig 1.5. Quito's Macroscopic Fundamental Diagram based on the traffic simulations.

Introducing a Low Emission Zone for Historical Center of Quito

The historic center of Quito is a parish with high population density and extensive commercial activity. There are at least 10 important logistic nodes within the area including 8 Malls, and 2 wholesale retail markets. Historic Center of Quito commercial density of 178 establishments per square kilometer is the highest in the Metropolitan District of Quito. Parts of the Historic Downtown Quito is declared as emission-free zone with several blocks of pedestrian streets. Traffic restrictions in this zone only allow public transport and taxis with zero-emission technology. This has led to a considerable decrease in emissions and improved air quality. However, according to estimates of the Mobility Secretariat (2018), 76,038 vans and 1,233 buses circulate the Historic Centre of Quito every day. It has been proposed that after 2030 all the vehicles that circulate in the area will have to be zero emissions. Based on this goal, the impact of introducing a low-emission zone to the Historic Downtown Quito was modelled.

Quito Historic Center of Quito Center 'business-as-usual' scenario

To model a 'business-as-usual' scenario of no change, University of Helsinki created a network of Quito center with 49k edges. network size) and vehicles are allowed to travel through the historic center. University of Helsinki ran 100K trips center in 1 day, which is equivalent to

4,166 per hour (Fig 1.6A) . This is in line with the report of 2010, where approximately 3,300 cars per hour circulated in Historic Center of Quito with average speeds of 10 Km per h during peak hours and 30 Km per hour during non-rush hours. The macroscopic fundamental diagram (the average traffic flow per road) shows in many lanes, traffic is in free flow when traffic flow is below of 240 vehicles per hour and density of 120 vehicles per km (Fig 1.6B). Elsewhere, many lanes supported 120 up to a density of 280 vehicles and the scatter indicates traffic becoming congeste increasingly over-saturated for the road network.

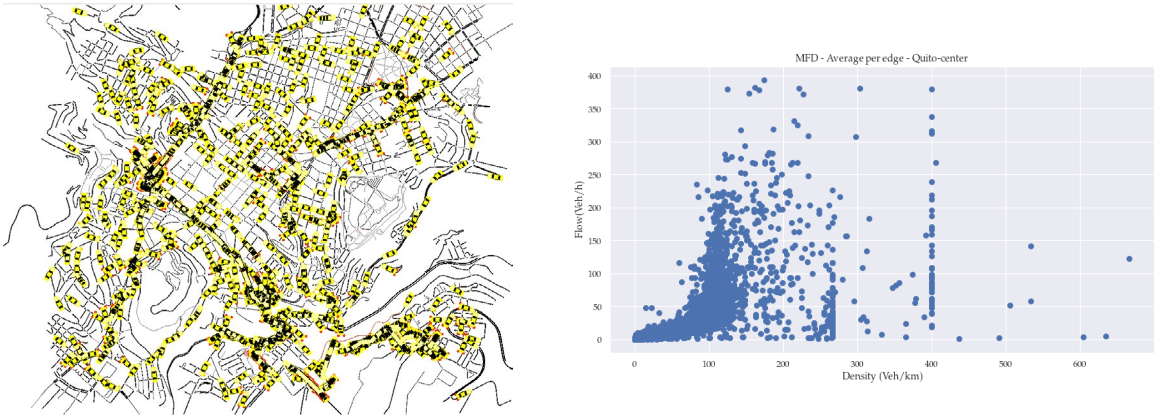


Fig 1.6. Quito center traffic network simulated (A) Macroscopic Fundamental Diagram (B)

Traffic simulation of proposed Low Emission Zone

To model a ’low-emission zone’ scenario, A second network of Historic Center of Quito was created with 49k edges and vehicles are not allowed to travel through the historic center. University of Helsinki ran 100K trips center in 1 day (Fig 1.7A) . The Access to the historical center was shut down.. Meaning that no vehicles could travel through and had to find another route. The macroscopic fundamental diagram (the average traffic flow per road) shows traffic in many lanes is in free flow below up to 450 vehicles per hour and 110 vehicles per road km, inferring that the traffic flows better (by 200 cars per hour) with the LEZ compared to central city business-as-usual scenario (by 10 cars km) (Fig 1.7B).

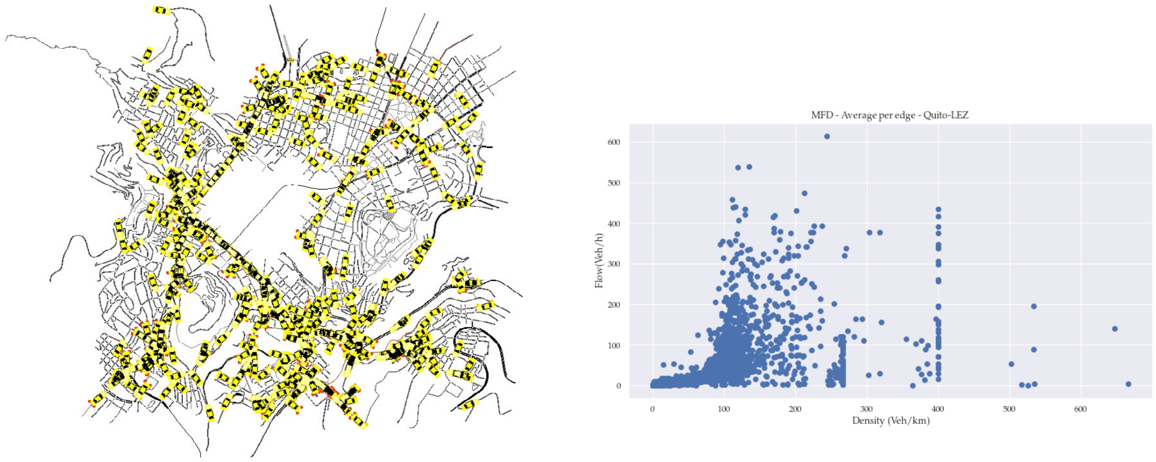


Fig 1.7. Historic Center of Quito Low Emission Zone traffic network (A) Macroscopic Fundamental Diagram inferring better traffic flow in many streets with LEZ (B). Many lanes experience traffic density between 120 and 220 vehicles per hour inferring congestion as the flow of vehicles per km reduces significantly. Visually, there is more congestion flowing around the Historic Center of Quito LEZ in comparison with the business-as-usual scenario.

Atmospheric dispersion modelling for Sept 2019

The traffic emission inventory hourly gridded data outputs were used as configuration files by FMI SILAM atmospheric dispersion model for two scenarios in Quito. University of Helsinki added global meteorological conditions (60km resolution) of August-September 2019 to predict PMx, NOx and CO spatial-temporal concentrations across Quito for the two scenarios. Between September 11th to September 27th 2019, the average temperature was 18C. There were clear days and cloudy days with rain showers and thunderstorms and this influence the spatial distribution and temporal intensity of air pollution (see Table below).

2019	Precipitation	Wind Direction	Wind speed m/s	Weather
Sep 12	Showers	South	9.8	Cloudy
Sep 14	Showers	South	11.8	Cloudy
Sep 15	Showers	South	9.8	Cloudy
Sep 17	Showers	South	8.2	Cloudy
Sep 18	Showers	South	7.2	Cloudy
Sep 19	Thunderstorm, Light Rain	South West	6.2	Overcast
Sep 20	Thunderstorm, Light Rain	South West	8.2	Overcast
Sep 23	Rain, Showers	South	7.7	Cloudy
Sep 24	Thunderstorm, Showers	South	9.3	Cloudy

Calibrating the FMI SILAM model with in-situ air quality measurements

FMI SILAM atmospheric dispersion model air pollution forecasts are based on emissions from the vehicle engine types and traffic patterns. This approach underestimates the actual in-situ air pollution concentration, as measured by city monitoring stations because there are many other sources of air pollution in Quito in addition to traffic. Traffic emissions may be resuspended (e.g., road dust) which is not captured by the simulation. To calibrate the FMI SILAM (see Fig 1.8 & 1.9), the modelled values of air pollution (*upper left panel*) is adjusted (*upper middle panel*) according to city monitoring station observations. The adjustment is done by matching the model to the observations using a quantile-quantile approach. Modelled levels of pollutants are extracted at observation station locations; the measurement location is indicated by a star in the upper left and upper middle panels (Fig 1.8 & Fig 1.9). These modelled observations becomes the input for the quantile-quantile model adjustment. The adjustment is done by fitting sigmoid functions to a range of quantiles for both the modelled and measured observations. These fits are then used to interpolate from one distribution (modelled observations) to the another (measured observations). This adjustment is then applied to the whole model domain. Fig 8 show the SILAM calibration process for PM_x using one city monitoring stations in the LEZ and Fig 9 shows the same calibration procedure for NO_2.

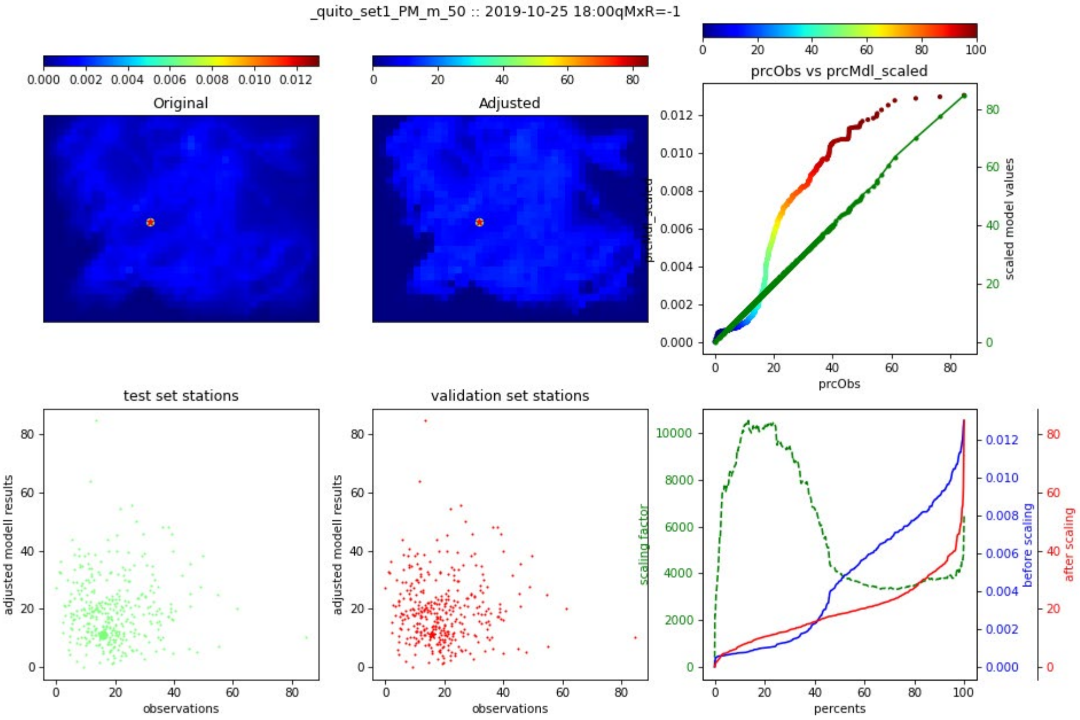


Fig 1.8. PM$_x$ scaling: FMI SILAM model observations are compared to observations from a City Monitoring station in LEZ; the model measurements are adjusted according to the observations.

PMm50 means particulate matter with a modal peak at 500 nm

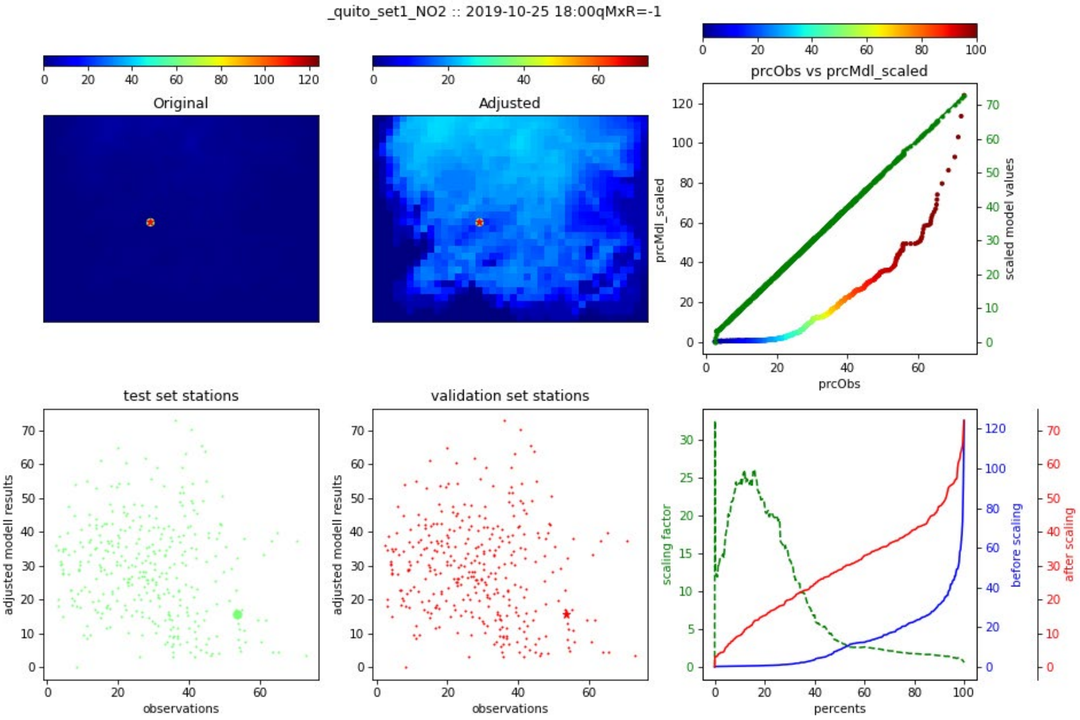


Fig 1.9. NO_2 scaling: FMI SILAM model observations are compared to observations from a City Monitoring station in LEZ; the model measurements are adjusted according to the observations.

Historic Center of Quito LEZ leading to lower $PM_{2.5}$ exposure

Following the calibration of the FMI SILAM model outputs, one can analyze the spatial distribution and temporal intensification of air pollution in Quito during the studied time. The atmosphere dispersion adjusted model outcomes shows a decrease of PM_x concentration in the modelled Historic Center of Quito LEZ network (Fig1.10). This spatial distribution of air pollutant - ambient $PM_{2.5}$ concentration is decreased by 10-20 $\mu g/m^3$ in the LEZ leading critical health benefits. However, the model shows that traffic is routed along major roads adjacent to the LEZ and congestion may lead to elevated concentrations of $PM_{2.5}$; up 70 $\mu g/m^3$ on AV.24 de Mayo and junction AV.Mariscal Surce, and access to roundabout from Piedra. Similarly, elevated $PM_{2.5}$ of similar magnitude in the districts Chilibulo and Villaflora. The increased spatial concentrations maybe due to LEZ restricting the flow of north-south traffic leading to congestion at junctions and districts near the major junctions. The PM$_{2.5}$ concentrations from one spot receptor location at historical center demonstrates the benefits of imposing a LEZ (Fig 1.11). Compared to center business-as-user the LEZ PM$_{2.5}$ concentrations are reduced by an average of 20 μg/m^3 within the historical center. Decreases in PM$_{2.5}$ have significant long-term and short-term health impacts for those living near to the historical center. A decrease by 5 μg/m^3 in the average PM$_{2.5}$ levels may lead to a gain in life expectancy at 30 of 3 to 5 months. Alternatively, for those living in the areas of elevated PM$_{2.5}$ studies have shown that a rise of 10μg/m^3 in PM$_{2.5}$ concentration results in increased hospitalization for cerebrovascular disease, ischemic heart disease, arrhythmias, peripheral arterial disease and heart failure. Other studies show PM$_{2.5}$ increase of 10μg/m^3 per day: lung cancer mortality increased by 15-27%; CVD for women increased by 24%; the incidence of type 2 diabetes may increase by 25%. From the simulations, the within the Historic Center of Quito LEZ leads to low air pollution exposure, however, additional effort is needed to ensure that the air pollution is not moved to the adjacent districts.

