# ODD Protocol: Estimating Personal Exposure to Non-Exhaust Road Emissions in Central Seoul using an Agent-based Simulation)

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## ABSTRACT

This protocol describes the essential settings of the agent-based model to examine commuter's exposure to non-exhaust $PM_{10}$ emissions, and to make a preliminary estimate of their health effects. The model is based on the new ODD protocol[1] which differs to the initial publication[2] whereby has deprecated the "Detail" section, and suggests the attachment of codes to the document to avoid any ambiguity. The protocol begins with the 1) Model Purpose, followed by the 2) Entities, State Variables, and Scales, 3) Process Overview and Scheduling, 4) Design Concepts, 5) Initialisation, 6) Input Data, and finally 7) Sub-Models. NetLogo 6.0.4 was used for simulation.

## 1 Model Purpose

The purpose of this model is to understand commuter's exposure to non-exhaust $PM_{10}$ emissions, and to make a preliminary estimate of their health effects. Specifically, this study addresses the following questions: (1) how does health risk vary between resident drivers and subway commuters?, (2) how might vehicle restriction plans for cars mitigate the level of exposure and air quality in the CBD?, and (3) how might awareness of pollution levels (e.g. via phone applications) reduce the risk of exposure?

The model illustrates the following patterns: (1) the fraction of population at risk by mode of transport and (2) the total numbers of traffic and pollution levels by road in a context that is representative of realistic conditions in the Seoul CBD.

Pattern 1: Population at risk by the mode of transport

- This pattern reflects how an individual's health might deteriorate from $PM_{10}$ exposure depending on the mode of transport they take, and how much time is spent under extreme $PM_{10}$ conditions. Health decline occurs when $PM_{10}$ exceeds the $100\mu g/m^3$ level: a nominal health index is used, starting at 300, and individuals are labelled as "at risk" if the value drops below 100. The population at risk is a fraction of individuals with a health value less than 100 relative to the total population.

Pattern 2: Traffic load and pollution concentration

- This pattern emphasises the spatial variation of the pollution attempts to understand how one road is polluted relative to other roads, and how much traffic contributed to that. In other words, the commuting patterns and traffic flow generate some fraction of the emissions that impact people's health. This potentially allows a feedback between pollution and behaviour to be simulated. Although only a fraction of vehicles is represented, we can use sensitivity studies to test how important this might be to the realism of the output.

## 2 Initialisation

### 2.1 Vehicles

A) **Resident vehicles**: 399 resident vehicles were sampled and imported in the model. The vehicles accounted for 1% of the total vehicles registered in each sub-district that mobilise within the district. During weekdays, trips are made along the shortest path and will not change throughout the simulation, while the weekend journeys are random. During each trip, the vehicles will keep some distance from other vehicles. Vehicles contribute pollution to the surrounding atmosphere as they move along the streets. Details about trips, emissions, and exposure are explained in the following sections.

B) **Non-Resident vehicles**: Non-resident vehicles do not have any specific navigation aims, but rather, play a role as pollution-generators inside the study domain. The vehicles will follow traffic signals and keep their distance from the vehicles in front, but however, will be removed completely when they reach the end of the road (at the domain boundary). The randomness of travel directions is to simulate general movement during the vehicle's time in the CBD, in the absence of more detailed data. These vehicles are not present during the model settings but will appear when the model is executed.

### 2.2 People

C) **Resident drivers** (tied with resident cars): The drivers are tied with cars but do not move nor appear on the interface. This is to improve the model running speed and to prevent any computational errors between linking and unlinking cars from people. The drivers lose health when they are instantaneously exposed to the nominal $PM_{10}$ threshold of 100µg/$m^3$.

D) **Subway commuters**: To execute the model efficiently, the model populated 1932 persons (1% of the subway commuters) and gave each agent a random building location within 10 patches from the subway entrance. Once the location was assigned, the agents are asked to walk to their offices based on the local search algorithm (see details in Section 6).

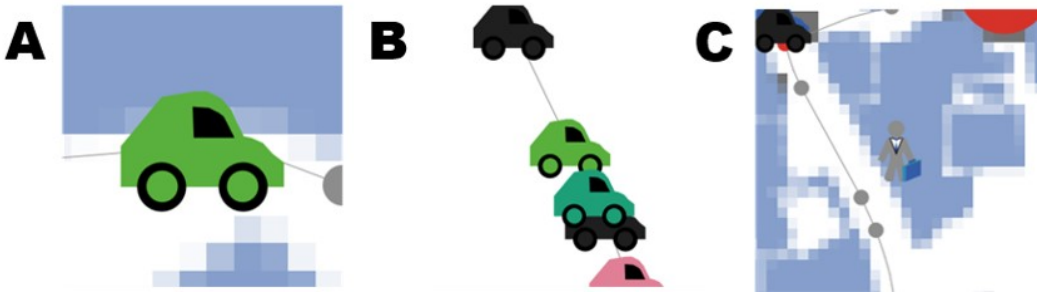


**Figure 1.** Agent types used in the simulation. Type A is a resident vehicle (tied with a driver), Type B is a non-resident vehicle, and Type C is a pedestrian commuting by metro

## 3 Entities, state variables, and scales

As mentioned in the previous section, this model consists of three types of mobile agents (resident cars with drivers, non-resident cars, and subway commuters) and two types of fixed agents (traffic signals and entry points where the vehicles are fed into the study area). Since all mobile agents were introduced in the previous section, this section adds state variables as well as the introduction of fixed agents.

The state variables for the mobile agents, vehicles and people, are documented in Table 1 and Table 2. Resident vehicles have their origin and destination both in patches and nodes, where `home` and `destination` patches are

**Table 1.** Vehicles in the model have state variables related to their trip

| Code | Description | Example |
|---|---|---|
| `fueltype` | Type of fuel | "Gasoline" |
| `origin` | One of nodes set as origin | (node 1) |
| `destination` | Patch set as destination | (patch 40 40) |
| `goal` | The closest node from destined patch | (node 2) |
| `path-work` | List of nodes between home and work | [(node 1) (node 2)] |
| `path-home` | List of nodes between work and home | [(node 2) (node 1)] |
| `nodes-remaining` | Number of nodes from the list | 24 |
| `myroad` | List of roads between home and work | [(link 1 2) (link 2 3)] |
| `current-link` | Current road | (link 1 2) |
| `district_name` | Name of district | "Myungdong" |
| `district_code` | Code of district | 1102055 |
| `link-counter` | Cumulative counter to arrival | 0 |
| `direction` | Direction to work (1); to home(-1) | 1 |
| `time-at-work` | Minutes at work | 524 |
| `random-car` | Boolean of random / resident cars | True/false |
| `parked` | If the vehicle is parked | True/false |

considered as indoor spaces that require $PM_{10}$ to be adjusted to the indoor level[3]. The indoor/outdoor ratio is further explained in Section 5.6. `path-work` and `path-home` provide links between home and the destination node, and the `positive direction` guides vehicles to follow the links of `path-work`, whereas the `negative direction` guides vehicles to follow that of `path-home`. `Link-counter` answers the question, "How many links before the vehicle stops?" Incrementing by 1, the `link-counter` will stop when it meets the `nodes-remaining` value, and then `parked` changes from false to true. After spending time-at-work for 480+$\alpha$ minutes ($\alpha < 60$), the cars will start the journey back home.

