Saving Lives and Time: Tackling Transportation Induced Air Pollution in Jakarta

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Abstract – Respiratory illness due to air pollution from transportation activities is a major health-related issue in Jakarta. Besides, the city has been experiencing a degradation of the transportation system, due to the growth in travel demand, which cannot be balanced with the available space for motorized vehicle movements. Despite the fact that various governmental departments in Indonesia have proposed and implemented measures to control these issues, the effectiveness of their policies has not been examined properly, and it seems that they only focus on certain aspects of the system. The aim of this study is to provide a systemic perspective of the traffic congestion, air pollution and its health impact issues in Jakarta, through the identification of relevant interrelated feedback loops, the exploration of various policy options, and the assessment of the effectiveness of these policies under deep uncertainty. Simulation results indicate that the population subsystem is the main driver of air pollution and traffic congestion. Taking these results into account, we show that the traditional debated policies are ineffective, as they fail to address this main driver.

Keywords – Public health, air pollution, traffic congestion, transportation, uncertainty analysis.

I. BACKGROUND

Air pollution due to transportation is a large problem in Indonesia, and especially in its capital city Jakarta. According to the Jakarta Police Traffic Directorate, the concentration of toxic pollutants in the air, which has grown to alarming levels since 2008 (Maulia, 2014), is for 70% attributable to vehicle movements (Cochrane, 2015). As such, it is not a surprise that the US embassy in Jakarta has recently issued a message to alert US citizens residing in Indonesia to take appropriate measures for these increased levels of particulate air pollution (U.S. Department of State, 2015). Two major trends can be identified that contribute to the air pollution problem: growth in travel demand, and rapid motorization (i.e. private transport mode ownership). In general, it can be stated that the growth in travel demand, caused by an average annual positive population growth of 1.1%, cannot be balanced with the available space for motorized vehicle movements. Over the past decades, this has led to a degradation of the transportation system, through an immense increase of traffic congestion (Badan Pusat Statistik, 2010, 2015b). In addition to an increase of citizens' wealth, rapid motorization is a result of preferring (i.e. high attractiveness of) private transportation to fulfil travel demand, as public transportation is not flexible, reliable, and operates almost on full capacity (Asri & Hidayat, 2005; Wijaya, 2009).

Despite the fact that there are different types of air pollutants, this study focuses on airborne particular matter (PM_{10}) emissions specifically, since they have the most severe health impact on humans (World Health Organisation, 2005), and their concentration in Jakarta's air is the highest of all types (Asri & Hidayat, 2005). Diseases that originate from vehicular PM_{10} emissions include acute respiratory infections, chronic bronchitis, asthma attacks, eye / skin irritations, and in the worst case, premature mortality (Firdaus, 2013; Haryanto & Franklin, 2011).

Until now, various governmental departments in Indonesia have tried to control air pollution in the area of transportation. Some examples of proposed and implemented measures include: the establishment of threshold limit values for vehicle emissions, the use of cleaner fuel,

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emission monitoring, maintenance for vehicles, national planning program, construction of a mass transit system, creation of green spaces, and electronic road pricing (Cochrane, 2015; Haryanto & Franklin, 2011; Putjuk, 2014; Yulinawati, 2010). Despite the governmental efforts, it seems that each measure only focuses on one symptom of the problem, and moreover, their effectiveness in tackling air pollution over time has not been examined properly.

There have been several System Dynamics (SD) studies that have modelled air pollution in the scope of the transportation system, or that have examined problems regarding urban transportation systems in general.

The first study is that of Vafa-Arani, Jahani, Dashti, Heydari, & Moazen (2014), who included two subsystems in their SD model of Teheran's (capital of Iran) air pollution: the transportation subsystem, and the industrial subsystem. The model was simulated under several scenarios, to assess the effectiveness of four specific air pollution mitigation policies: (1) road construction, (2) technology improvement in fuel and automotive industries, (3) traffic control plans, and, (4) development of public transportation infrastructures. In their conclusion, Vafa-Arani et al. (2014) state that their study can be extended through consideration of green fuels, development of green parks, and strategies to reduce population density.

The second study is that of Anh (2003), who analyzed the urban traffic problem of Hanoi (capital of Vietnam) based on a system dynamic approach, and argued for six important feedback loops: (1) short-term reduction of traffic congestion through construction of roads, (2) increase of traffic congestion through road construction activities, (3) increase of traffic congestion through road attractiveness, after road construction, (4) increase of traffic congestion through urban expansion (i.e. increase of average travel distance), (5) environmental impact through transportation system degradation, and (6) increase of social benefit through the transition of transport mode to public transportation. Based on these feedback loops, Anh (2003) identified different causes and effects of traffic congestion in Hanoi, and suggested three policies to reduce it: public transport system development, road network expanding and enhancing, and travel demand management alternatives.