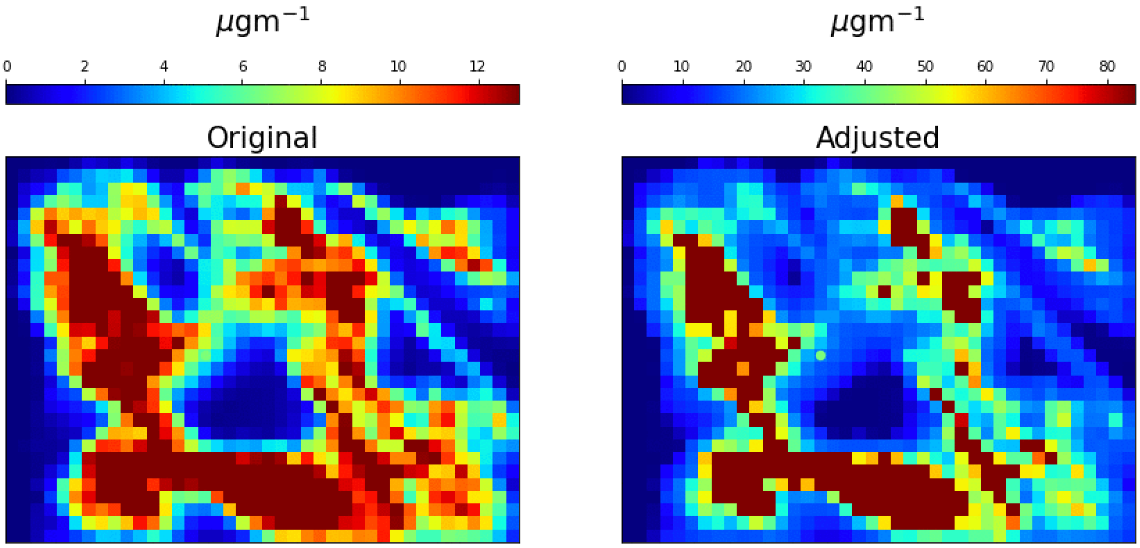


Fig 1.10. Adjusted spatial distribution of PM$_x$ spatial forecasts increase PMx concentrations on major highways at the boundary of the LEZ

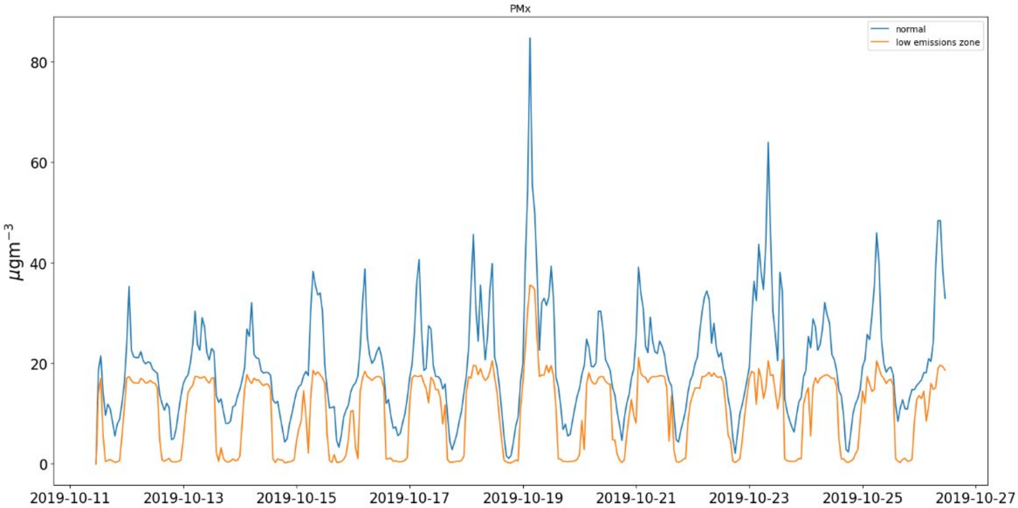


Fig 1.11. Adjusted temporal analysis of PM_x scenarios with meteorological conditions of Sept 2019: normal/business-as-usual measurements are much higher than Historic Center of Quito LEZ forecasts.

Historic Center of Quito LEZ leading to lower NO_2 concentrations

The atmosphere dispersion adjusted model outcomes shows a decrease of NO_2 concentration in the modelled Historic Center of Quito LEZ network (Fig 12). This spatial distribution of air pollution shows moderate ambient NO_2 concentration 20-30 $\mu g/m^3$ in the LEZ. However similarly, $PM_{2.5}$, NO_2 concentrations are elevated in areas adjacent to the LEZ, although, as it is an atmospheric gas, the spatial distribution is different (Fig 1.12). Elevated NO_2 up to 50-60 $\mu g/m^3$ along hilly areas in the districts and Itchimbia and Nueva Tola Bella, and in San Roque. The causes of these concentrations may be due to Quito topographical features such as rivers and hills channelling and modify the local wind patterns and affecting the NO_2 dispersion process. The NO_2 concentrations from one spot receptor location at historical center demonstrates the benefits of imposing a LEZ (Fig1.13). Compared to center business-as-user the LEZ $PM_{2.5}$ concentrations are reduced by an average of 10 $\mu g/m^3$ within the historical center. For 10 $\mu g/m^3$ increase in the daily NO_2 concentrations has been associated with a 0.30% increase in total deaths from cardiovascular mortality and 0.40% and from respiratory mortality.

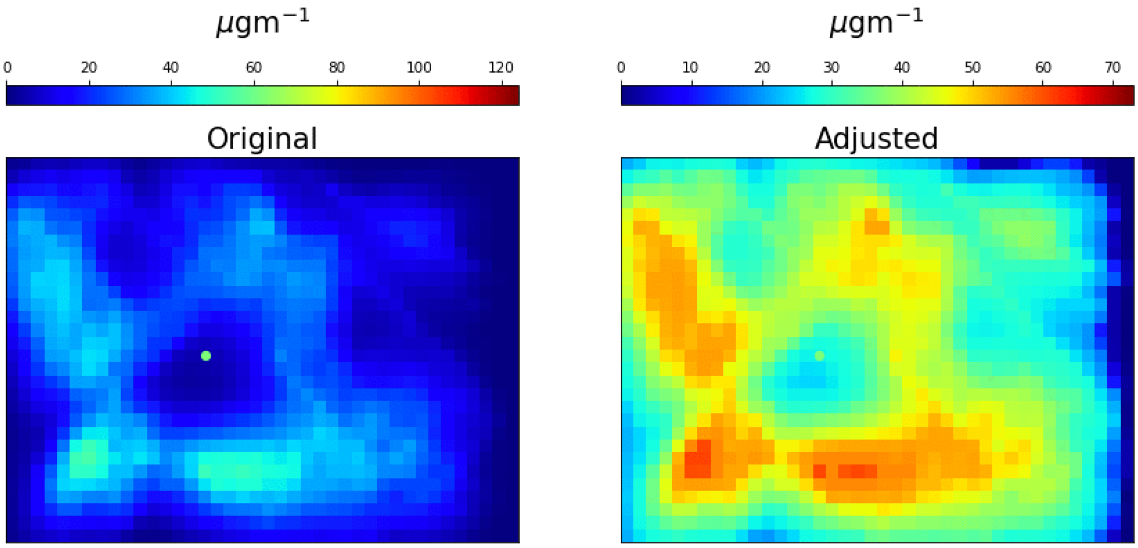


Fig 1.12. Adjusted spatial distribution of NO_2 spatial forecasts increase NO_2 concentrations on influenced by topography.

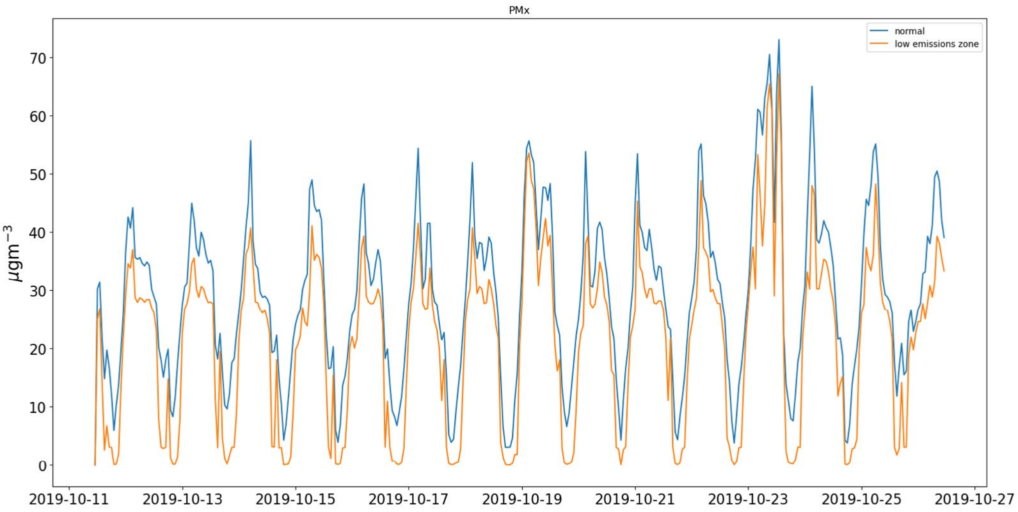


Fig 1.13. Adjusted temporal analysis of NO_2 scenarios with meteorological conditions of Sept 2019: normal/business-as-usual measurements are moderately higher than Historic Center of Quito LEZ forecasts.

Other sources of air pollution

In Quito air pollution concentrations are magnified by the high altitude in which oxygen levels are 27% lower compared to other cities leading to inefficient combustion and high vehicular emissions. To the extent that traffic emissions account for almost 46% of the annual PM emissions. The other sources derive from industrial point sources, and previously the high sulfur content in the fuel. Particulate matter element concentrations are emitted from vehicles (tailpipe, brake and tire wear, engine abrasion), industrial facilities (heavy metal industries, smelting operations, fuel and coal combustion), and uncontrolled waste incineration and biomass burning.

Recommendations

Introduce a comprehensive city-wide approach to modelling air quality to the city of Quito. To produce traffic emission inventories, University of Helsinki demonstrated that road traffic on the map of city of Quito and historic center can by simulated with minimum effort. University of Helsinki note that Quito road network topology and the relationship between traffic flow and traffic density has a significant influence on spatial distribution of traffic emissions.

Our first recommendation is to simulate the traffic behaviour to give insight into the development of traffic emissions.

University of Helsinki set up a high resolution atmospheric dispersion model using the simulated traffic emissions and real meteorological conditions from September 2019 to create a credible air quality model for Quito. University of Helsinki modelled the impacts of creating ultra low emission zone in the historic centre by restricting all traffic in this area. University of Helsinki scaled the simulated predicted emissions of NO_x, $PM_{2.5}$, and CO against the observed measurements of a air quality monitoring station in historical center. This resulted in realistic concentration of the modelled pollutants.

Our second recommendation is to simulate the atmospheric dispersion of simulated and measured traffic sourced emissions against real meteorological conditions and scale the model predictions against local monitoring stations to give insight into the spatial distribution of air pollution over Quito and how the concentrations change in time.

RECOMMENDATIONS

University of Helsinki created a decision support system (DSS) based on traffic emission simulations and atmospheric dispersion modelling of Quito. This enabled us to investigate the potential spatial effects of imposing a Low Emission Zone in historical Quito on $PM_{2.5}$ concentrations inferring a significant decrease in $PM_{2.5}$ concentrations within the LEZ and increased concentrations on the traffic junctions adjacent to the LEZ. University of Helsinki infer that NO_x savings are not so significant and concentrations may accumulate by the hillsides.

Our third recommendation is for government administration and local businesses to use an air quality decision support system to underline the need for continually improve air quality standards and environmental protection. To introduce an LEZ to the historical center and create target-based incentives for low-to zero emission vehicles, investment in cleaner vehicle technologies to avoid the LEZ air pollution savings moving to other areas of Quito.

University of Helsinki managed to formulate an understanding of air quality in Quito through literature review, applying atmospheric science principles, and desk top modelling in Finland. University of Helsinki calibrated our air quality suppositions against local reference instruments and this improved our prediction in order to match air pollution experienced by people living in Quito. University of Helsinki did not validate any traffic simulations against the actual traffic behavioural patterns, such as engine idling, as our intention is to generate approximate traffic emission inventories. University of Helsinki did not model the true diversity of vehicles in Quito including super emitters such as old buses and poorly maintained lorries. University of Helsinki made reference to other sources of air pollution in Quito indicating that traffic air pollution may account to 43% of the average breathable air made worse by the low oxygen levels in the air. To improve the model predictions one needs to consider the other pollution from industrial sources and uncontrolled burning of biomass, and re-suspension of road dust and bare earth. Meteorological conditions and seasonality play a key role in the dilution and dispersion of air pollution concentration, and the time air pollutants remain in the atmosphere before deposition is also a important factor.

Our fourth recommendation is is to calibrate the models and DSS against local evidence and accurately measured local air quality and meteorological data. To take a deductive approach and apply simulations and models to make general statements on the causes and distribution of poor air quality in Quito. Then examine the possibilities by validating the models against real local data to make justifiable inferences and reach a specific, logical conclusions

CASE STUDY 2 KIGALI, RWANDA: CITY DECISION SUPPORT SYSTEM

Located amidst Central and East Africa, Rwanda is bordered to the north by Uganda, to the east by Tanzania, the south by Burundi and the west by the Democratic Republic of Congo. Kigali, located in the geographical centre of Rwanda is the administrative and commercial capital and the largest city of the country. The 2018 population for Kigali was approximately 1.5 million and is forecasted to grow to approximately 3.8 million in 2050.

Poor air quality is an environmental health risk and the Inventory of Sources of Air Pollution in Rwanda (REMA, 2018) states that road traffic is a large contributor to air pollution. GreenHouse Gases (GHG) also require reduction to ensure long- term environmental safety. Private road vehicles are a large contributor to GHG. Possible recommendations for the reduction of air pollution include restrictions around importing older vehicles, investing in public transport systems, and reducing emissions from bus fleets. In this chapter, University of Helsinki are guided by the Kigali master plan by Surbana Jurong Consultants (Pty) Ltd and SMEC International (2018).

Kigali traffic network

Kigali is a city in Rwanda at latitude 10 57 00 00 South, longitude 300 04 48 00 East. The city is roughly 30km in width/length (from north to south and east to west). University of Helsinki extracted the digital map of Kigali from Open Street Networks and created a traffic network of 173851 edges (lanes) and nodes (connections between lanes at junctions). The network included the position, shape and default speed limit of every lane, traffic light logic referenced by junctions, junctions, including their right of way regulation.

University of Helsinki chose the default vehicle type (EURO4 emission class, max speed (70km), acceleration and deceleration rates) and defined the direction of traffic flow (see below). For the first simulation University of Helsinki ran 170,000 trips on the Kigali Road network. Fig 2.1 shows the vehicles, coloured yellow, on the Kigali traffic network used to simulate traffic behaviour. In later simulations, the University of Helsinki modified vehicle type parameters and increase the number of trips.

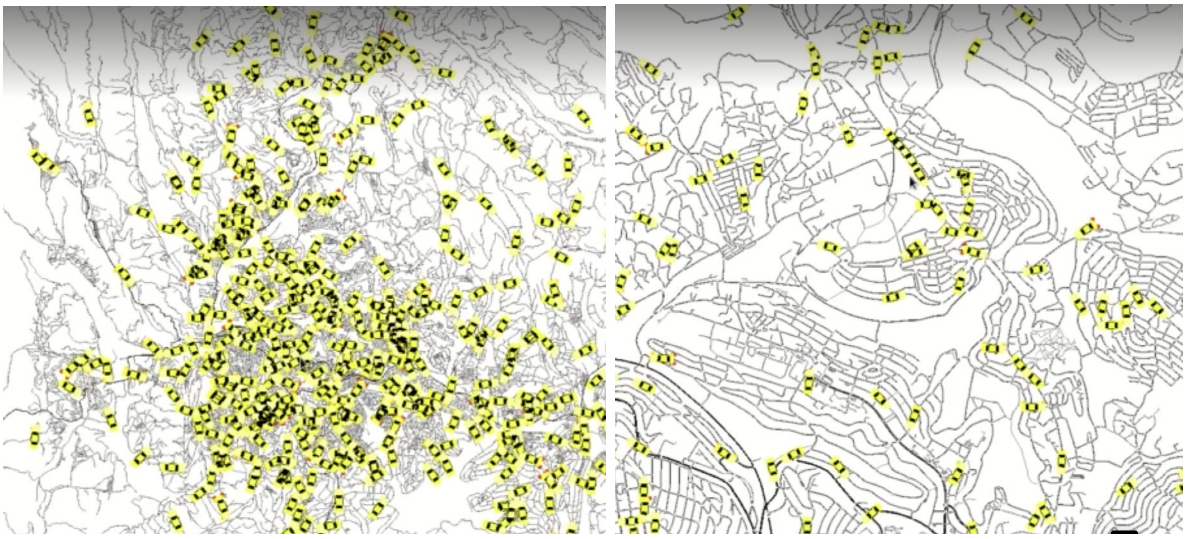


Fig 2.1. Kigali traffic network of 173,851 nodes with simulated congestion in the CBD.