For subway commuters, as they come out of the subway entrance, known as the origin, they walk to their goal patch using the shortest distance, when the awareness scenarios are not activated. If awareness is activated, the individual moves to one of the three patches on the direction that has the lowest $PM_{10}$. `Heuristics` is the distance between the origin and goal, which will decrease as the individual moves towards the `goal` patch. As soon as the individual reaches the goal, the `arrival?` status will change to `TRUE`. Note that for some agents whose `Heuristics` is less than 1 and less than the walking speed will be stuck at that location. To avoid the error, the individuals whose `Heuristics` is less than 1 will automatically move to the office location and will convert their `arrival?` to `TRUE` and start working. As with resident vehicles, `time-at-work` shows the remainder of the working time. For example, if an individual arrived with 500 minutes the minutes will decrease and the departure will be made once the minutes reach zero. For visual purposes, this model temporarily removes the workers whose arrive-tick is over 80 so that the display is less cluttered, but makes them re-appear after work.

Traffic signals are arbitrarily created at junctions that consist of three roads or more (see Table 3). More traffic lights are installed between road segments in the real world, but the intention here is to control the traffic and to articulate the resuspension of dust – the emitted $PM_{10}$ will remain a little longer due to the traffic queues in front of the traffic signal. `Intersection` is a Boolean variable that determines whether they have three roads to become qualified. The duration of red and green signals are determined by a timer variable termed Auto?. If `Auto?` is over five (ticks) and the traffic signal is coloured green, the `Green-light?` will become true and vice versa.
Subway entrances are set as an origin for subway commuters (see Table 4). There are 26 subway stations in the

**Table 2.** People in the model have state variables related to their trip

| Code | Description | Example |
|---|---|---|
| `origin` | Subway node set as origin | (exit 20) |
| `origin_patch` | Patch of origin | (patch 20 20) |
| `goal` | Patch set as destination | (patch 40 40) |
| `current` | Current patch | (patch 30 30) |
| `Heuristics` | Distance between current and goal | 0.11 |
| `arrived?` | Whether they arrived to their workplace or not | T / F |
| `time-at-work` | Number of ticks spent after arrived? | 480 |
| `direction` | Direction to work (1), stay (0), and home (-1) | 1/0/-1 |
| `arrive-tick` | Ticks spent between exit and arrived? | 39 |
| `Health` | Nominal health level (starts from 300) | 275 |
| `Hour` | Hour when the agent arrives at the subway station | 7 |
| `Minute` | Minute when the agent arrives at the subway station | 48 |

**Table 3.** Variables of a traffic signal

| Code | Description | Example |
|---|---|---|
| `Dong_code` | Code of admin (provided by Census) | 1102055 |
| `Intersection` | Boolean of road intersections | T/F |
| `Auto?` | A timer to change signals | 15 |
| `Green-light?` | Boolean of green lights | T/F |

study area with line numbers 1, 2, 3, 4, and 5, and coded as `s_entrance`.

## 4 Process overview and scheduling

The model runs at ***a one-minute time step***, and variables are collectively updated until the simulation terminates (see Figure 2). The simulation starts at 7:00am on January 1st, and ends at 23:59 on March 31st 2018. The diagram shows the journey of vehicles and humans, and where the vehicles produce pollution (see Figure 2 process a and Figure 3), the agents who are exposed to over 100μg/$m^3$ of ambient $PM_{10}$ in the study area are expected to have their health decreased (see Figure 2 process b and Figure 4). Although the full journey to the CBD is not simulated in this study, subway commuters are assumed to be exposed to the ambient level $PM_{10}$ between early morning and late in the evening even if they do not appear on the interface. The cumulative updates of the risk population and the $PM_{10}$ concentration by roads are exported to a single spreadsheet at the end of the simulation.

### 4.1 Vehicles

Vehicles are divided into two groups: 1) resident vehicles or 2) vehicles with random movement (see Figure 3 for details). The driver's health loss will be explained in the later section.

**Vehicles in general:**

**Table 4.** Variables of a traffic signal

| Code | Description | Example |
|---|---|---|
| `Line` | Line number of Seoul Metro | 1 |

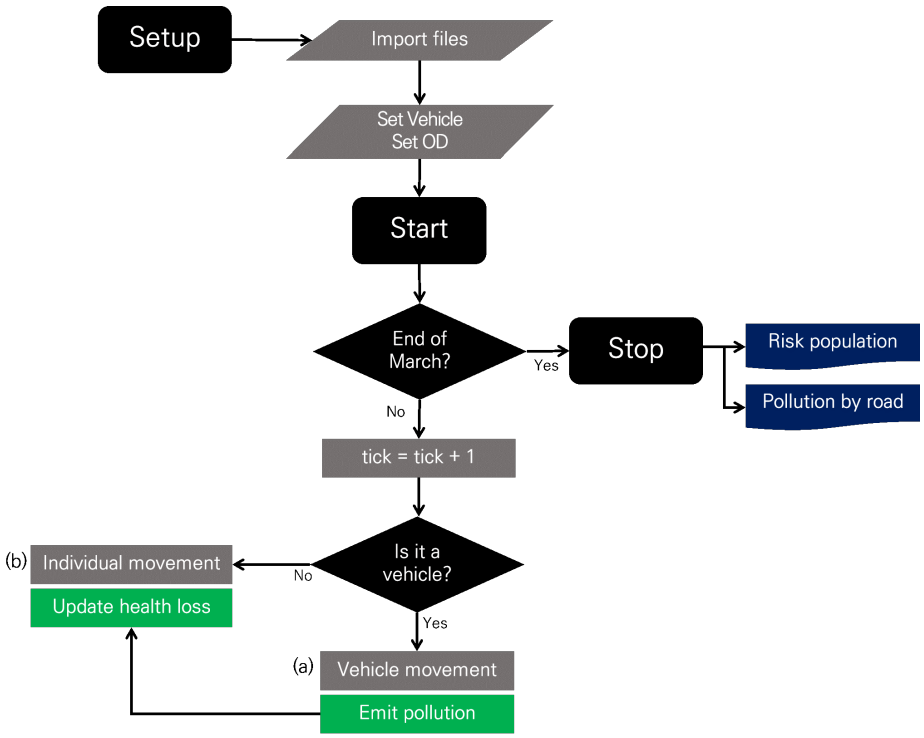


**Figure 2.** A nested flow diagram describing the behaviour of agents and their landscape. During the setup period, buildings, pollution and roads are created. Registered vehicles are also created with their allocated destinations. The model starts at 6:00am on January 1st, and ends at 23:59 on March 31st 2018. Each tick will count as one minute. If the agent is a vehicle, then it follows the behaviour of a vehicle (see Figure 4 for details); otherwise, it follows the behaviour of an individual (see Figure 3 for details). If the simulation stops, then it will print the population at risk and pollution levels by road.