Traffic Assignment Zones

The City of Kigali is divided into three districts namely Nyarugenge, Kicukiro and Gasabo. The centre of Kigali is mostly located in the Nyarugenge district near the Kicukiro and Gasabo borders. Most people live within 2km of their place of work. Most commuter trips are currently shorter than 5km which is considered an acceptable cycling distance and a relatively acceptable walking distance. University of Helsinki assumed that Motorised traffic in the morning would flow to the central business district (CBD), located on an elevated plateau in the Nyarugenge sector. Taking this migratory behaviour into account University of Helsinki created traffic assignment zones (a predefined list of edges) in Gasabo, Kicukiro and Nyarugene. University of Helsinki assumed that vehicles would depart with Gasabo and Kicukiro zones (sources - from a random starting point) and travel to Nyarugene travel assignment zone (stopping at sinks - random edges) during the morning rush hour and return from the CBD during the evening rush hour (the behaviour is reversed). The traffic assignment zones are shown in Fig 2.2.

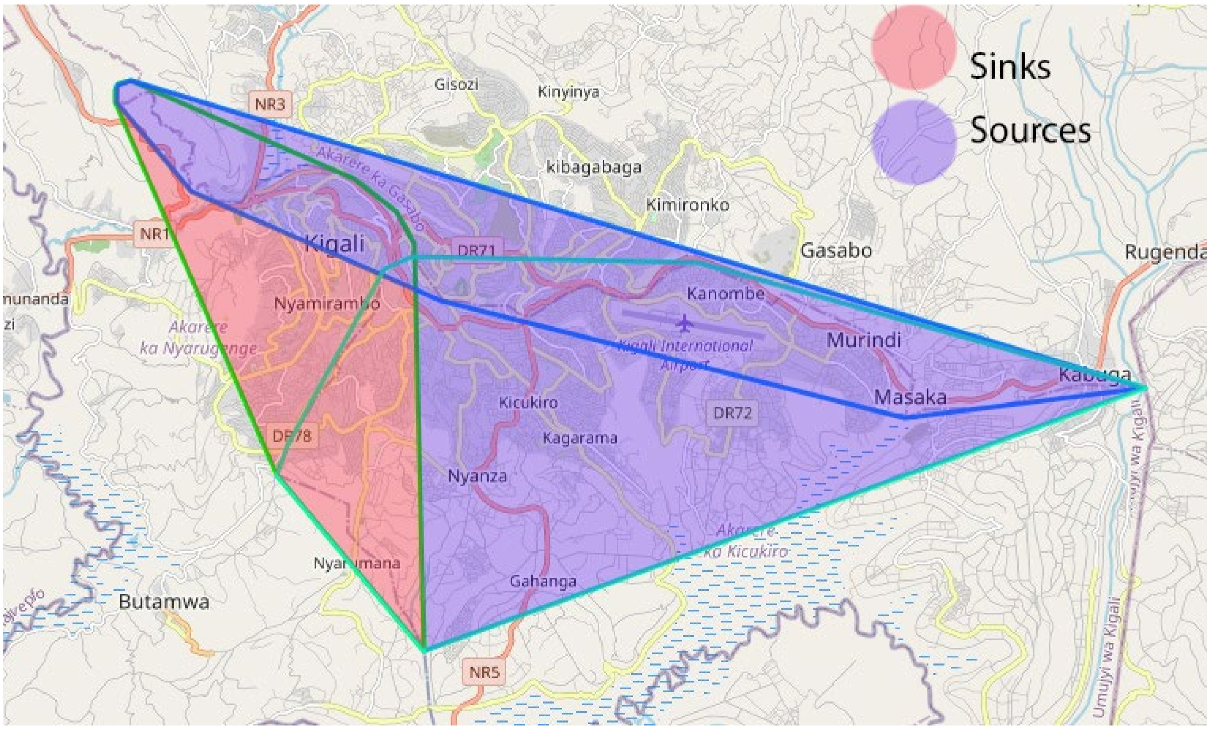


Fig 2.2. Traffic Assignment Zones source (depart) to sink (arrive) trips 08:00 - 12:00

By applying traffic assignment zones (neighbourhoods) and simulating the total number of cars on the road at any given time (the accumulation) with the rate at which trips reach their destinations (the output), University of Helsinki assess the relations between traffic flow, traffic density and velocity. With demand being the number of vehicles in flow, and supply being the road network (the number of roads). The Table below, shows the areas were assigned as traffic zones defined as the sources of the traffic and conversely, sinks are the end of the routes. Each zone is a portion of the city, the exact start and end point are picked at random. The number p defines a fraction of the trips made in the opposite direction (sinks to sources) for a given hour of the day, and the number of trips from each zone.

Routing	**Sources**		**Sinks**		**Parameters**	
	Leave Zone	Leave Zone	Arrive Zone	Arrive Zone	P	Trips
08:00-12:00	Gasabo	Kicukiro	Nyarugenge	Nyarugenge	0.5	60000
12:00-16:00	Gasabo	Gasabo	Nyarugenge	Nyarugenge	0.005	30000
16:00-20:00	Nyarugenge	Nyarugenge	Gasabo	Kicukiro	0.1	60000

Traffic Network Behaviour

The existing road network in Kigali is very much a closed network mainly due to topographical constraints. The benefit of a closed network is that fast moving through traffic is limited and it presents a safer environment than an open network. Fig 2.3 shows the average macroscopic fundamental diagram for each edge (one dot is a street the simulated traffic was routed through) in Kigali. One can see that traffic is in free flow or unsaturated up to a density of 100 vehicles per km and flow of 2000 vehicles per hour. Between a density of 100 to 130 vehicles per km the network capacity seems to have been reached with many vehicles (up 60,000) completing their trips. After 130 vehicles per km the network was congested and over-saturated. In the first scenario, it was demonstrated that vehicle traffic can be simulated for Kigali and traffic emisson inventories based on this behaviour were created.

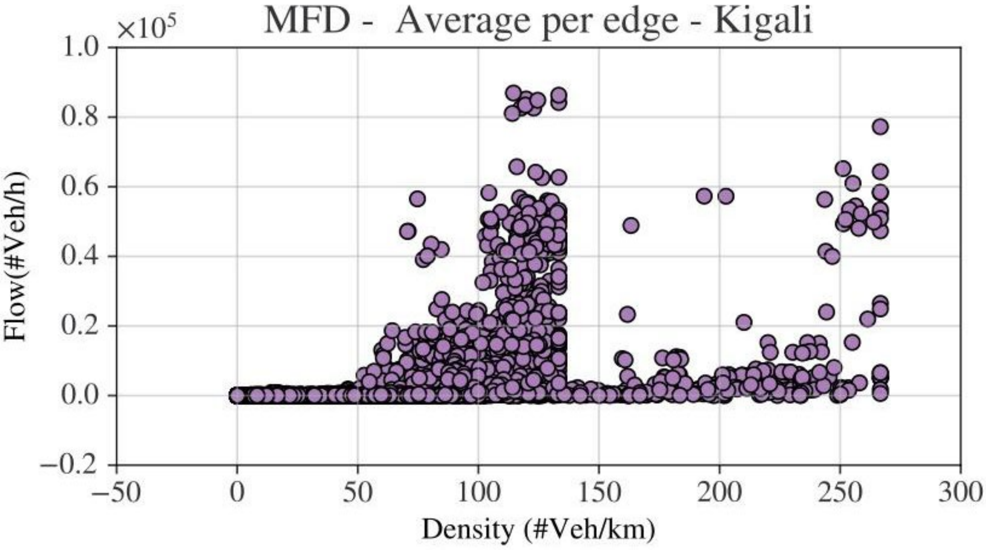


Fig 2.3. Macroscopic fundamental diagram for each street in Kigali

Increase of car ownership 2020, 2030, 2050

According to the Kigali master plan (2018) there is an expected traffic volume increase on roads between 2018 and 2050 due to population growth and an increase in car ownership. This road traffic demand increase will cater for an estimated population in 2050 of 3.8 million, an increase from 1.5 million in 2020. According to forecasts, the total demand for peak hour car trips increases from 88,397 in 2018 to 342,552 trips in 2050 and moto-taxi trips increase from 47,162 trips in 2018 to 111,179 trips in 2050. Fig 2.4, created by a PTV VISUM macro-simulation model shows significant increase expected all over the Kigali network and many new trips are concentrated in the southeast of Kigali and the north of Kigali by 2050.

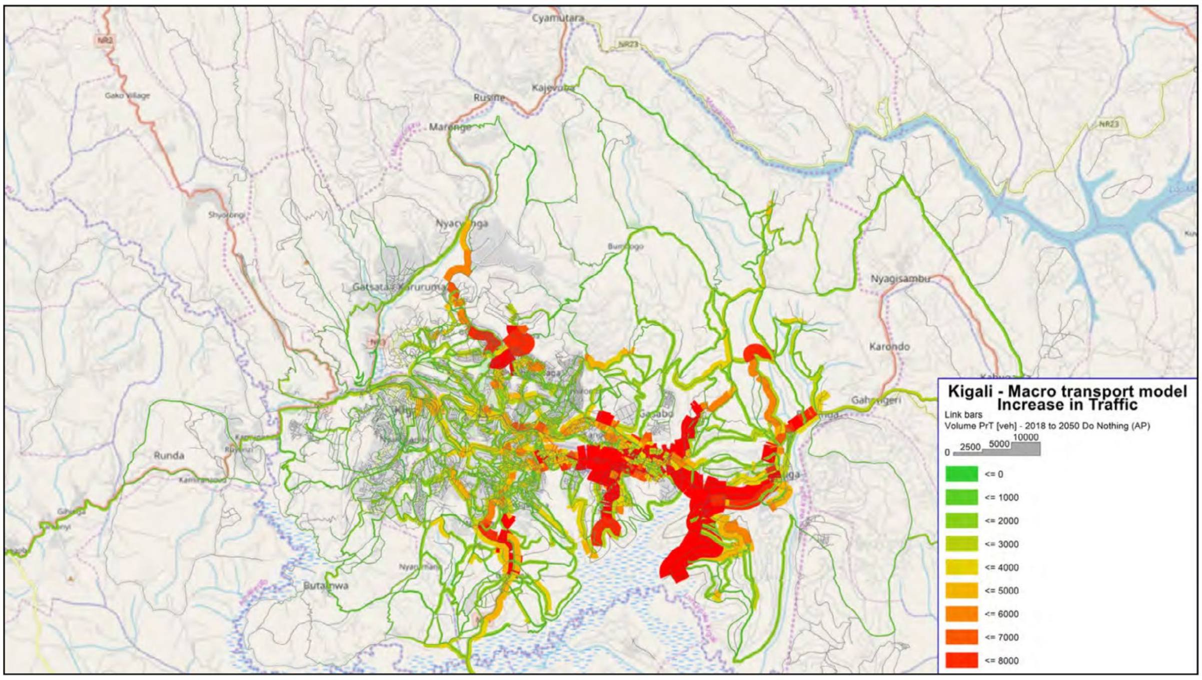


Fig 2.4. Forecast demand for car trips and moto-taxi trips up to 2050 from the master plan, Kigali

Traffic simulation for 2020, 2030, 2050

To simulate the expected traffic volume increase in Kigali between 2020 and 2050, University of Helsinki modified the vehicles running on the SUMO traffic network and increased the number of trips (see Table 2.2). University of Helsinki ran three simulation conditions: (1) a simulation for 2020 where all vehicles are assigned EURO 3 engines and 475,200 trips; (2)

a simulation for 2030 where 50% of vehicles were assigned EURO 6 engines and 923,951 trips; (3) a simulation for 2050 where 70% of vehicles were assigned EURO 6 engines and 2,107,102 trips. Each simulation produced grid files where the where the emissions (CO_2, CO, PMx, NOx) of the vehicles were recorded both spatially (per grid cell) and temporally (over the simulations). The grid files formed the configuration files for the SILAM atmospheric dispersion model.

Mode	**2020**	**2030**	**2050**
Car Engine	EURO 3	EURO 6	EURO 6
Fleet share	100%	50%	70%
Trips per day	475,200	923,951	2,107,102

Atmospheric dispersion modelling

The simulated traffic configuration files were used as traffic emission inventories by the SILAM atmospheric dispersion model for three scenarios in Kigali: 2020, 2030, and 2050. University of Helsinki added global meteorological conditions (60km resolution) of August-September 2019 to predict PMx, NOx and CO spatial-temporal concentrations across Kigali. The general meteorological for dispersion modelling were temperature approximately 30C, partly cloudy and more details shown in the Table below.

2019	**Precipitation**	**Wind Direction**	**Wind speed m/s**	**Weather**
Aug 25	Rain, Light Rain	West	4.6	Cloudy
Aug 28	Rain, Light Rain	East	4.1	Cloudy
Aug 29	Rain, Light Rain	East	5.1	Cloudy
Aug 30	Thunderstorm, Light Rain	East	5.7	Overcast
Aug 31	Strong Thunderstorm	East	11.8	Cloudy
Sep 1	Light Rain, Mist	East	3.6	Cloudy
Sep 2	Rain, Distant Fog, Mist	Southeast	5.1	Cloudy
Sep 3	Rain, Light Rain	West	2.6	Cloudy
Sep 4	Mist	Southeast	5.1	Clear
Sep 6	Rain, Light Rain	West South	5.7	Cloudy

Sep 7	Rain, Light Rain	Southeast	7.7	Cloudy
Sep 8	Light Rain	Southeast	6.7	Clear

PMx predictions 2020, 2030, 2050

The atmosphere dispersion model outcomes show significant increase of PM_x concentration across the Kigali network and becomes more concentrated in the southeast of Kigali and the north of Kigali by 2050 (Fig 2.5). This spatial distribution of air pollution seems to replicate the growth of car ownership as described above, although the original trip rules were based on the target assignment zones. The reasons for increased spatial concentrations may be due to the road network configuration in these areas leading to congestion and the prevailing meteorological conditions. The PM_x concentrations from spot receptor locations were low. Due to heterogeneity of $PM_{2.5}$, University of Helsinki can only model the primary aerosol PM_x particles from the traffic emissions. Without further local measurements, University of Helsinki cannot add secondary aerosol mass to increase the $PM_{2.5}$concentrations as is the case in real life. From the data, University of Helsinki are assuming that 10% of urban PM emissions are emitted as primary aerosol particles from vehicles, one would only see 10% of what the sensors would see in SILAM with the SUMO emissions. In Fig 2.6 PMm50 means particulate matter with a modal peak at 500 nm. 'm' indicates that it is condensed matter and indicates the decimal point of the modal peak in the size distribution in micrometres.

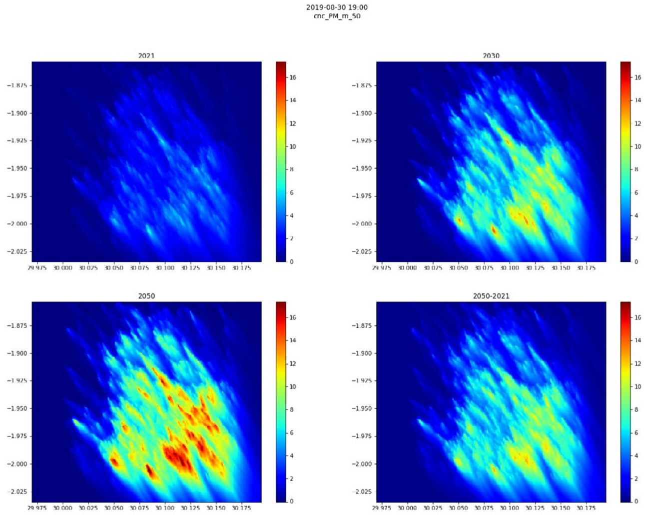


Fig 2.5. PMx concentrated in the southeast of Kigali and the north of Kigali by 2050

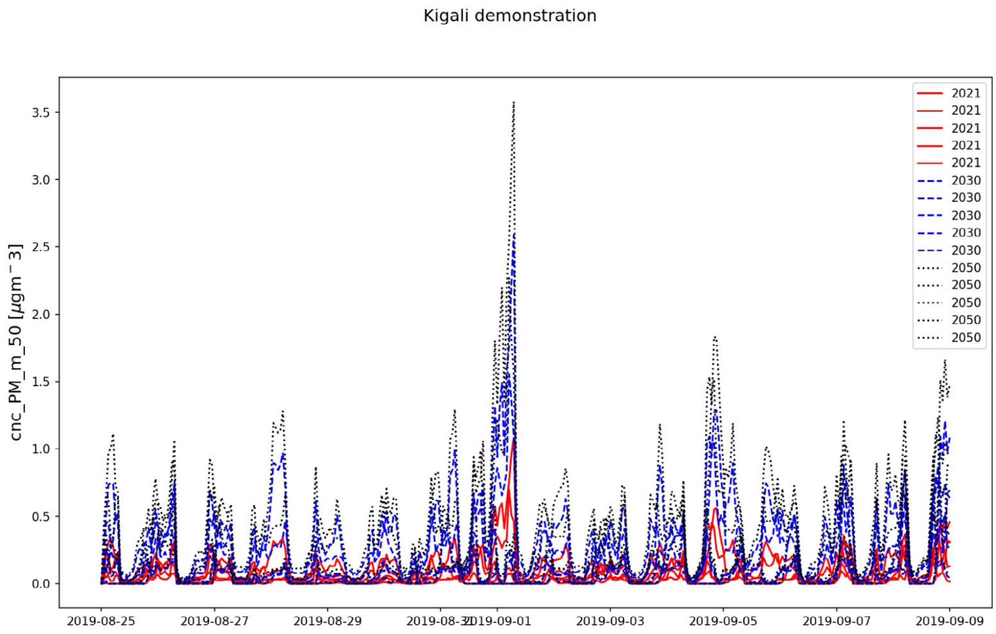


Fig 2.6. PM time series from 5 points in Kigali, 2020, 2030, 2050. PMm50 means particulate matter with a modal peak at 500 nm

NO2 2020, 2030, 2050 predictions

The atmosphere dispersion model outcomes show significant increase of NO$_2$ concentration across the Kigali network and initially is more concentrated in the south- east of Kigali and the north in 2030 and covers most of Kigali by 2050 (Fig 2.7). At the beginning, the spatial distribution of NO$_2$ seems to replicate the growth of car ownership as described and spreads as more of the road network becomes congested. The initial NO$_x$ concentrations from spot receptor locations were in line with the global emission inventory. NO$_x$ is an atmospheric gas and does not form aerosol mass. It is primarily formed because of high temperature combustion when nitrogen in the atmosphere and in fuel is partially oxidised via a series of reactions to produce NO$_x$. Most NO$_x$ exhausting from a combustion process is in the form of NO, with a smaller proportion directly emitted as NO$_2$ (primary' NO$_2$). The process, and hence the proportion of primary NO$_2$ produced, is dependent on the temperature, pressure, oxygen concentration and residence time of the combustion gases in the combustion zone. The proportion of primary NO$_2$ produced during combustion has been estimated to be around 5. Fig 2.8 shows predicted NO$_2$ from 5 locations measured for NO$_2$ against 2019 meteorological conditions. There is an increase in NO_2 and subsequently NO_2 for 2030 and 2050. The impacts of the increased NO_2 exposure may increase incidence of eye and lung irritation and respiratory illnesses such as asthma. Long term increases in NO_x concentrations will also lead to an acceleration of freshwater eutrophication and acidification of soils and freshwater ecosystems, which can cause widespread damage to terrestrial and aquatic ecosystems.

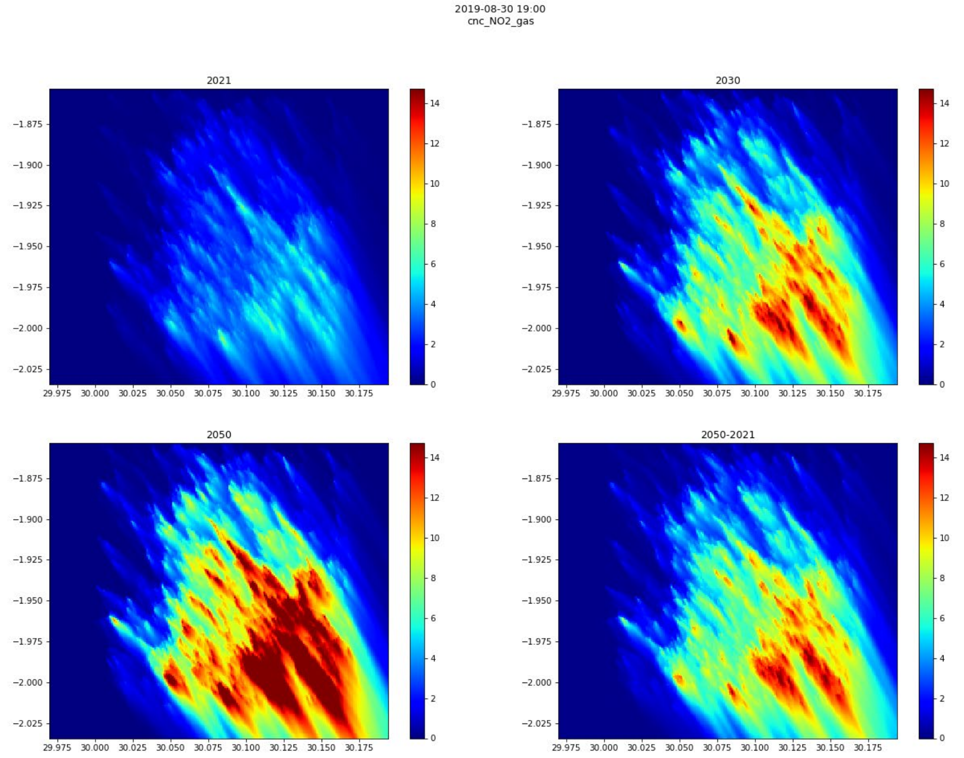


Fig 2.7. NO_2 concentrated in the southeast of Kigali and the north of Kigali by 2050

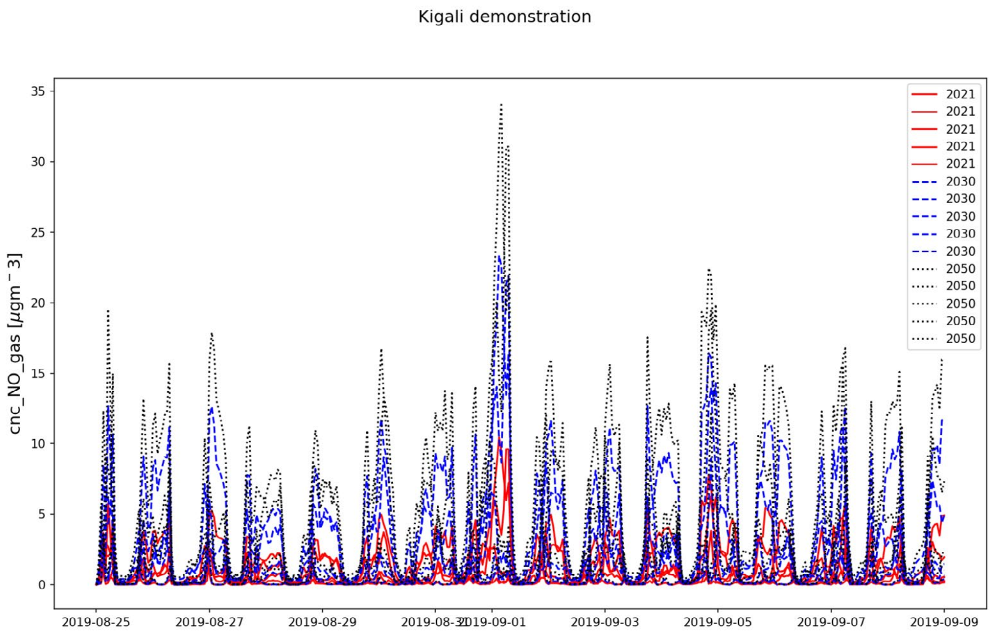


Fig 2.8. NO_2 time series from 5 points in Kigali, 2020, 2030, 2050

Carbon Monoxide (CO) predictions

The atmosphere dispersion model outcome shows significant increase of traffic related CO concentration across the Kigali network, like NO, and initially is more concentrated in the southeast of Kigali and the north in 2030 and covers most of Kigali by 2050. The initial CO concentrations from spot receptor locations were in line with the global emission inventory. CO is produced by the incomplete or inefficient combustion of carbon-based fuels and by biological and industrial processes. Fig 2.9 shows predicted CO from 5 locations against 2019 meteorological conditions. There is an increase in CO for 2030 and 2050. Although, in outdoor (ambient) air, CO is rapidly dispersed away from the source of heavily congested traffic areas and enclosed spaces (such as inside vehicles, tunnels, or multi-storey car parks) citizens can experience elevated CO and health impacting concentrations.

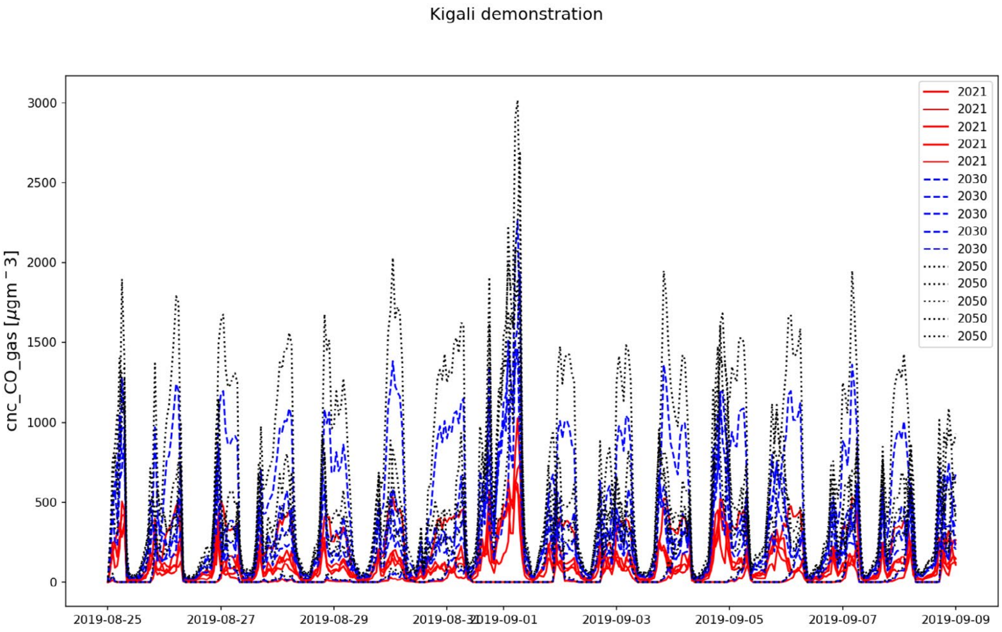


Fig 2.9. CO time series from 5 points in Kigali 2020, 2030, 2050

Multi-modal planning 2020 – 2050

Multi-modal planning refers to planning that considers various modes (walking, cycling, automobile, public transit, etc.) and connections among modes. The goals of the 2018 Transport Master Plan are:

- To become a Public Transport-Orientated City
- To establish a complete Transport System
- To create a Sustainable Transport Network

Achieving these factors requires improved public transport services and the prioritisation of non-motorised transport (NMT) and NMT infrastructure. Higher congestion and environmental pollution are to be avoided through the planning and implementation of larger scale public transport and non- motorised transport projects. It is widely assumed that attractive green transport infrastructure encourages more people to walk which will decrease pressure on the road network, it improves the health of citizens who use the network, it has low capital investment required and very low operation and maintenance costs and it has minimal impacts on the environment.

Traffic simulations for 2020 – 2050

To simulate the multi-model planning scenarios for Kigali between 2020 and 2050, University of Helsinki modified the vehicles running on the SUMO traffic network and aligned the number of trips to the Kigali master plan (2018). University of Helsinki ran four simulation conditions with all vehicles with EURO 4 engines and the trip time represent the busy hour: Business-as-usual; Sustainable; Low EV penetration and high EV penetration Each simulation produced grid files where the where the emissions (CO_2, CO, PM_x, NO_x) which is discuss below.

Share	2020	Projected to 2050			
	Start	BAU	Sustainable	Low Electrification	High Electrification
NMT	50%	30%	46%	44%	44%
Cars	25%	40%	20%	26%	26%
Busses	25%	30%	34%	30%	30%
Vehicle Trips	475,200	2,107,102 (excluding NMT trips)			

The number of trips is estimated based on the data in the master plan. The number of trips per person is 1.8 and with the estimated population growth University of Helsinki created a simulation based on the number of daily trips per day.

Share	BAU	Sustainable	Low Electrification	High Electrification
NMT	+2.55%/y	4.77%/y	4.61%/y	4.61%/y
Busses	+4.17%/y	4.51%/y	4.15%/y	4.15%/y
Cars/taxis	+6.42%/y	2.79%/y	3.62%/y	3.62%/y
EV Car growth	11%	11%	+8%/y	14%/y
EV Bus growth	11%	11%	+8%/y	15%/y
Cars	0	0	+3%/y	-0.2%/y

Business-as-usual scenario

The Business-as-usual scenario (BAU) follows the trend of population growth leading to increased car ownership. In the scenario, University of Helsinki assume that with increased car ownership the number of NMT trips will decrease from 50% in 2020 to 30% in 2050. As citizens invest in new cars the share of private cars increases from 25% in 2020 to 40% in 2050. There will be an increase of public transport trips by 5%. Although the number of vehicles on the road network will increase dramatically, the emission will be offset by a growing number of electrical vehicles at 11%. Fig 2.10 shows the increased number of trips as the population grows and purchasing power increases. There will be increasingly more private in Kigali between 2025 and 2050.

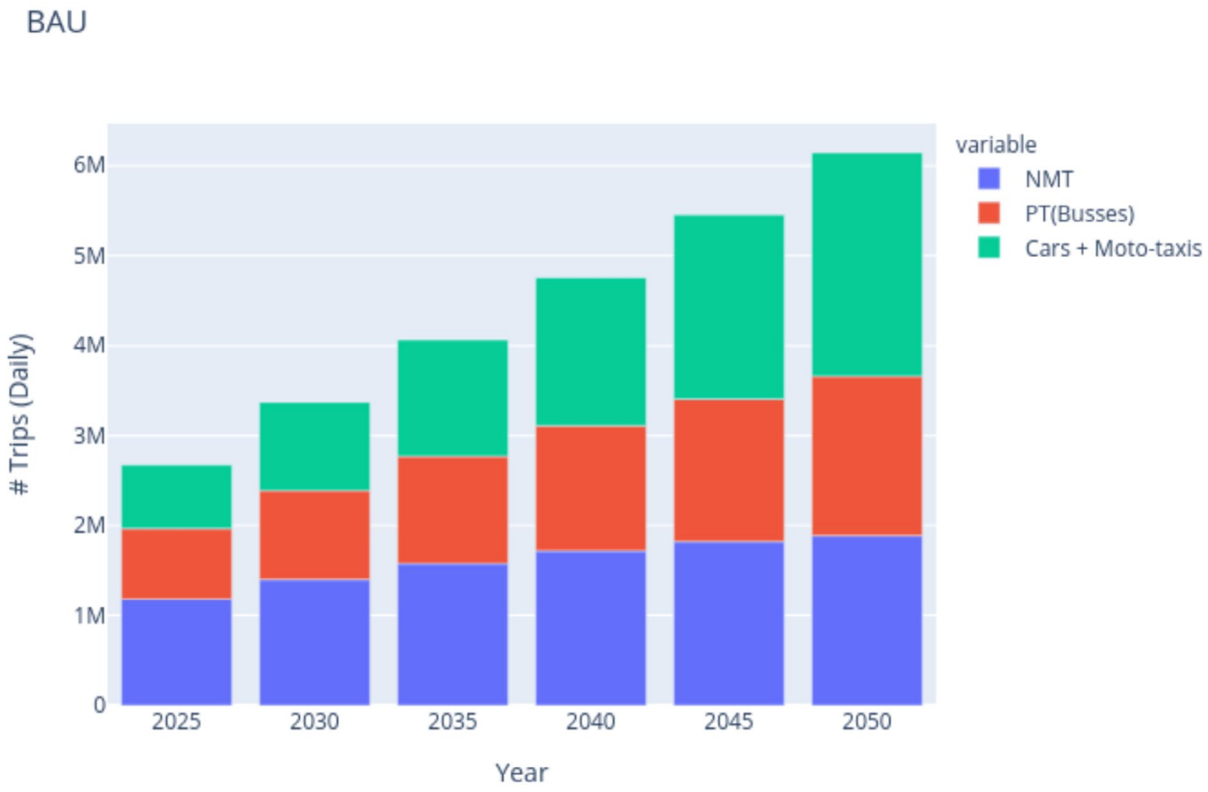


Fig 2.10. Business-As-Usual scenario transportation mode share

Sustainable scenario

The sustainable scenario is aligned to the measures to help reduce air pollution and carbon emissions in Kigali in the Transport Master Plan: to promote NMT and invest in NMT infrastructure; and to invest in Public Transport systems. In the scenario, University of Helsinki assume that the share of NMT trips will only slightly decline from 50% in 2020 to 46% in 2050 due to investment in sustainable and active transport that encourages the existing culture of walking and cycling, and investments in green infrastructure. That share of public transport (buses) will increase from 25% in 2020 to 34% in 2050. That the use of private cars will decrease from 25% in 2020 to 20% in 2050. The emissions of public transport and private cars will be incrementally offset with the increase of electric vehicles 11%/y). Fig 2.11 shows the increased number of trips as the population grows and NMT increases, and the share of private vehicles remains relatively constant in Kigali between 2025 and 2050.