- Both vehicle profiles maintain a safety distance of 1 patch ($\approx$ 30m) between themselves and the vehicle in front. During the journey, vehicles will pollute and disperse non-exhaust $PM_{10}$, regardless of fuel types. Vehicles are asked to stop in front of the "Red" traffic signal. More information regarding the pathfinding algorithm and $PM_{10}$ pollution will be introduced in the Sub-Model section.

**Resident Vehicles:**

- Vehicles will move across road networks to their destination node, stop during office hours, and head back to the `origin (node)` again using the same route during weekdays, but will move away from the study area over the weekends for non-working activities, e.g. shopping, weekend journeys, and places to worship. During weekdays, each vehicle will stop the journey if the vehicle has arrived at its destination node. After its arrival, the state variable, timer, counts down from $\geq$480mins, and as soon as the timer reaches zero, the vehicle will head back home. Extra time from 0 to 59 minutes is given to all agents assuming agents walking to car parks or spending additional time to wrap up their work. Each vehicle has a driver whose health will decline if the $PM_{10}$ inside the vehicle is over 100µg/$m^3$.

**Vehicles with random movement:**

- Vehicles are assumed to have come from the outside. These incoming vehicles make trips to any areas inside the CBD, generating vehicles from the hourly traffic data. Since the spatial extent is restricted to the CBD zone, this model made the outbound cars disappear at any endpoints of the road network. Since the model had

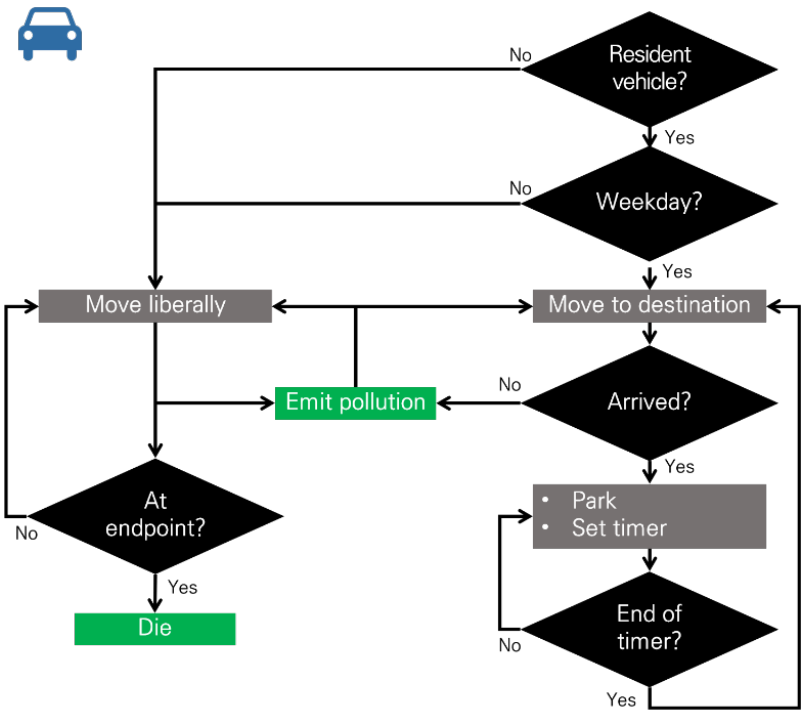


**Figure 3.** Flow chart for resident and incoming vehicles. If the vehicle's owner is a CBD resident, the vehicles will move to their assigned destination. The vehicle will emit pollution until it ends the journey. As the vehicle parks at the destination, the timer will start to countdown from 480+$\alpha$ ($\alpha$<60 mins) to 0 mins and will head back home once the timer reaches zero. If the vehicle is non-resident, it will move generally and disperse non-exhaust pollution until it leaves the domain.

a limited capacity of vehicles (~2,500), the traffic count was further decomposed by 5% on the scenario, as well as 2.5%, 10%, and 20% on the sensitivity experiment. Note that if a vehicle checkpoint station had less than 1,200 vehicles in an hour, then a 5% sample would not feed in any vehicles for that hour, but this was not a problem since not a large difference was seen in between the ratios – details are demonstrated in the Sensitivity section.

The basic code for the vehicle's movement was based on the Venice model (unpublished, but the source code was shared in 2017 on Professor Andrew Crooks Webpage)

### 4.2 Subway Commuters

When the simulation commences, the subway commuters are transported to the subway entrances at the hour and minute they have on their state variables. Once the agents arrive at their subway entrances, they walk to their destination buildings using the shortest distance regardless of the pollution levels. However, if the awareness scenario is activated, they will navigate following the lowest $PM_{10}$ to their destinations.

While walking, everyone gets an equal chance of exposure to the $PM_{10}$ threshold, but the degree of health loss will depend on how much time is spent outside when the $PM_{10}$ is over 100, and how long the distance is between the subway entrance and the agents office. Moreover, the agents whose office is adjacent to roads might lose more health because the pollution generated from the roadside can affect the indoor pollution, e.g. opening and closing windows[3].

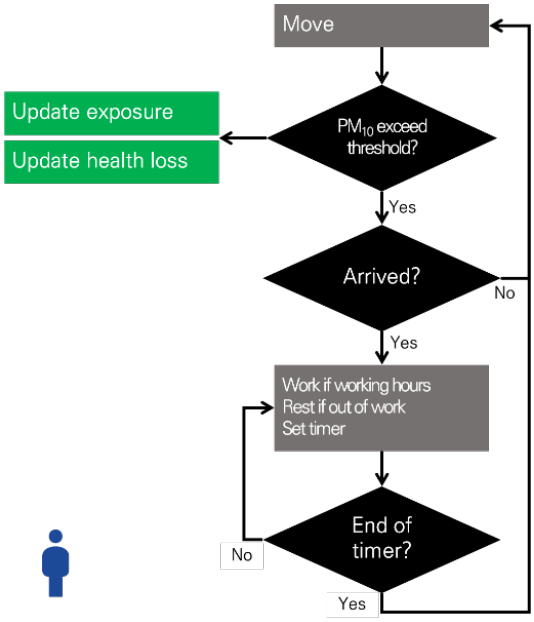


**Figure 4.** Flow chart of a subway commuter's journey. While the person is walking, it's health will degrade when the $PM_{10}$ is above 100. If arrived, the person will stay until the timer ends and head back to the station..

### 4.3 Traffic Signals

When the simulation starts, each signal will be given a random number between 0 and 11 and will count down to 0. Between 5-10 is the red light that allows the vehicles to pass, and 0-4 stops the vehicles. The timer will reset to a random number again once the counter reaches 0. This will give full randomness to the traffic signals in the study area.

### 4.4 Subway Entrances

As the simulation commences, the model chooses 4 out of 26 random stations to create commuters. It will be a returning point for commuters to travel home.

## 5 Design Concepts

### 5.1 Basic Principles

This exposure model was developed to illustrate how the population in the CBD zone can be exposed and possibly lose health in response to non-exhaust $PM_{10}$ emissions. There is extensive literature on traffic-related exposure, mainly associated with $NO_x$ emissions, or with population exposure to $NO_x$[4–6], but not with non-exhaust emissions of particles. With increasing awareness that non-exhaust emissions are important[7,8], this study builds a health impact assessment model based on non-exhaust $PM_{10}$ emissions.

The rationale is that the particles generated by non-exhaust emissions (i.e. tyre and road wear particles) have been problematic for many years[3], but despite new vehicle models that comply with the environmental regulation, the percentage of non-exhaust emissions are increasing in many countries[8,9], and population health may be under a serious threat from instantaneous pollution rise. As experts raise concerns about the potential threat that the non-exhaust particles can bring to the local atmosphere, there should be a preparation for further regulations to non-exhaust particles in the near future[8].

As a starting point, the model asked resident and non-resident vehicles to generate and disperse $PM_{10}$ to the

local atmosphere, namely on road and nearby pavements, while subway commuters and drivers are the susceptible individuals who are exposed to $PM_{10}$ emissions. On the other hand, the background $PM_{10}$ generated the value from the urban monitoring stations within the study domain. Each agent group has different behavioural patterns, which was explained in the previous section.

### 5.2 Emergence

The percentage of the population at risk (i.e. those with health under 100) emerges from a balance between exposure to a $PM_{10}$ threshold of 100μg/m$^3$ and recovery. In practice, the emergence can be an acute response to $PM_{10}$ exposure before the natural recovery begins to take effect. The emergence pattern will differ by which means of transport the individual is commuting with. This is because subway commuters are exposed to the ambient atmosphere during their walk from subway entrances to offices, while resident drivers spend most of their time indoors or in transit but have a higher chance of inhaling polluted air from road traffic. Despite the fact that extreme particulates were even higher than other transport modes have been investigated[10,11], this study omitted the journey of subway commuters because information of the start and end stations are not provided in the OD data, which is very crucial for microscopic modelling.

### 5.3 Adaptation

This study has two aspects of adaptation: pathfinding and health recovery. With regard to pathfinding, the subway commuters either walk along the shortest path when the awareness scenario is deactivated or find the best way to avoid high-polluted locations of $PM_{10}$ exceeding over 100μg/m$^3$ when the awareness scenario is activated. If the awareness scenario is activated but the agent struggles to find a path below 100μg/m$^3$, the agent will then find the lowest $PM_{10}$ of the possible routes and move to that location. Resident drivers have their health deteriorate when the patch on the road is at least 144μg/m$^3$ because the indoor-outdoor ratio between inside-vehicle and ambient air is 0.7.

If the awareness scenario is activated, the driver will take a free trip during weekends – at the beginning of Saturday or Sunday – and only when the driver's health is over 100. Conversely, if the awareness scenario is not activated, the drivers will take a trip regardless of their health. Both groups have their health recovered by the same amount at a nominal value of 10 out of 300 per timestep.

### 5.4 Sensing

Subway commuters are exposed to the $PM_{10}$ at which they are located. If the $PM_{10}$ is over 100, the commuters will lose health according to the health loss equation. Subway commuters also use the shortest distance to their workplace when the awareness scenario is not activating or find the lowest value of $PM_{10}$ amongst the front three patches in the direction they are moving. Additionally, everyone has its own time of arrival at the subway station. For instance, if the hour and minute variable of AGENT X is 8 and 12, AGENT X will appear at the station at 8:12 am. Both subway commuters and drivers have fixed working hours with a few minutes of extra time (up to one hour) to finish the daily work. The extra minutes differ every day.

The vehicles can sense one radius distance between the vehicles in front and behind and the traffic signals. As with subway commuters, drivers also have their destination time to work. After departure, the vehicles travel on the shortest route to their workplace.

### 5.5 Interaction

Interactions occur between the $PM_{10}$ levels and the agent's health. That is, subway commuters who are exposed to over 100μg/m$^3$ of ambient $PM_{10}$ on the current patch will lose health, while the drivers will lose health according to the non-exhaust emissions from vehicles. Vehicles interact with traffic signals. The vehicles stop in front of the red lights and start when the light changes to green.

## 5.6 Stochasticity

### Vehicles

- Vehicles have different origin and destination locations at every setup.
- Resident vehicles park for 480 mins (ticks) with a random number of extra numbers (up to 60).
- A vehicle has a minimum speed of 0.5 patches per tick and a maximum speed of 3.5. In cases of queueing, the deceleration ranges between 0-0.7 and the acceleration ranges between 0-0.5.
- Non-resident vehicles are fed into the study area according to the traffic monitoring statistics; however, the direction and time spent are random. Since the model has a limited capacity of vehicle numbers, a randomly selected 0.1% of the vehicles will disappear every minute between 10pm and 4am and 0.25% during the rest of the hours. This is to assume that the vehicles have driven out of the CBD[1]. For example, if there were 2000 vehicles in the study area at 10am, five vehicles[2] will disappear, and four vehicles in the next minute.
- Resident vehicles will select a random road to travel outside of the CBD.

### Subway Commuters

- In the setup process, subway commuters choose a random subway station, then assign one of the buildings within 10 radii as their workplace.

### Health loss and recovery

- When a human agent is exposed to $PM_{10}$ over 100μg/$m^3$, the health loss equation subtracts the amount of health based on the factor $\alpha$, where $\alpha$ ranges between 0 and 0.2. The parameters are tested for sensitivity, but only one parameter is used for scenario forecasting. See Section "Health Loss and Recovery" for details (p.232).
- Infiltration ratio (indoor/outdoor ratio) varies by the microenvironment and the time spent. This study estimates the infiltration from the ambient $PM_{10}$ of the current patch to indoor spaces such as houses, workplaces, and transits[3]. Ratios for each microenvironment compared to the outdoors are described as follows:
  - Houses: 0.2-0.7[3,12]. The home patch discounts the ambient $PM_{10}$ by an index between 0.2 and 0.7.
  - Workplaces: 0.2[3]. The work patch discounts the ambient $PM_{10}$ by 0.2.
  - Vehicle: 0.7[3]. The patch where the vehicle is stopped decreases by 0.7 of the ambient $PM_{10}$.
- Health recovery is stochastic at the assumption that one can recover better than another. Any agent whose health is below 100 and remains at a stable place (home/office) will recover by $10 + \varepsilon$ per minute ($\varepsilon$ being between 10 and 20), until its health returns to the 'non-risk' state.