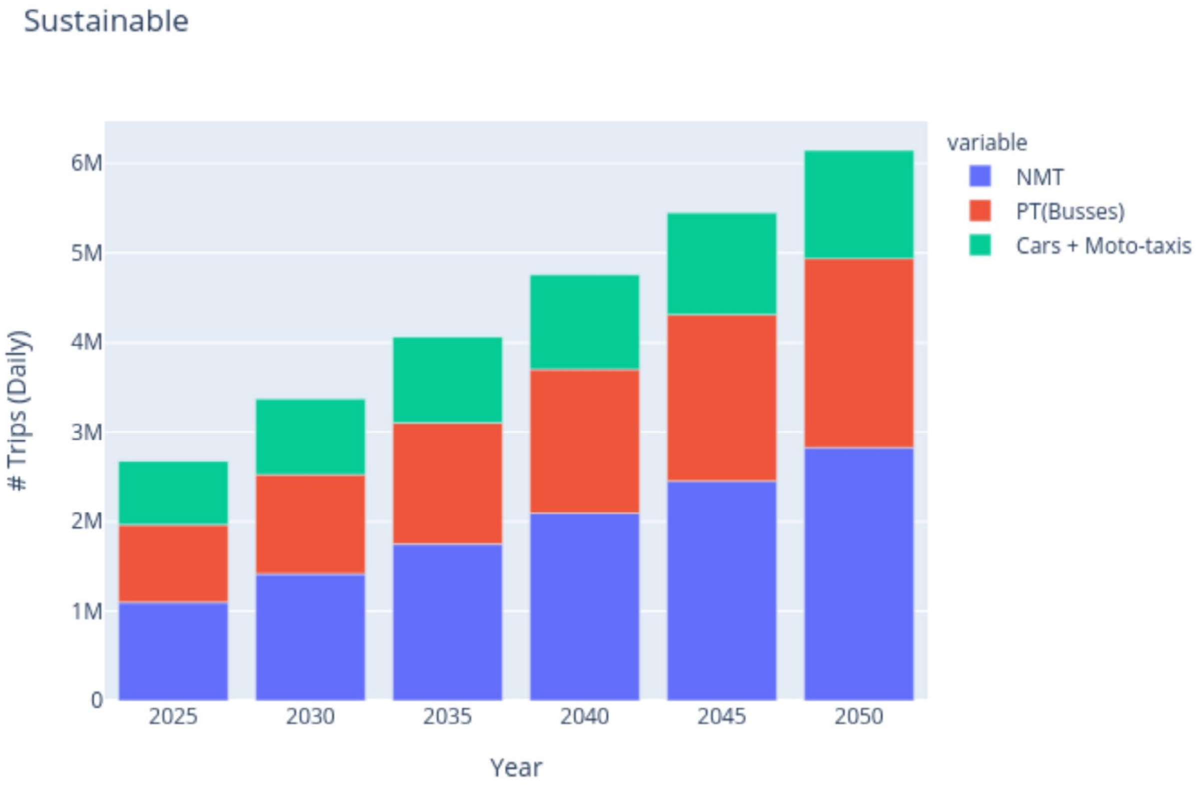


Fig. 2.11 Sustainable Scenario transportation mode share

Electrification scenarios

There is a government strategy for electric mobility adaptation and increasing the share of electric vehicles and motorcycles. With an annual vehicle growth rate of 12% in Rwanda, the administration has provided incentives making owning and maintaining an electric car less costly in comparison to a fuel-powered vehicle. With incentives, Rwanda aims to reduce emissions by 38% by 2030 with electric vehicles estimated to represent 9% of potential energy-related emissions under the country's ten-year climate action plan. It has been estimated that the cost of transitioning to e-mobility and the adoption of electric vehicles in Rwanda is 900 million USD. However, transitioning to electric motorcycles alone would save the Rwandan economy 22 million USD in fuel imports per year. Accordingly, a feasibility study Sweco-ifeu e-mobility recommended the following 2030 targets at national level:

- 30% of electric motorcycles
- 8% of electric cars (including jeeps)
- 20% electric buses
- 25% for electric taxis and mini/microbuses

University of Helsinki present two scenarios to illustrate the effects of EV penetration on emissions and air pollution. In both scenarios, University of Helsinki assume that between 2020 and 2050, the share of NMT will decline by 6%, the bus share will increase by 5%, and private car share will only increase by 1%. However, University of Helsinki classify 'low electrification' scenario where the growth of EV cars is 8% and EV buses is 8%, and private cars growth is 3% per year, and 'high electrification scenario where the growth of EV cars is 14% and EV buses is 15%, and private cars decrease by -0.2% per year.

Road transport CO_2 predictions

Rwanda has a long-term goal to be a carbon neutral nation by 2050. In the short term, Rwanda aims to reduce CO_2 emissions by 38% compared to business as usual by 2030 and electric vehicles are estimated to represent 9% of potential energy-related emissions mitigated under the country's climate action plan (NDC). In a Rwanda Government business as usual scenario, total carbon emissions from Kigali will in- crease by 122% from 2018 levels by 2032, while emissions per capita will increase 33%. CO_2 emissions from road transport account for 13% of the total emissions in Rwanda and are expected to continue to rise. Although buses comprise only 15% of the total vehicles in Rwanda, they constitute approximately 40% of the total emissions from the transport sector.

Our simulated road transport predictions are only based on vehicle EURO 4 engine CO_2 emissions which underestimate the real production values, since trucks and buses produce much more CO_2 emissions than cars, and fuel quality is also an important contributor. The current understanding of road transport CO_2 in Kigali is in the range of 527,000 to 689,000 tons of carbon dioxide per year. This is based on the consumption petrol and diesel fuel petrol is consumed annually in Rwanda and 30% of consumed diesel and petrol is used by diesel vehicles (EURO3 and older engine types) outside the city of Kigali. The predicted CO_2 values from the different scenarios are much lower as shown in Figure 2.12. Business as Usual our model calculates CO_2 at 125,000 tons per year (2025) increases to over 500,000 per year (2050) as the number of private cars increase. The Sustainable scenario calculates CO_2 as 110,000 per year and because there is emphasis on NMT, the CO_2 levels stay constant until 2050. The two electrification scenarios demonstrate the impact of the high fleet conversion to EV against low fleet conversion. The CO_2 emissions of low electrification scenarios grow from 260,000 tonnes per year to 600,000 tonnes per year, whereas the levels of high electrification stay below 300,000 tonnes per year from 2025 to 2050.

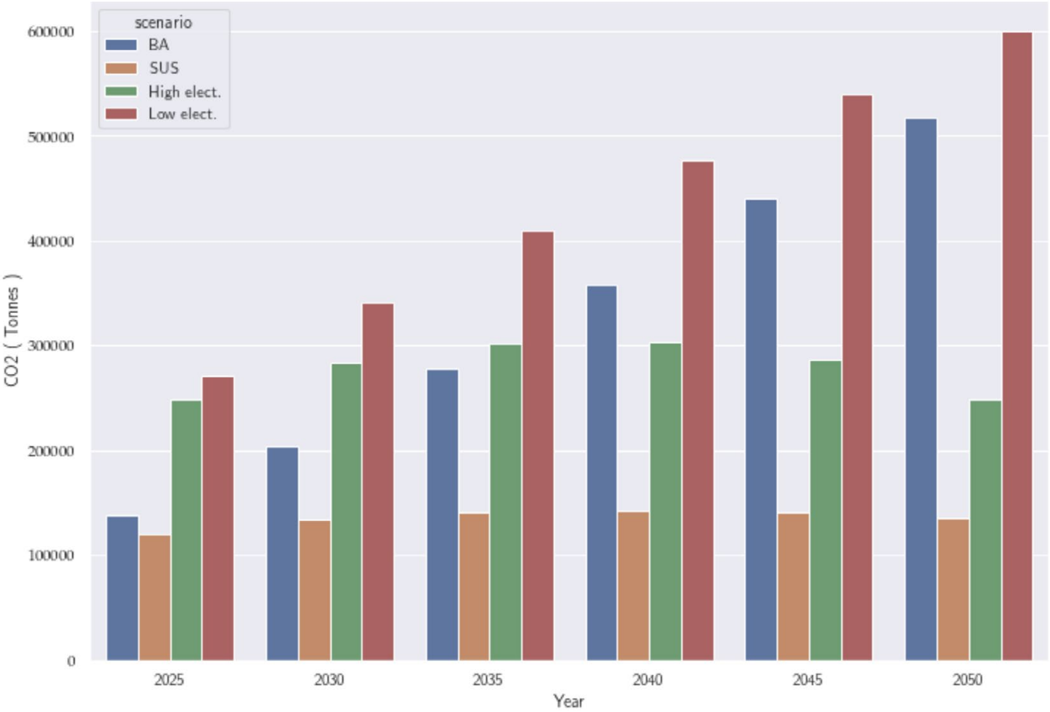


Fig 2.12. CO_2 multi scenario forecast 2020 - 2050

Road transport NOx predictions

Our simulated road transport predictions are only based on vehicle EURO 4 engine NO_2 emissions which underestimate the real production values (Fig 2.13). For example, a single line-haul truck emits the NOx equivalent of 100 cars for each mile driven in urban driving. Under urban driving conditions, line-haul trucks are emitting on average 7.0 g/mi of NO_x, compared with less than 0.07 g/mi for a gasoline car (2019). Furthermore, heavy-duty vehicles emit more than 5 times NO_x emissions during the low-speed (less than 25 mph) operation characteristic of urban driving, which the normal case in congested cities or idling in traffic jams. There is limited comparative data for NO_x annual emissions, however from the energy sector, thermal power generation the overall station annual emissions per MW is NO_x 611.80 tonnes. The traffic simulations do show the overall air pollution trends generated from the different scenarios:

- Business-as-usual: traffic sourced air pollution will increase by 5 times. NO_x annual emissions from 60 tons in 2025 to 225 tones in 2050 due to population growth and increase car ownership leading to serious health impacts.
- Sustainable: traffic air pollution will not increase even though there is population growth. NO_x annual emissions remain constant at 50 tones in 20205 and 50 tones in 2050 due to emphasise on NMT and increase in public transport.
- High electrification incentives: traffic sourced air pollution will slightly increase and then decrease as the electric fleet reduces overall traffic emissions. NO_x annual emissions at 110 tons in 2025 and 110 tons in 2050 due to high yearly conversions to EVs (electric cars, bikes, and buses).
- Low electrification incentive: traffic sourced air pollution will increase by 3 times. NO_x annual emission from 120 tons in 2025 to 260 tons in 2050 due current expected conversions to EVs, at a growth rate of 8% per year.

The same trends apply to the PM_x, although it is more problematic to calculate traffic generated $PM_{2.5}$ without improved understanding of other source contributions and nucleation and secondary particle formation.

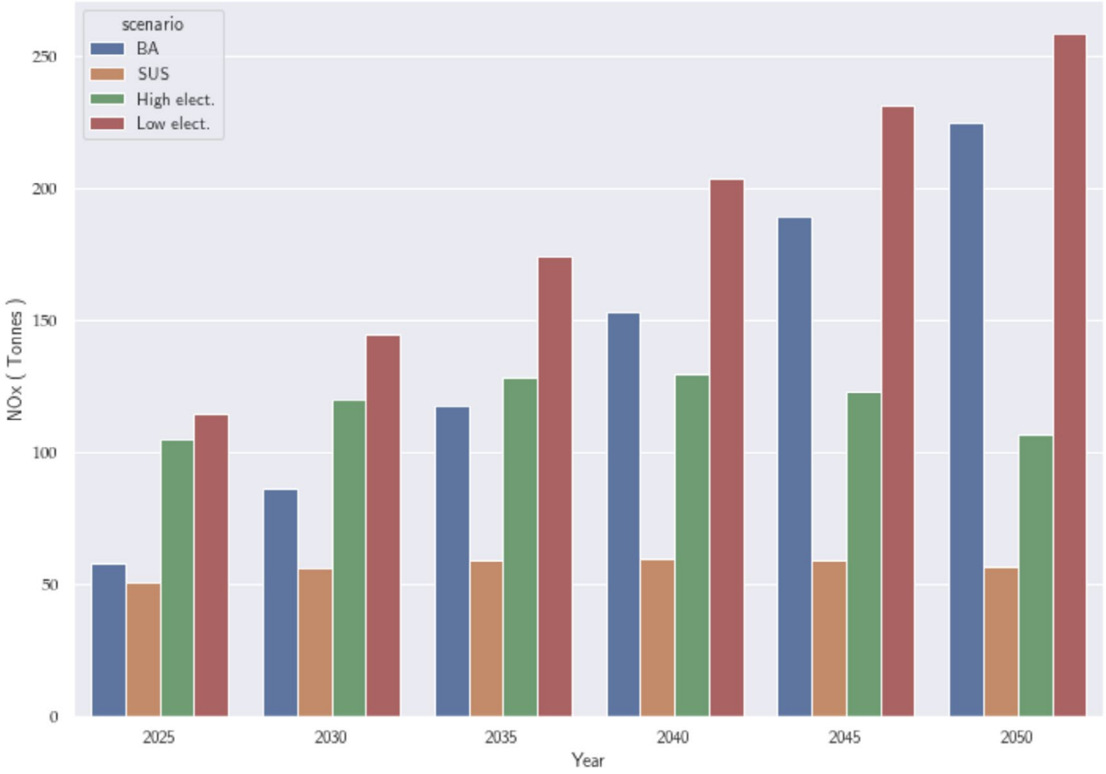


Fig 2.13. NOx multi-scenario forecast 2020 - 2030 - 2050

Other sources of air pollution

In Rwanda there is no one sector that is the biggest contributor to air pollution as the levels of air pollution in a specific area are dependent on its location in relation to pollution sources.

- Adjacent to busy roads, vehicle emissions are the biggest contributor to poor air quality whereas in areas away from busy roads in residential areas the biggest contributor is domestic burning.
- Power plants have high emission rates of pollutants but their effects on air quality are mitigated because the plants have stacks to aid dispersion, and they are not located in residential areas. However, they produce significant annual air pollution per MW to the ambient air which can be dispersed across Kigali (SO_x 3083 tonnes, NO_x 611 tonnes, CO 119 tonnes, PM_{10} 86 tonnes and $PM_{2.5}$ 43 tonnes).
- Construction from activities such as demolition, earthworks, energy usage from furnaces/heavy oils, Cement plants and small-scale brick kilns contribute high localised air pollution concentrations.

- Cooking stoves and the burning of waste using solid fuels such as biomass (88%) peat, coke, coal, and wood are commonly used in Rwanda and incomplete combustion produces high levels of CO and a variety of particulates that contribute to both household air pollution and outdoor air pollution.