## 5.7 Observation

As the first research question asks whether the risk rate varies by groups, the graphical output of the model shows the risk rate of subway commuters and resident drivers by time. Date, hour, and time are displayed on the interface to inform the current time. The average $PM_{10}$ and a few road points are collectively monitored until the simulation ends. Subway commuters will not appear on weekends but will still be exposed to $PM_{10}$. Resident drivers, on the other hand, will travel in a random direction during weekends, but once they reach the end of the road they will stop until 10pm and return to their origin. The returning procedure moves cars directly to their origin, which is intended to simplify the process.

[1] Having tried multiple ways to induce the non-resident vehicles outside, the most effective method was to eliminate a random set of vehicles

[2] 2000×.0025 = 5

Subway commuters and resident vehicles do not travel to work on weekends and national holidays. So, the interface will look less busy on Saturdays, Sundays, Lunar New Year (February 15-17th), and Independence Movement Day (March 1st).

### 5.8 Input Data

**Area**: The CBD area (16.7km$^2$) comprises two districts of Seoul, namely Jongno and Jung. Jongno has 8 sub-districts and Jung has 7 sub-districts. This model used 30m resolution, making 155 horizontal and 192 vertical patches.
**Roads**: Road layer is the most important component to simulate vehicle trips along with the road network and emit pollution. Roads in the real-world have different hierarchies (e.g. two lanes, four lanes, eight lanes), but this study started with a single type of road.
**Buildings**: Buildings are used as the agent's office places which are brought in from OpenStreetMap. When the model is loaded, commuters are allocated their own building ID through a random allotment.
**Hourly Traffic**: Hourly traffic was provided from the Traffic Monitoring Department affiliated with Seoul Metropolitan Government. The traffic counts from the simulation by the monthly and weekly period. It is seen that the traffic volume declines on weekends, and on the Lunar New Year holiday (February 15-17th).

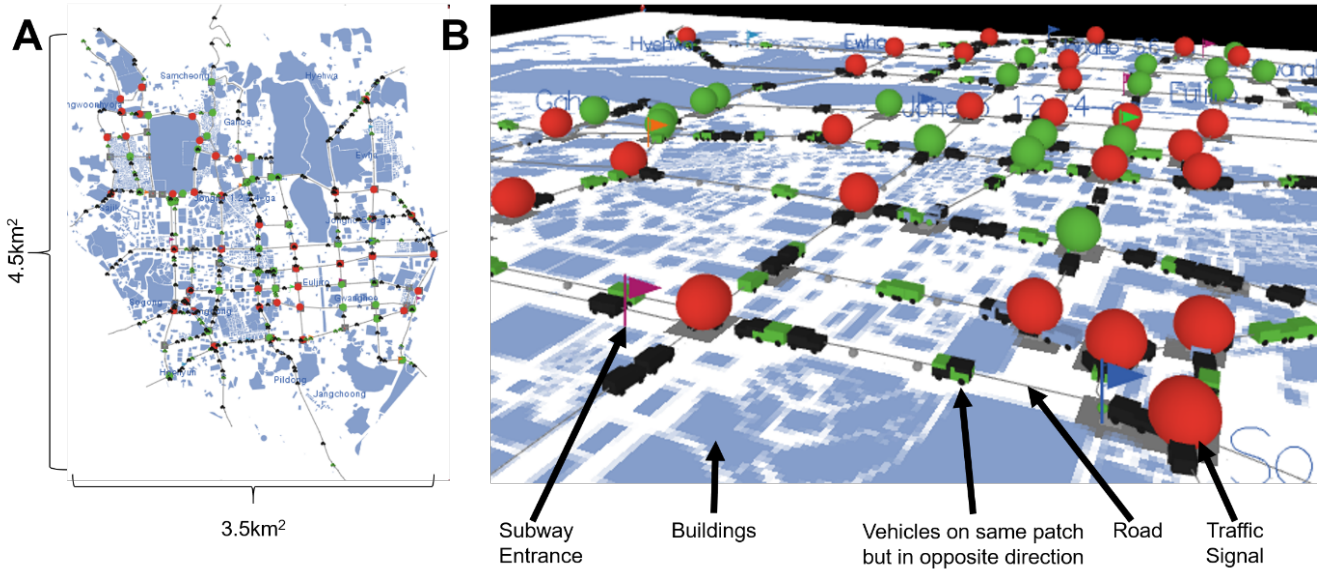


**Figure 5.** Study area in 2D (A) and 3D (B)

## 6 Sub-models

### 6.1 The Pathfinding Algorithm: A* and the Local Search Algorithm

In line with the previous chapter, this study also assigns the agent's origins and destinations according to the Origin-Destination Matrix; however, the way of application is slightly different. As a quick repetition, the previous chapter used the matrix to choose a fraction of the population from their origins and allocate it to their destinations. The fraction of the population that was allocated outside the study area was not considered for further measurement. This chapter considers the same mechanism by gathering the population of the origin and assigning destinations based on the fraction assigned in the matrix. While the previous chapter only considered agents moving between their origins and destinations, this chapter specifies the resident vehicles to follow the shortest route between their origins and destinations on the road link.

Once an agent's origin and destination are assigned, the mechanism to connect the two points requires a

pathfinding algorithm. This study gives a separate algorithm to vehicles and people. For vehicles, the model used A*[313]. A* calculates the lowest cost distance from its origin and destination and traces the path where the cost is smaller. This can be formulated as:

$$f(s) = g(s) + h(s), \tag{1}$$

where `s` is the state, `g(s)` is the cost from the origin to the current `s`, and `h(s)` is the heuristic estimation between the current state and destination, which adds up to the total cost at `f(s)`. In this context, an individual's heuristic measurement is referred to as the shortest Euclidean distance to its destination. The A* algorithm is based upon Dijkstra's algorithm but uses the heuristic framework to shorten the calculation time and optimise the shortest path.

The interface below is an example of an A* algorithm (see Figure 6A, Figure 6B). Figure 6A indicates a gridded guideway between the vehicle's origin (red) and destination (green). set-path finds all the steps from the origin patch to all possible steps inside the virtual world. The code will colour the road green and add a step label on the path. Among the steps, the shortest-path section traces the shortest grids as per the A* method, which then allows the vehicle along the path with the move section. Figure 6B is an A* algorithm based on the road network, which is embedded in the NetLogo network extension, `nw`[14]. This algorithm applies to resident drivers.

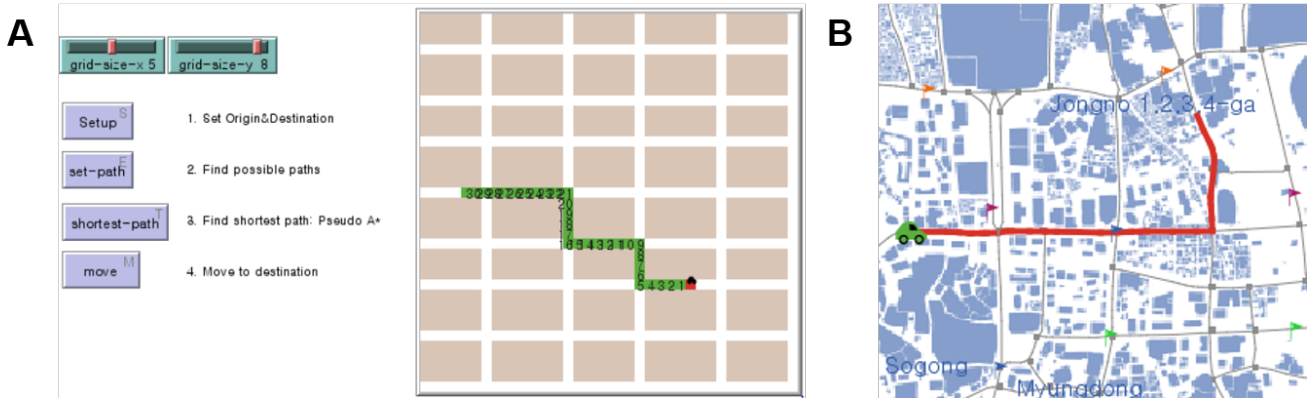


**Figure 6.** (A) is a sample of an agent finding the shortest path from the origin (red patch) to its destination (light green patch), and(B) is the application of the shortest distance on link data

For subway commuters, this chapter employs a Local Search Algorithm (LSA) for pathfinding (see Figure 7). LSA is an algorithm where the agent knows the goal state and the distance from the optimised path (termed error of distance) and asks the algorithm to rewrite the path to minimise further errors, which makes it memory efficient. A* was replaced with LSA because the algorithm that was asked to find the lowest pollution patch between the current step and the final goal kept changing every step, which led to repetitive recalculation on every step, slowing the execution speed.

Amongst the searching functions of LSA, this study uses a "random-walk" or "hill-climbing search", where the agent iteratively searches the maximum value (or minimum value) within the boundary until it reaches the target. However, the function has a major drawback as the searching terminates either when it reaches the local maximum instead of the global maximum, or there is a huge plateau which does not have a higher surrounding value. Nevertheless, this study applied this method because the commuters in the CBD normally do not have any issues in

[3] A* is one of the most popular path-finding algorithms together with Dijkstra's from their vertices and segments, which in real life may represent road networks.

getting lost when they are heading to work and back home. This study also created another scenario, *Awareness*, that asks agents to take an alternative route to avoid high $PM_{10}$. Details are documented in the scenario section.

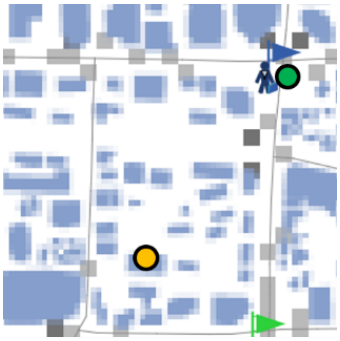

**Figure 7.** The person next to the starting point (green) walks towards the goal point (yellow) following the shortest path, which is a straight line. Here, the agent decides to move closer to the goal point, but the route will be created at every step. Pedestrians penetrating the buildings is a downside of this method

### 6.2 Non-Exhaust Emissions and Dispersion

Recent studies from the UK and Europe equally documented the main sources of non-exhaust emissions such as tyre wear, brake wear, and road surface wear[8,15]. A few papers included resuspension as a fourth contributor, but this study articulates resuspension in the dispersion section below. Figure 8 illustrates the non-exhaust emissions, dispersion, and dilution.

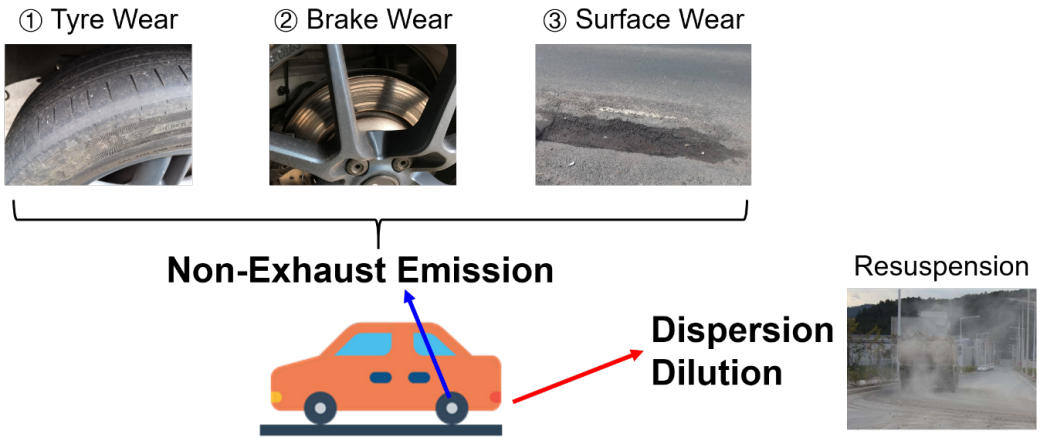


**Figure 8.** Graphical explanation of non-exhaust emissions, dispersion, and dilution

According to[15], the total of non-exhaust emissions is estimated with the following equation.

$$E_{total} = E_{Tyre} + E_{Brake} + E_{Road} \tag{2}$$

- $E_{Total}$: the total non-exhaust PM emissions
- $E_{Tyre}$: PM emissions from tyre wear
- $E_{Brake}$: PM emissions from brake wear

**Table 5.** TSP (Total Suspended Particles) emission factors for source category road vehicle tyre wear[15]

| Vehicle class (j) | TSP emission factor (g/km) | Uncertainty range |
|---|---|---|
| Two-wheel vehicles | 0.0046 | 0.0042 - 0.0053 |
| Passenger cars | 0.0107 | 0.0067 - 0.0162 |
| Light-duty trucks | 0.0169 | 0.0088 - 0.0217 |
| Heavy-duty vehicles | Separate Equation | 0.0227 - 0.0898 |

**Table 6.** Size distribution of tyre wear particles[15]

| Particle size class (i) | Mass Fraction of TSP |
|---|---|
| TSP | 1 |
| $PM_{10}$ | 0.6 |
| $PM_{2.5}$ | 0.42 |
| $PM_1$ | 0.06 |
| $PM_{0.1}$ | 0.048 |

- $E_{Road}$: PM emissions due to road abrasion

Each component will be investigated in the following sections.