Recommendations

Introduce a comprehensive city-wide approach to modelling air quality to the city of Kigali. To produce traffic emission inventories, University of Helsinki demonstrated that road traffic on the map of Kigali can be simulated with minimum effort. It is noted that Kigali's Road network topology and the relationship between traffic flow and traffic density has a significant influence on spatial distribution of traffic emissions.

Our first recommendation is to simulate the traffic behaviour to give insight into the development of traffic emissions.

University of Helsinki set up a high-resolution atmospheric dispersion model using the simulated traffic emissions and real meteorological conditions to create a credible air quality model for Kigali. University of Helsinki modelled the increase of car ownership up to 2050 by modifying the traffic emission inventories. Applying business-as-usual engine technologies it is noted that air pollution from NO_2 and CO will increase by three times again the current measurements. The spatial distribution of the increases will be in the southeast of Kigali.

Our second recommendation is to simulate the atmospheric dispersion of simulated and measured traffic sourced emissions against real meteorological conditions to give insight into the spatial distribution of air pollution over Kigali and how the concentrations change in time.

University of Helsinki created a **decision support system (DSS)** based on traffic emission simulations and atmospheric dispersion modelling of Kigali. This enabled to investigate future-based scenarios grounded matching current interest in increasing the share of electric vehicles against internal combustion engines and promoting non-motorised trips. Our results show that relatively small modifications in the multi-modal planning can lead to significant reduction in total emissions and atmospheric concentrations of CO_2, PMx, NOx, and CO.

Our third recommendation is for government administration and local businesses to use an air quality decision support system to underline the need for continually improve air quality standards and environmental protection, and to generate target- based incentives for purchasing of low-to zero emission vehicles, investment in cleaner vehicle technologies, and implementing a scrappage program for old polluting vehicles.

University of Helsinki managed to formulate an understanding of air quality in Kigali through literature review, applying atmospheric science principles, and desk top modelling in Finland. University of Helsinki did not calibrate our air quality suppositions against local reference instruments, and this is required to scale our findings to match air pollution experienced by people living in Kigali. University of Helsinki did not validate any traffic simulations against the actual traffic behavioural patterns, such as engine idling, as our only intention is to generate approximate traffic emission inventories. University of Helsinki did not model the true diversity of vehicles in Kigali including super emitters such as old buses and poorly maintained lorries. University of Helsinki referred to other sources of air pollution in Kigali indicating that traffic air pollution may only account to 30% of the average breath- able air. Common sources for most of the air pollution are power generation by fossil fuels, uncontrolled burning of biomass, and resuspension of dust and bare earth. Meteorological conditions and seasonality play a key role in the dilution and dispersion of air pollution concentration, and the time air pollutants remain in the atmosphere before deposition is also an important factor.

Our fourth recommendation is to calibrate the models and DSS against local evidence and accurately measured local air quality data. To take a deductive approach and apply simulations and models to make general statements on the causes and distribution of poor air quality in Kigali. Then examine the possibilities by validating the models against real local data to make justifiable inferences and reach specific, logical conclusions.

CASE STUDY 3 KATHMANDU, NEPAL: CITY DECISION SUPPORT SYSTEM

Kathmandu is the capital city of Nepal located in the Kathmandu Valley and it is surrounded by high mountains with 2000 meters in height. The climate of the Kathmandu Valley is sub-tropical in nature which is influenced by the south-west monsoon during summer. The Kathmandu Valley comprising of three districts, i.e., Kathmandu, Lalitpur, and Bhaktapur includes five major municipalities, namely, Kathmandu, Lalitpur, Bhaktapur, Kirtipur, and Thimi. Kathmandu's 2021 population is now estimated at 1,471,867. Kathmandu has grown by 48,352 since 2015, which represents a 3.40% annual change.

The Kathmandu Valley is served with a ring road and radial pattern of road network and the expansion of urban areas have proceeded along the major (or primary) feeder roads radiating from the Ring Road. The number of registered vehicles is rapidly increasing in Kathmandu accompanied with the rapid increase of urban population and economic development. According to the Department of Transport Management, in Kathmandu, there are more than 1.2 million motorcycle and over 300,000 four-wheelers. Vehicular pollution is the main contributor to air pollution in the country.

In 2016, Environmental Performance Index (EPI) of Nepal's air quality ranked 177th out of 180 countries and, in Asia, Kathmandu is ranked one of the most polluted cities. According to a report of World Health Organization (WHO), the maximum status of fine Particulate Matter ($PM_{2.5}$) in urban areas of Nepal was noted to be 140 $\mu g/m^3$ which is 10 times higher than the desirable value

Kathmandu traffic network

A prominent feature of the Kathmandu Valley roadway network is a 27-km-long ring road (RR); it encompasses the urban centers of Kathmandu and Lalitpur, and carries two way traffic, with four lanes in each direction. University of Helsinki extracted the digital map of Kathmandu from Open Street Networks and created a traffic network of 397400 edges (lanes) and nodes - connections between lanes at junctions. The network included the position, shape and default speed limit of every lane, traffic light logic referenced by junctions, junctions, including their right of way regulation. For the initial scenario, University of Helsinki chose the default vehicle type (emission class, max speed (70km), acceleration and deacceleration rates) and defined the routes (see below). University of Helsinki ran 1,2 million trips on the Kathmandu road network. The traffic emission inventory were used by the FMI SILAM model using meteorological data for September 2019. The output in terms of $PM_{2.5}$ spatial distribution is shown in Fig 3.1. In the Figure the road network is clearly identifiable and there is higher $PM_{2.5}$ along the ring road.

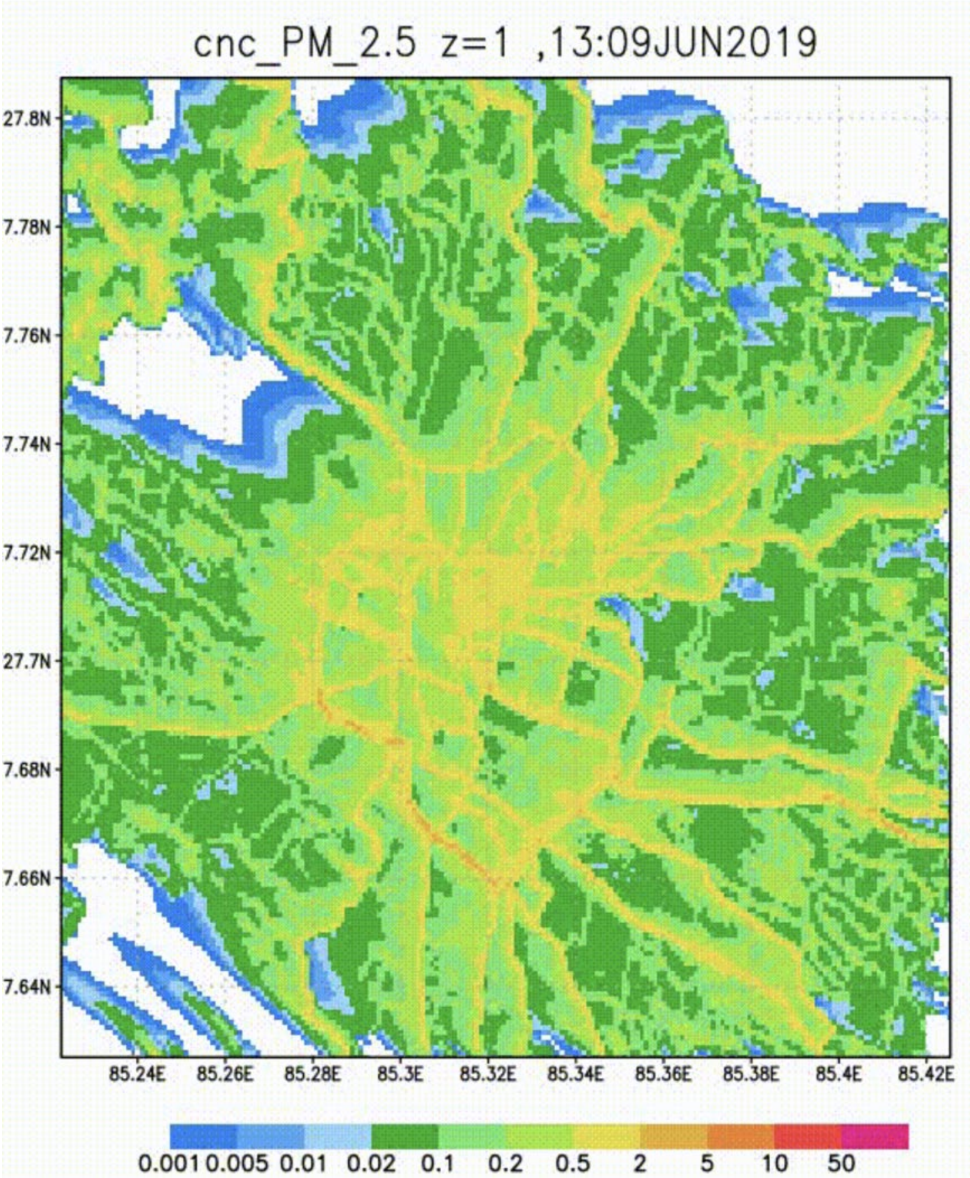


Fig 3.1. Kathmandu $PM_{2.5}$ spatial distribution based simulated traffic network with 397,400 edges and 1,2 million vehicle trips

Citizen Clean Air Routing for Kathmandu

To provide a green path solution, University of Helsinki applied a Clean Air Routing (CAR) algorithm to build a health-optimal route recommendation system between the origin and the destination in Kathmandu based on the FMI SILAM model using meteorological data for 2019 (Fig 3.2). Healthy green navigation paths are achieved by overlaying air pollution data (PM2.5 concentration data), with the road network graph obtained through OpenStreetMaps. To find the most suitable walking and cycling routes via the least cost path routing algorithm, the CAR software applies (edge) cost calculation principles to different travel modes and street types adopted and simplified from the OpenTripPlanner. University of Helsinki implemented a least cost path routing method where all cost attributes are pre-calculated and assigned to edges during the start-up of the application, i.e., prior to solving the least cost path problem with Dijkstra's algorithm. The air pollution exposure-adjusted edge costs were calculated from edge-level base costs and environmental exposure data using the environmental impedance function. The outcome is the Clean Air Routing navigation that help's citizens in Kathmandu reduce their overall PM2.5 exposure by offering a healthier alternative route which may be slightly longer than the shortest path in some cases.

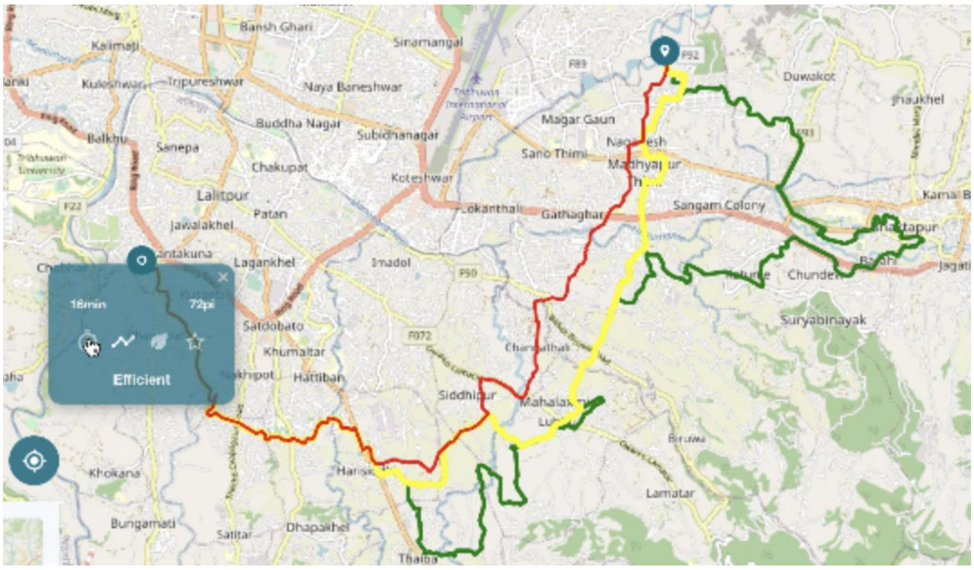


Fig 3.2. MetaTavu Clean Air Routing application for Kathmandu based on the modelled spatial distribution of $PM_{2.5}$ (see Fig 3.1). The Red route is the fastest navigation. Green route is the healthiest navigation Yellow route is the most convenient navigation

Congestion on the ring road

A prominent feature of the Kathmandu Valley roadway network is a 27-km-long ring road (RR); it encompasses the urban centers of Kathmandu and Lalitpur, and carries two way traffic, with four lanes in each direction. According to Himalayan News Service 9.6 kilometres stretch of Ring Road from Koteshwor to Kalanki suffers the worst traffic jams in the Kathmandu Valley. Buses stop haphazardly and pedestrians do not have proper pavements to walk on or zebra crossings, increasing the risk of accidents. In 2020 an estimated 971,000 vehicles passed through the Koteshwor area daily between 8am and 6pm resulting in massive congestion. University of Helsinki extracted the ring road of Kathmandu from Open Street Networks and created a traffic network of 49,000 edges (lanes). It was challenging to isolate the ring road from the traffic network mesh. For the ring road scenario, University of Helsinki chose the bus and vehicle types with different engine types (emission class EURO 3, EURO, 5, EURO 6) and defined the vehicles to join and leave and travel on the around ring road, as a circuit. University of Helsinki ran 16,000 trips on the ring road a day with mixed traffic: 10,000 buses (with bus stops)and 6,000 private cars. Figure 3.3 shows the yellow buses and cars joining and leaving the ring road. These are low numbers of trips on the ring road, however, our objectives are the model the relation between trips, vehicle engine types (emissions) and effects of junctions on the ring road.

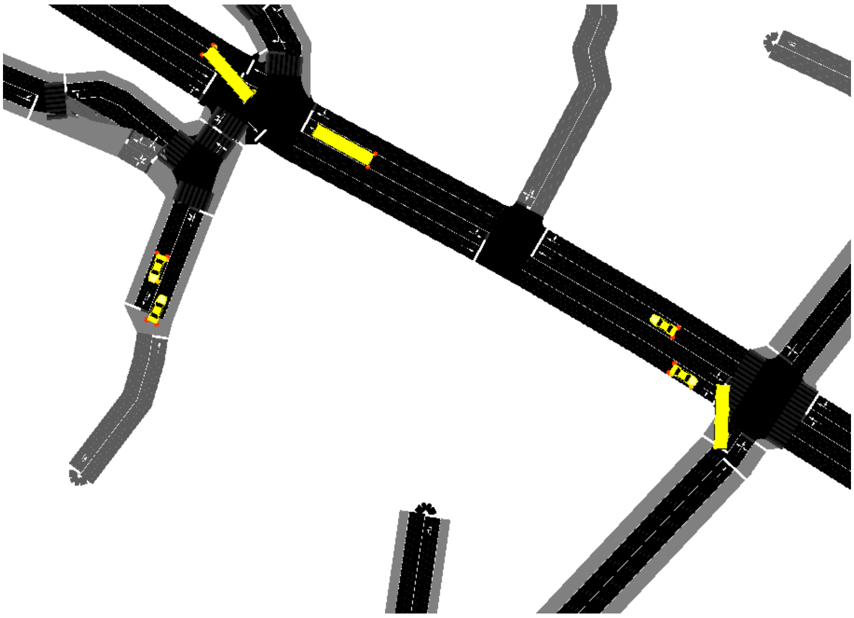


Fig 3.3. Simulated buses and cars joining and leaving the ring road, Kathmandu used to generated traffic emission inventories

Traffic simulation of congestion
Traffic simulations revealed congestion at certain points on the ring road network. Even though the modelled traffic load was relatively light there was traffic congestion after Koteshwar and near to the airport and at junction called Bansbari road, seen as the vehicle bulges in Fig 3.4. The modelled congestion was caused by the road network topology – the location of junctions that moderate and slow down vehicles entering and leaving the ring road. Once there is a traffic queue, congestion is caused by the number of trips (vehicles) circulating the ring road. There was heavy traffic by bus stops near Thasikhel due to slow traffic flow (measured by vehicles per hour) and buses stoping and starting.