#### 6.2.1 Tyre Wear

$$E_{Tyre} = \sum_{i=1}^{n} N_j \times M_j \times EF_{Tyre,j} \times F_{s,i} \times S(V) \tag{3}$$

- $E_{Tyre}$: Total emission for the defined time and spatial boundary (g/km)
- $N_j$: Number of vehicles in category j within the defined spatial boundary
- $M_j$: Mileage (km) driven by each vehicle in category j during the defined time (not used)
- $EF_{Tyre,\,j}$: TSP mass emission factor for vehicles in category j (g/km)
- $F_{s,i}$: mass fraction of Particles that can be attributed to particle size class i
- S(V): Correction factor for a mean vehicle travelling speed $V$

As this equation was designed to measure the bulk emissions from a number of vehicles (e.g. 20g/km from 10 vehicles in a 5km trip between 10:00-15:00), it is not appropriate to measure the emissions of hundreds of vehicles that have separate journeys. To find a solution, this study manipulates $N_j$ at an appropriate number based on sensitivity analysis, converts emission levels from g/km to µg/30m (equal to a size of one patch in the simulation), and spatial and temporal units at 30m and on a minute by minute basis.

For example, one passenger car (j) has an emission factor of .0107 (.0067-.0162) (g/km) (see Table 7), and to get an estimate of $PM_{10}$, the size distribution $F_{s,i}$ converts the TSP estimate to $PM_{10}$ multiplying by a fraction of 0.6 (see Table 7). This can result in 32.1µg/$m^3$ per patch with an uncertainty range of 20.1 - 48.6.

In terms of vehicle speed, EEA sets the parameter V at 1.39 below 40km/h, and declining effect of (-0.00974 * V + 1.78) between 40-90km/h. It assumes that frequent brakes and accelerations are expected below 40km/h but less as the vehicle speeds up.

**Table 7.** Speed Correction[15]

| Velocity (km/h) | Factors (V) |
|---|---|
| V <40 | 1.39 |
| 40 ≤ V ≤ 90 | -0.00974 * V + 1.78 |
| V >90 | 0.902 |

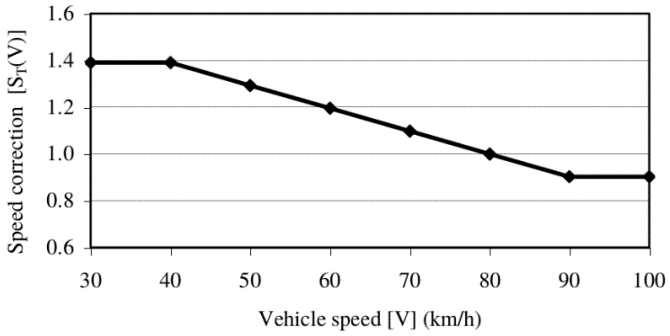


**Figure 9.** Speed: tyre wear

#### *6.2.2 Tyre Wear*

The equation for brake wear is the same as tyre wear, and has only a few differences in parameters.

$$E_{Brake} = \sum_{i=1}^{n} N_j \times M_j \times EF_{Brake,j} \times F_{s,i} \times S(V) \tag{4}$$

- $E_{Brake}$: Total emission for the defined time and spatial boundary (g/km)
- $N_j$: Number of vehicles in category j within the defined spatial boundary
- $M_j$: Mileage (km) driven by each vehicle in category j during the defined time (not used)
- $EF_{Br,j}$: TSP mass emission factor from road wear for vehicles in category j (g/km)
- $F_{s,i}$: mass fraction of Particles that can be attributed to particle size class i
- S(V): Correction factor for a mean vehicle travelling speed *V*

As mentioned in the Tyre Wear section, emission factors for passenger cars must fit a unit set in the virtual environment. Thus, the $EF_{Br,j}$ value of .0075 (g/km) converts to 21.5 (µg/patch). The size distribution of $PM_{10}$ is 0.98. The brake wear, particularly from the linings, are worn out quickly when the driver accelerates and decelerates frequently, and this tends to happen when the traffic volume is high.

#### *6.2.3 Surface Wear (i.e. Road Abrasion)*

Road surface wear is caused by the appearance of wheel marks when the vehicle passes over the road or parts of the road are destroyed by heavy vehicles. The formula is as follows.

$$E_{Surface} = \sum_{i=1}^{n} N_j \times M_j \times EF_{SW,j} \tag{5}$$

- $E_{Surface}$: Total emissions for the defined time and spatial boundary (g/km)

**Table 8.** TSP (Total Suspended Particles) emission factors for source category road vehicle brake wear[15]. Here, this study only considers passenger cars.

| Vehicle class (j) | TSP emission factor (g/km) | Uncertainty range |
|---|---|---|
| Two-wheeled vehicles | 0.0037 | 0.0022 - 0.0050 |
| Passenger cars | 0.0075 | 0.0044 - 0.0010 |
| Light-duty trucks | 0.0117 | 0.0088 - 0.0145 |
| Heavy-duty vehicles | Separate equation | 0.0235 - 0.0420 |

**Table 9.** Size distribution of brake wear particles[15]

| Particle size class (i) | Mass fraction of TSP |
|---|---|
| TSP | 1 |
| $PM_{10}$ | 0.98 |
| $PM_{2.5}$ | 0.39 |
| $PM_1$ | 0.1 |
| $PM_{0.1}$ | 0.08 |

**Table 10.** Speed Correction[15]

| Velocity (km/h) | Factors (V) |
|---|---|
| V <40 | 1.67 |
| $40 \leq V \leq 90$ | -0.0270 * V + 2.75 |
| V >90 | 0.185 |

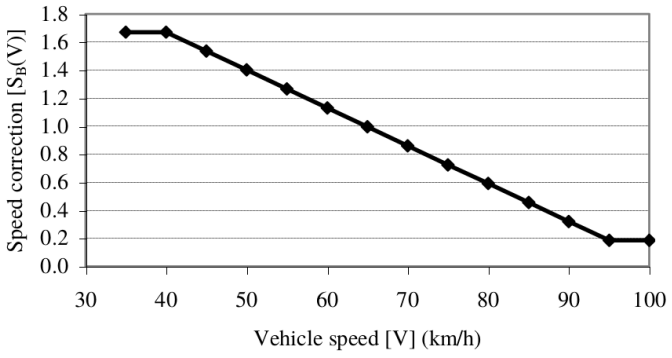


**Figure 10.** Speed: Brake wear

**Table 11.** TSP emission factors from road surface wear[15]. Here, this study only considers passenger cars.

| Vehicle class (j) | TSP emission factor (g/km) |
|---|---|
| Two-wheeled vehicles | 0.006 |
| Passenger cars | 0.015 |
| Light-duty trucks | 0.015 |
| Heavy-duty vehicles | 0.076 |

**Table 12.** Size distribution of road surface wear particles[15]

| Particle size class (i) | Mass fraction (FR,i) of TSP |
|---|---|
| TSP | 1 |
| $PM_{10}$ | 0.5 |
| $PM_{2.5}$ | 0.27 |

- $N_j$: Number of vehicles in category j within the defined spatial boundary
- $M_j$: Mileage (km) driven by each vehicle in category j during the defined time (not used)
- $EF_{SW,j}$ = TSP mass emission factor from surface wear for vehicles in category j (g/km)
- $F_{s,i}$ = Mass fraction of TSP that can be attributed to particle size class i

#### *6.2.4 Dispersion and Dilution*

There are many dispersion models applicable for exhaust emissions, but according to early research[4,16], many things related to non-exhaust dispersion remain unknown. The University of California, Riverside (UCR) team is conducting an on-going project to understand the severity of non-exhaust emissions at nearer roads and is currently testing non-exhaust parameters in their existing dispersion model[4]. In line with the UCR project, this study also attempts to disperse pollution with a spread function, in-cone in NetLogo, as a surrogate of dust resuspension.