The traffic simulations confirm the influence of number of trips has a critical effect on the flow and density of vehicles around the ring road. When comparing the timetable of an operator 5 buses per hour an against an operator with 1.5 buses per hour passes through an edge alongside 6000 private vehicles moving on the ring road, one sees how more buses on the road is conducive with congestion. With a 5 buses an hour, which is quite normal for public transport provided, Figure 3.5 shows that vehicle flow – the average movement of all vehicles – is reduced to 30 vehicles/hour with a density (25 vehicles/km) encouraging traffic congestion. Whereas with the low provision of buses of 1.5 buses per hour, the flow rate is increased, as shown in Figure 3.6 - up to 60 vehicles per at a density up to 50 vehicles per km resulting in traffic free flow.

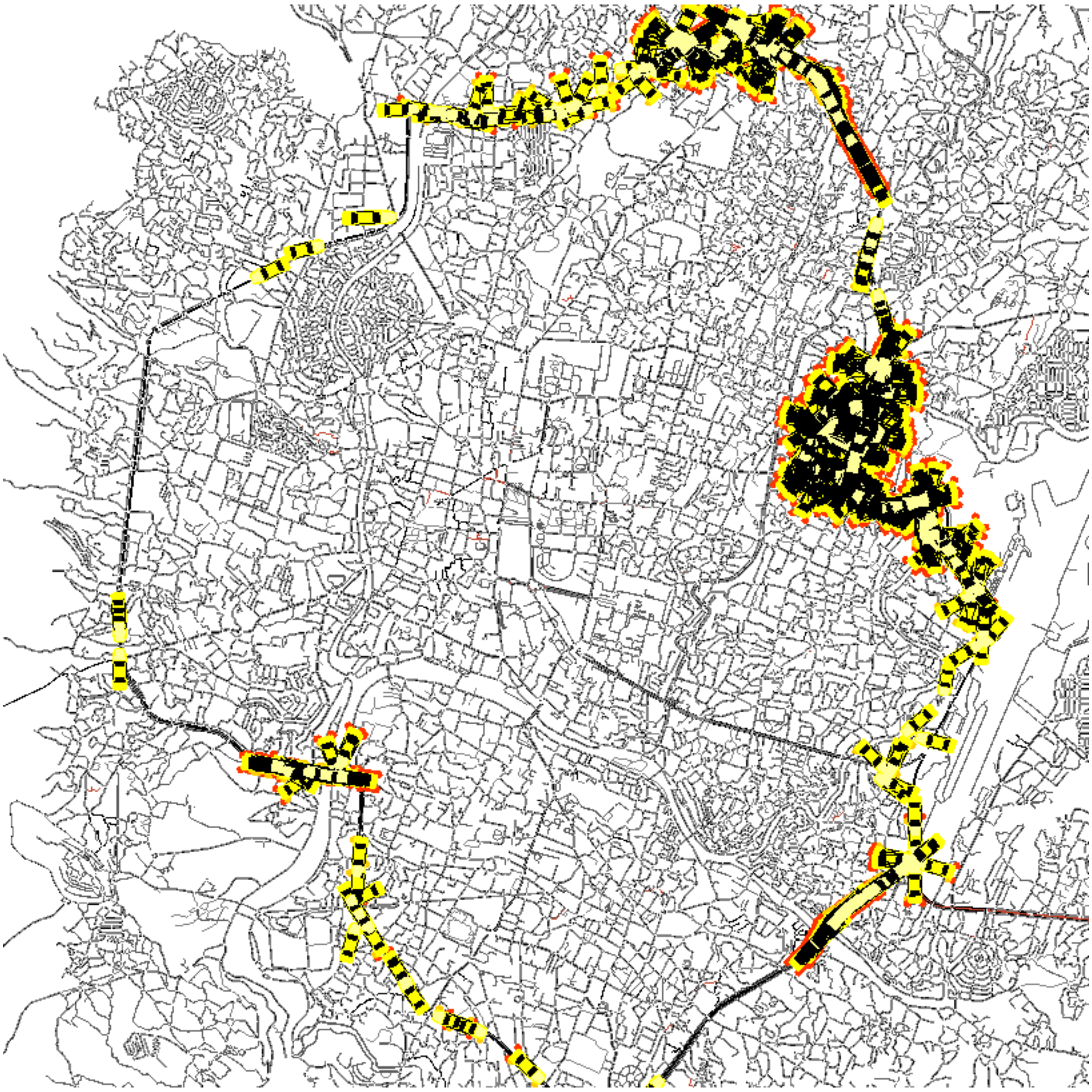


Fig 3.4. Simulated traffic congestion on ring road influenced by adjoining junctions and traffic mix leads to spatial-temporally confined high traffic emissions episodes

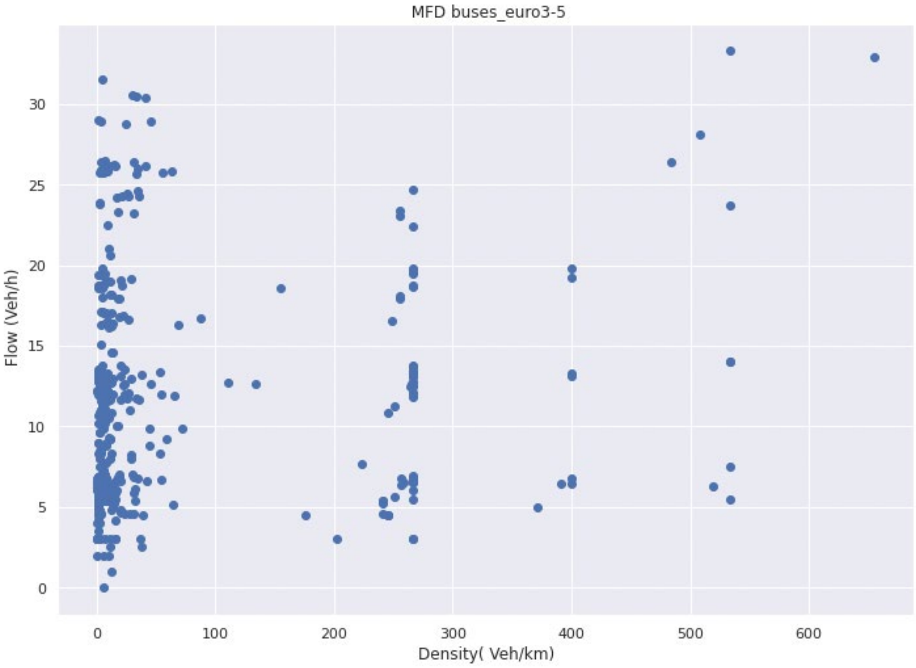


Fig 3.5. Operator with 5 buses at hour scenario leads to slow flow at (30 vehicles an hour).

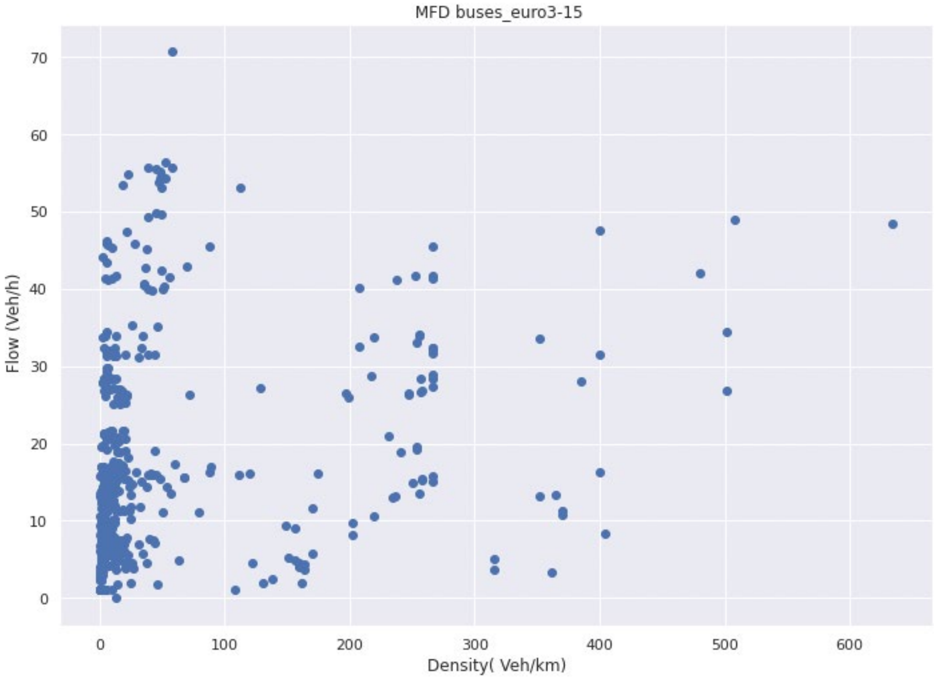


Fig 3.6. Operator with 1.5 buses at hour scenario leads to faster flow (60 vehicles an hour more vehicles per km)

Dispersion modelling Air Quality Modelling

The traffic emission inventory generated from the different bus scenarios per hour circulating the ring road 5 (base), 2.5 (half) and 1.5 (low) with 6000 private vehicles were applied to the FMI SILAM model. University of Helsinki added global meteorological conditions (60km resolution) of September 2019 to assess the dispersion of PM_x, NO_x and CO due to the traffic patterns such as congestion shown in Figure 3.4. It is important to factor in meteorological conditions, as the Kathmandu valley is surrounded by hills, forming a bowl-shaped topography, and this restricts wind movement and retains the pollution for a long period. Although, University of Helsinki only modelled September, a key influence on air pollution in Kathmandu valley is the winter thermal inversion when cold air flowing down from the mountains is trapped under a layer of warmer air and acts as a lid, creating a trap for pollutants close to the ground for an extended period. For our simulation, University of Helsinki disperse the air pollutants against based on meteorological data of September 2019, with an average temperature 28C. It was mostly cloudy with rainfall, as shown in the following Table 3.1.

2019	Precipitation	Wind Direction	Wind speed m/s	Weather
Sep 16	Thunderstorm, Rain, Mist	West	5.7	Cloudy
Sep 17	Thunderstorm, Rain, Drizzle	South	2.6	Overcast
Sep 18	**Rain, Light Rain, Drizzle**	**East**	**7.35**	**Cloudy**
Sep 19	**Light Rain, Drizzle**	**East**	**2**	**Cloudy**
Sep 20	**Mist**	**West**	**5.1**	**Clear**
Sep 21	Thunderstorm, Light Rain	South West	5.1	Clear
Sep 22	**Thunderstorm, Light Rain**	**East**	**4.6**	**Cloudy**
Sep 23	**Light Rain, Drizzle**	**East**	**5.1**	**Cloudy**
Sep 24	Thunderstorm, Drizzle	West	8.2	Cloudy
Sep 25	Thunderstorm,Rain,Drizzle	South	4.1	Cloudy
Sep 26	**Rain, Light Rain, Drizzle**	**South East**	**4.6**	**Cloudy**
Sep 27	**Rain, Light Rain, Drizzle**	**South**	**5.1**	**Cloudy**
Sep 28	Light Rain, Drizzle	East	4.6	Cloudy
Sep 29	Light Rain, Drizzle	East	5.7	Cloudy

The effects of meteorological conditions on vehicle PM_X

The dispersion of small particles ($PM_{2.5}$) is aggravated by meteorological conditions of wind direction and wind speed. Fig 3.7 shows PM_x from the vehicles in congested areas being blown towards a southward direction for the three scenarios. The time series of 5 stations on the ring road, indicates that easterly wind may have a stronger effect. The time series data shows that PM_x peaks are much stronger during the day time reflecting the direct influence of the road traffic passing the stations. The changing magnitude of PM_x in Fig 3.7 due to the influence of meteorological conditions of September 2019 on the chemical equations in the SILAM dispersion model. When one compares the meteorological conditions from the Table 3.1 to the PMx peaks in Fig 3.8, one sees three episodes related to easterly winds: Sept 18-19-20 with wind speed of 7.35 m/s; Sept 22-23 with wind speed 5.1 m/s, and Sept 26-27 with wind speed of 5.1 m/s. In these episodes, precipitation was light rain and drizzle compared to the other days of the week, characterised by thunderstorms. This supports the general understanding that precipitation has a wet scavenging effect on $PM_{2.5,}$ - the rainfall removes pollutants. However, it more complicated because the change of in the ambient $PM_{2.5}$ concentration is related to the initial concentration of $PM_{2.5}$ before precipitation, precipitation intensity, and precipitation duration.

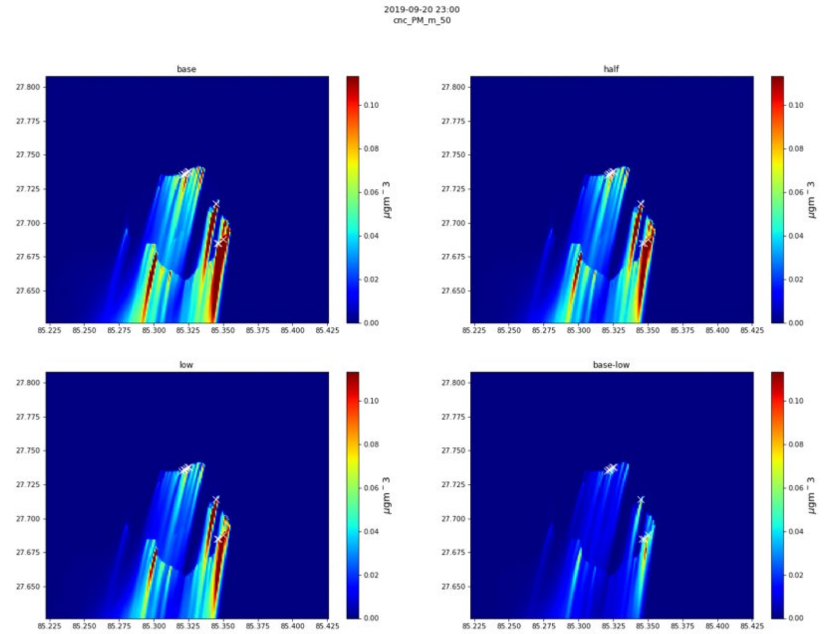


Fig 3.7. PM_x spatial dispersion due to wind direction and speed. The intensity of air pollution dispersion is conditioned by the three scenarios

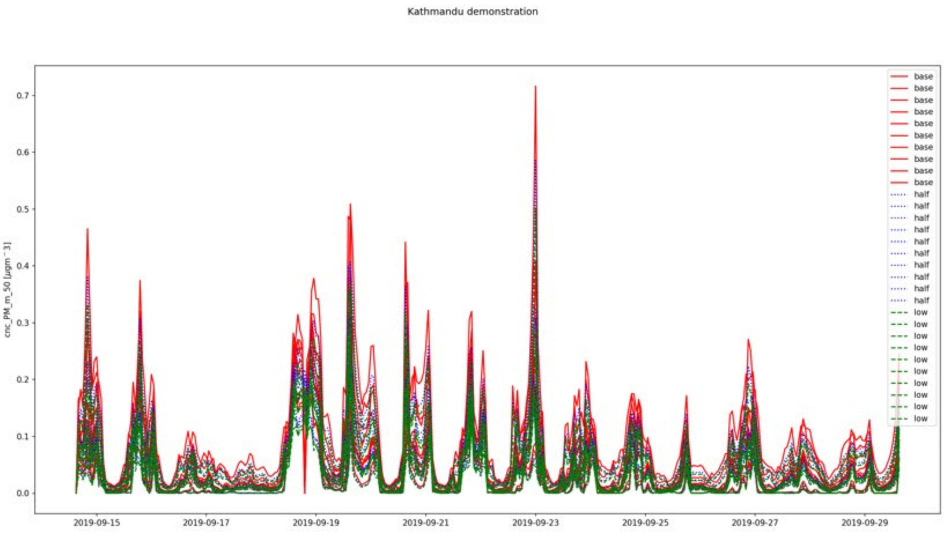


Fig. 3.8 PM_x time series from five stations on the ring road for the three scenarios. The peaks are caused by meteorological conditions outlined in Table 3.1

The effects of meteorological conditions on NO2

The dispersion of NO_2 gas is also aggravated by meteorological conditions of wind direction and wind speed. Figure 3.9 shows NO_2 is more pronounced on the ring road and in congested areas is blown towards a eastern direction for the three scenarios. Similar to the PM_x discussion above, the time series of 5 stations on the ring road, indicates a possible effect from easterly winds and the effects of light and absence of precipitation (Fig 3.10). The direct effect of rainfall is mostly the washing effect to decrease the pollution concentration. High humidity can also reduce the concentration of NO_2 as the pollutant deposit more strongly on moist surfaces. However, there indirect effect when rainfall leads to increasing the pollution concentration. Heavy rainfall can decrease vehicle speed and via increased traffic volume lead to congestion on the ring road and increased NO_2 air pollution.

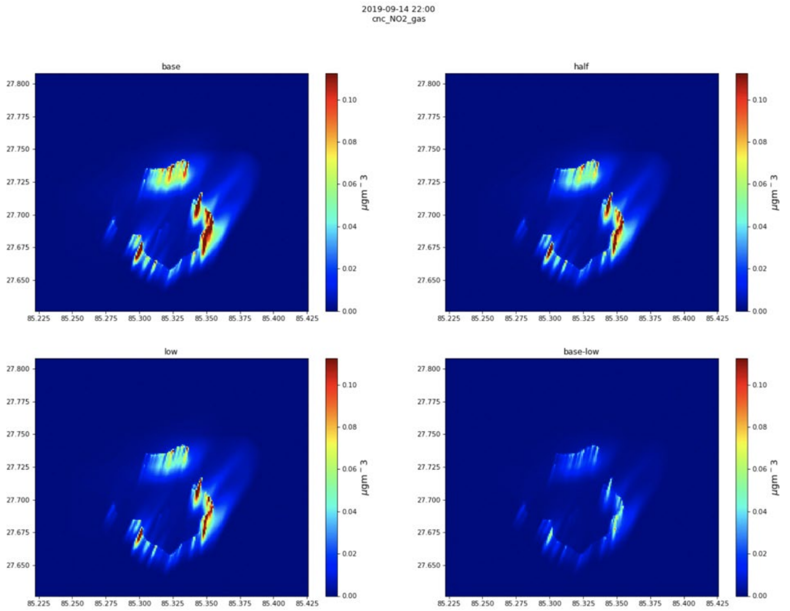


Fig 3.9. NO_2 spatial dispersion due to wind direction and speed. The intensity of air pollution dispersion is conditioned by the three scenarios

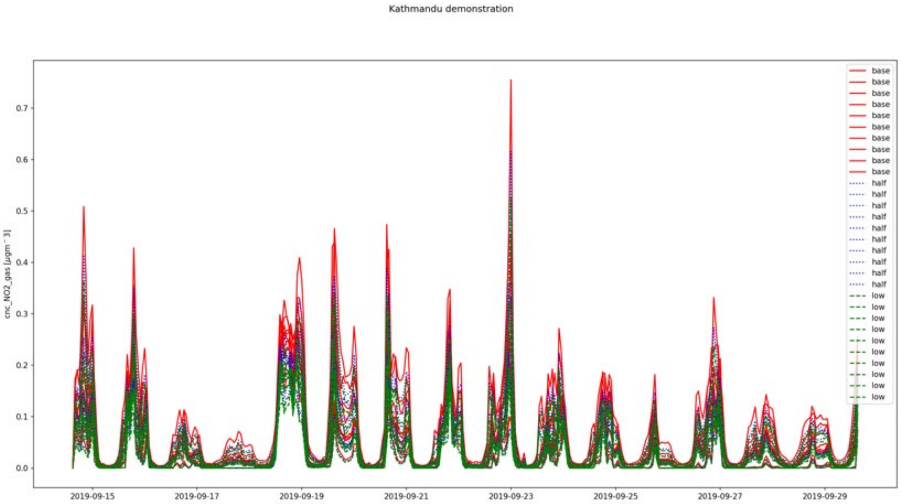


Fig 3.10. NO_2 time series from five stations on the ring road for the three scenarios. The peaks are caused by meteorological conditions outlined in Table 3.1

Practical approaches to lower emissions

There are two practical approaches to lower emissions and improve air quality. The first is to reduce the number of vehicle trips. Implementing bus time table to reduce the number of buses and increasing the distance between bus stops on the ring road will lead to reductions in air pollution. The second is to upgrade buses and heavy vehicles to low emission engines and to electric engines will significant reductions in vehicle emissions causing air pollution.

Benefits of reducing the number of bus trips

The public transport system of the valley is generally owned and operated by private companies. There is no fixed bus schedule and is mostly random and uncertain and operators compete by running more services along competitive lines, causing high traffic congestion and service operation inefficient.

Public transport vehicle are managed by approximately 100 private operators. There are approximately 42 bus stops along the route. The lack of a well-facilitated bus stop allows the bus to stop in any undesignated locations. Most of the stops are in between 2-3 minutes distance in regular traffic and maximum 10-15 minutes in a few places because of congestion. The averaged number trips per hour along the circular route is 160, which indicates the availability of more than 2 bus per min.

Our modeled scenarios shown in Fig 3.11, infers that if private operators reduce or optimize their trips, this will lead to significant reductions of emissions. If a service with 5 buses per hour that produces CO_2 15,029 tonnes, NO_x 9,411 tonnes is reduced 2.5 buses an hour, University of Helsinki calculate an 47% emission reduction (CO_2 7,965 tonnes and NO_x 4,987) and reducing 1.5 buses per hour, University of Helsinki calculate an 67% emission reduction (CO_2 4,959 tonnes, NO_x 3,105 tonnes). This magnitude of reduction can be achieved with other measures that reduce the number of bus trips such as fixed time tables and reducing the number of bus stops leading to longer travel times.

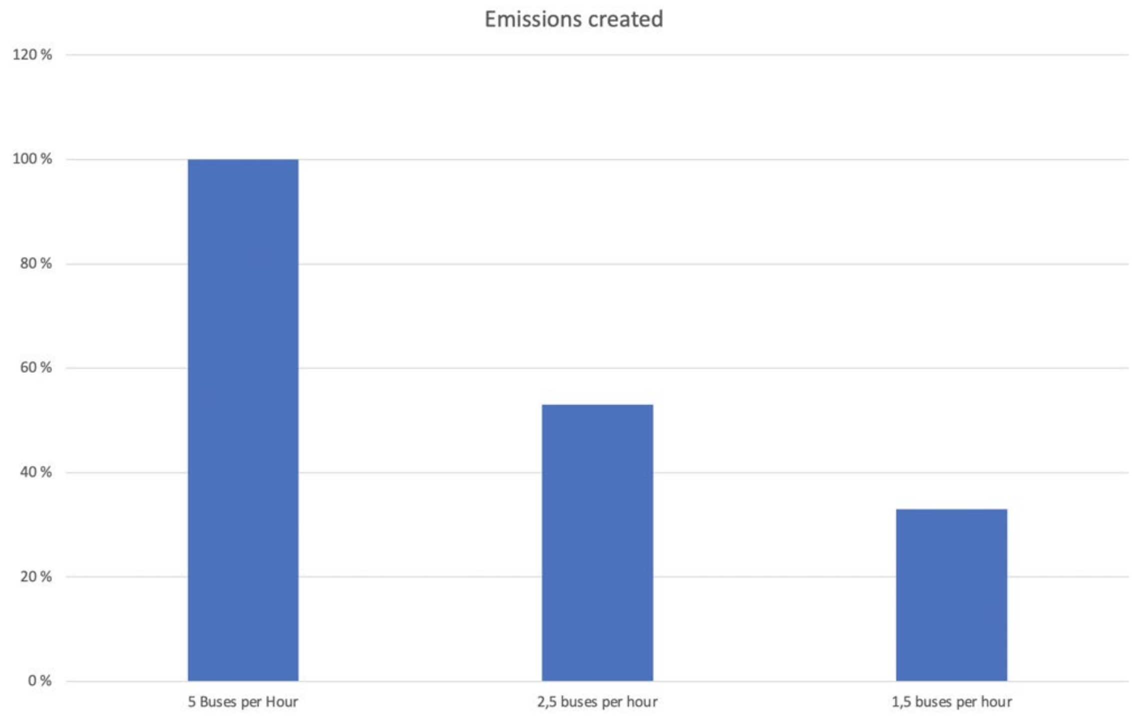


Fig 3.11. Emissions reductions created by reducing the number of bus trips

Benefits of upgrading to lower emission engines

A small proportion of high-emission or “super-emitter” vehicles (about 25% of the total diesel vehicle fleet) contributed to half of the emissions in Kathmandu Valley. A recent survey measured that out 12,039 diesel-powered vehicles surveyed ring-road side survey, 53% were and cargo carriers and 47% and passenger buses. Many super-emitters are EURO-3 emission standard engine and older. However there is transition towards newer vehicles in Nepal but due to cost is is slow: A fleet of 17 low-emission (Euro-4 emission standard engines) high-tech buses started to operate in 2018. The total cost of this urban transport project was 22.37 million U.S. dollars, with the government of Nepal contributing 7.9 million U.S. dollars (2018). In December 2018, the government had decided to purchase 300 electric buses for public transportation but due to delays the pandemic the procurement of these buses started in 2021.

There are many benefits for heavy vehicles and buses to upgrade to a more efficient Euro 6 standard diesel engine. These being: a 55% decrease of emissions compared to Euro 5 standards in 2009; a 30% better fuel economy compared to a similar petrol engine; and a 25% reduction in CO_2 emission compared to a similar petrol version. These improvements means that diesel engines are almost as environmentally friendly as their petrol equivalents.

University of Helsinki simulated the 5 buses a hour scenario around the ring road with three conditions: buses with EURO3 engines, EURO 5 engines and EURO 6 engines and the emissions were analysed. It is clear that the EURO 3 buses created the most emissions (CO_2 15,029 tonnes, NO_x 9,41 and PM_x 0.938 tonne). Figure 3.12 shows the emission savings when the same buses are upgraded to EURO5 and EURO 6 type engines. Upgrading from EURO3 to EURO 5 the savings are: CO_2 20%, PMx 60%, and NO_x 55%. Upgrading from EURO3 to EURO 6 the savings are: CO_2 27%, PM_x 57%, and NO_x 60%. Accepting that financially, this is difficult to achieve, however, if the diesel super emitters upgraded the EURO 6 then nearly 40% of air pollution on the ring road could be reduced. If the bus trips are regulated, then total air pollution on the Kathmandu rind road could be reduced by more than half leading to significant social-economic benefits.

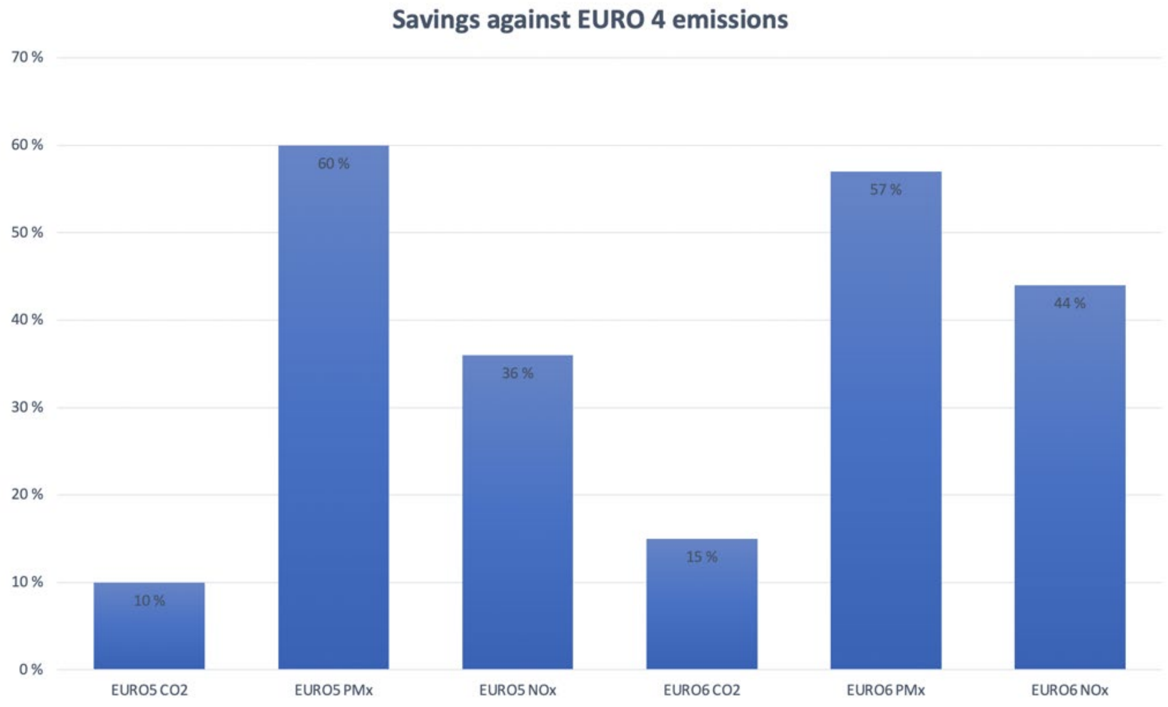


Fig 3.12. Emissions savings created by upgrading the engine types from EURO 3 to EURO 5 and EURO 6

Other pollution sources

The high pollution load in Kathmandu is attributed to rapid population and vehicular growth along with the increase in the energy demands of the valley. Source apportionment studies have indicated that emissions from vehicles, brick kilns, residential combustion, waste/biomass burning and soil dust, are the major contributors to pollution in the valley. Most studies suggest that vehicular emissions are one of the major contributing factors to the ambient air pollution throughout the year. However, in addition reducing emissions from vehicles, mitigation strategies should include improvements to waste management; higher efficiency of biomass use to reduce PM emissions from cooking, heating, or brick kilns.

Recommendations

Introduce a comprehensive city-wide approach to modelling air quality to the city of Kathmandu, Nepal. To produce traffic emission inventories, University of Helsinki demonstrated that road traffic on the map of city of Kathmandu and the ring road can by sim- ulated with minimum effort. University of Helsinki note that Kathmandu road network topology and the relationship between traffic flow at junctions and traffic density has a significant influence on spatial distribution of traffic emissions.

Our first recommendation is to simulate the traffic behaviour to give insight into the development of traffic emissions.

University of Helsinki set up a high resolution atmospheric dispersion model using the simulated traffic emissions and real meteorological conditions from September 2019 to create a credible air quality model for Kathmandu. University of Helsinki modelled the clean air routing paths for non motorist, allowing walkers and cyclists to avoid streets with high levels of air pollution. University of Helsinki modelled the meteorological conditions and showed the effects of precipitation and wind speed on 10 congestion points on the ring road for PMx, and NO_x

Our second recommendation is to simulate the atmospheric dispersion of simu- lated and measured traffic sourced emissions against real meteorological conditions and if data is available scale the model predictions against local monitoring stations to give insight into the spatial distribution of air pollution over Kathmandu and the ring road to show how the concentrations change in time.

University of Helsinki created a **decision support system (DSS)** based on traffic emission simulations and atmospheric dispersion modelling of Kathmandu. Two scenarios were modelled: reducing the number of bus trips per hour on the ring road and upgrading bus engine types to from EURO 3 to EURO 6 level. Reduction of bus trips can be introduced through simple measures such a strict time table and increasing the distance between bus stops. Upgrading the engine type of buses to diesel or electric will lead to significant reductions of air pollution in Kathmandu.

Our third recommendation is for government administration and local businesses to use an air quality decision support system to underline the need for continually improve air quality standards and environmental protection. To introduce incentives to reduce the number of super emitter or bus trips reduces congestion and upgrading to cleaner engines are sustainable measures for decreasing air pollution.

University of Helsinki managed to formulate an understanding of air quality in Kathmandu through literature review, applying atmospheric science principles, and desk top modelling in Finland. University of Helsinki calibrated our air quality suppositions against local reference instruments and this improved our prediction in order to match air pollution experienced by people living in Kathmandu. University of Helsinki did not validate any traffic simulations against the actual traffic behavioural patterns, such as engine idling, as our only intention is to generate approximate traffic emission inventories. University of Helsinki did not model the true diversity of vehicles in Kathmandu including super emitters such as old buses and poorly maintained lorries. To improve the model predictions one needs to consider the other pollution from industrial sources and uncontrolled burning of biomass, and re-suspension of road dust and bare earth. Meteorological conditions and seasonality play a key role in the dilution and dispersion of air pollution concentration, and the time air pollutants remain in the atmosphere before deposition is also a important factor.

Our fourth recommendation is is to calibrate the models and DSS against local evidence and accurately measured local air quality and meteorological data. To take a deductive approach and apply simulations and models to make general statements on the causes and distribution of poor air quality in Kathmandu. Then examine the possibilities by validating the models against real local data to make justifiable inferences and reach a specific, logical conclusions, and implement the solutions.

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