Dilution with non-combustible dust varies by meteorological or ventilation conditions. Less road dust would be generated on rainy days due to the additional weight that is deposited by the particle substances on the ground, and during night hours when there is less traffic. Cities like Seoul have employed water spraying trucks to spray moisture on the roads on dry days, which adheres the particles on the ground as well as keeps the resuspension low as possible. Since this study does not consider humidity or rain effects, the model will use the case from[17], where it takes 110 seconds to dilute completely. In NetLogo, this is assigned as three random ticks – ranging between 0-2 minutes. This study further investigates the sensitivity of road $PM_{10}$ by controlling both dispersion ranges and the extension of dilution.

#### *6.2.5 Application Inside the Simulation*

It is worth mentioning that the units change inside the *in silico* environment. Since one patch is equivalent to 30 metres and one car represents 10 vehicles, a car moving from one patch to the next means 10 cars moving 30 metres. The vehicle speed inside the simulation is assigned in Table 13.

In published studies, the emissions are calculated by g/km based on the total distance of which the car has travelled[18,19,20] argued that the atmospheric pollution is combined with emissions, humidity, wind, temperature, and other uncertain factors, and therefore the calibration process is normally tested in places where there are fewer

[4]https://ww2.arb.ca.gov/resources/documents/brake-tire-wear-emissions

**Table 13.** Conversion of Vehicle Speed in NetLogo

| Original | Simulation |
|---|---|
| 5km/h | 0.25 |
| 10km/h | 0.5 |
| 20km/h | 1 |
| 40km/h | 2 |

**Table 14.** Indoor-outdoor ratio of ambient $PM_{10}$

| Type | Ratio |
|---|---|
| Outdoor | 1 |
| Transit | 0.7 |
| Indoors (house, office) | 0.2-0.7 |

confounding variables, e.g. tunnels. Calibration with observational values can be inaccurate, but more than 15 studies have chosen this method due to restricted conditions[20].

For example, if a car travels over a patch, it releases 10μg/$m^3$ of tyre wear, 7μg/$m^3$ of brake wear, 10μg/$m^3$ of surface wear, and 3μg/$m^3$ of resuspension. It will also have a dilution at 5μg. Thus, the total $PM_{10}$ concentration would be the background $PM_{10}$ + 25μg/$m^3$ (Tyre + Brake + Surface + Resuspension – Dilution).

### 6.3 Health Loss and Recovery

The agent's health will decline on the assumption that it encounters over 100μg/$m^3$ at which they are currently located.

$$If PM_{10} \geq 100, \qquad \frac{dH}{dT} = -\alpha(H_{\max} - H(t)) + H_{\text{recov}} \tag{6}$$

While the equation above is equivalent to that of the previous chapter, there are several measurements in which the application differs from the previous chapter. First, the infiltration ratio, often termed as the I/O ratio, is used to estimate indoor exposure of individual agents. Infiltration ratio is applied to studies when only one has information about outdoor air pollution but less about indoor air pollution. Although the numbers seem quite simple, the ratio results from the consideration of the air exchange rate, windows opening, and type of housing. A few studies that used the I/O ratio also indicate that the ratio can vary by season (winter, summer) or types of microenvironments (classroom, house, office). This study chose the ratio from two studies,[3] where these authors took into account the I/O ratio from non-exhaust emissions, and[12] who reviewed a wide variety of households to get a parameter (see Table 14). The outdoor $PM_{10}$ is assigned at 1, transit at 0.7, and indoors (including house and office spaces) at 0.2-0.7.

With the equation and infiltration ratio, the health loss for both subway commuters and resident drivers is applied under the same conditions. However, the difference would be their mode of transport and behaviours during weekends. Subway commuters spend their time exposed to ambient air pollution between the subway station and office. It is also considered that when the commuters travel out of the study area, they take more than an hour to arrive home[5]. Assuming the commuters stay at home between 11pm-6am, the commuter will be exposed to 0.2 times the ambient $PM_{10}$ of the given patch. Resident drivers are mostly exposed to 0.7 times the ambient $PM_{10}$ of the patch in transits and 0.2-0.7 times of that of $PM_{10}$ when the vehicle is parked at the house or office. The vehicles are expected to be frequently exposed to high $PM_{10}$ due to the substantial load of $PM_{10}$ generated by road traffic.

[5]Joong-ang daily article, March 7th 2019, "South Korea's office workers spend 103 minutes on average to get to work"

Health recovery activates when the agent's health is below 100 and the agent is located at an indoor space. For a subway commuter, this will be when they are at home or office, while drivers recover when the car is parked. The recovery rate is given an arbitrary number of 10 by each minute but stops working when the health of an individual goes above 100.

### 6.4 Scenario Forecasting

This section outlines how vehicle prohibition can effectively improve air quality in Seoul CBD, as well as how people's information and awareness can prevent exposure to air pollution. The scenario was designed based on the 'Green Transport Scheme' initiated in December 2019, and thus it attempts to help measure the effectiveness of implementation that is already in place.

The Green Transport Scheme aims to improve air quality in Seoul by restricting high-emission vehicles from entering the CBD area. The municipal government restricts Grade 5 vehicles, mostly diesel cars, between 06:00-21:00, and violators are fined 100USD. This study looks at how the effects of non-exhaust emissions resulted from barring vehicle entry and illustrated how people's health might improve from the scenario.

**The first scenario is to restrict extra inbound vehicles**. It measures how $PM_{10}$ will improve if vehicles are restricted by 50% or 90%. **The second scenario compares the outcome of the population at risk depending on the awareness of individuals to extreme $PM_{10}$**. When the awareness scenario is not activated, the subway commuters will walk on the shortest distance to their destination and the resident drivers will take free trips within or outside the CBD over the weekend regardless of their health. When the awareness scenario is activated, the subway commuters either walk on the path that does not exceed 100μg/$m^3$ of $PM_{10}$ or on the lowest value of three patches in front of their path when all the surrounding patches exceed 100μg/$m^3$. The drivers below the nominal health of 100 will not take a journey. Both scenarios are implemented in combination.

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