The third study is that of Armah, Yawson, and Pappoe (2010), who applied a SD perspective on the traffic problem in Accra (capital of Ghana) to identify the different drivers, causes, and effects, and to propose some measures that policy makers could consider to improve the situation. An important difference with regard to the previous mentioned studies is that this one includes the concept of private transportation attractiveness, and its effect on transport demand fulfilment by different modes. In total, Armah et al. (2010) identified four important feedback loops: (1) increase of traffic volume (and congestion) through private transport attractiveness and increase of trips per day, (2) increase of traffic volume (and congestion) through private transport attractiveness and increase of average trip length, (3) increase of traffic volume (and congestion) through private transport attractiveness and increase of cars per capita, and (4) reduction of travel time through road construction (driven by pressure to reduce congestion). Armah et al. (2010) conclude from their analysis that policy makers should focus on the stimulation of public transport use, and reduction of private transport attractiveness.

For our study, we aim to provide a SD perspective of the problem of traffic congestion and air pollution in Jakarta. It is argued that until now, no studies have been conducted that assess the effectiveness of different proposed measures to tackle traffic congestion, air pollution, and its health effects in the context of Jakarta, taking into account the interaction of different relevant subsystems. Taking the further research suggestions of Vafa-Arani et al. (2014) into account, this study will be of added value through the consideration of green fuels, development of green parks, and strategies to reduce population density, as measures to mitigate traffic congestion, air pollution, and its health effects. Moreover, a research gap will be covered, through consideration of the tension between green space development, housing development, and road construction, in the scope of air pollution and traffic congestion problems. To address these aspects, the model proposed in this paper incorporates the interactions between the transportation subsystem, built environment subsystem, and population-health subsystem. The main purpose of the model is to examine the cause-effect relations, delays, and feedback loops in the system that lead to policy resistance. Accordingly, its aim is also to explore the performance of different policy options that influence the behavior of the system. Besides predicting how the different policies will behave in a given set of assumptions, this study also tested the robustness of the policies under various plausible futures. It is proposed that the study presented in this paper can be extended to different developing countries, to understand why current attempts to tackle traffic congestion, air pollution, and its health effects, are ineffective or have failed.

The remainder of this paper focuses on a description of the developed model, and the different policies that aim to reduce traffic congestion, air pollution, and its health effects. The structure of the paper is as following: **section II** presents the methodology of this study; **section III** provides the model boundaries, main feedback loops, simulation model, and subsystems; **section IV** elaborates on the model key performance indicators, policies, and uncertainties; **section V** addresses the base case, and the effect of each policy on the KPIs; **section VI** discusses the effectiveness of the policies under uncertainty; and finally, **section VII** briefly the implications of this study, and depicts the main conclusions and recommendations.

II. METHODOLOGY

As mentioned in the previous section, this study provides a SD perspective of the traffic congestion, and air pollution problem of Jakarta, through the development of a model, with the purpose of exploring different policy options that are directed to solve the problem. In this context, a simulation time frame from 2010 to 2040 was applied.

SD is a methodology for understanding the nonlinear behavior of systems over time, by making use of stock and flow diagrams (SFD) to represent such systems (Sterman, 2000). As such, its primary rationale is that feedback structures are responsible for the dynamic behaviour of a system. The objective of a SD model is to understand these feedback structures and their effects, so that effective policies can be formulated under different scenarios (Khalid, 1994; Pruyt, 2013)

Following the general steps of the SD methodology, initially, a bull’s eye diagram was created to determine what variables would be excluded, what variables would be included, and in what level of detail they would be modelled (i.e. determination of model boundaries). Afterwards, a conceptual model was developed by means of a Causal Loop Diagram (CLD), to elicit the feedback structures and the different subsystems. Furthermore.

After the conceptualization phase, the real model was built in an iterative process, where each phase in the process revealed the need to adjust the model structure (most frequently between model testing and formulation). After numerous iterations, enough understanding, insight, and confidence were gained to develop and to implement different policies. Each of these policies were directed to change the system parameter values and/or the model structure.

The initial parameter values of the model were calibrated according to the dataset of Wismadi, Soemardjito, and Sutomo (2013), the Jakarta in Figure 2010 – 2015 dataset of the Indonesian Central Agency on Statistics (Badan Pusat Statistik, 2010, 2011, 2013, 2014, 2015a), the dataset of Firdaus (2013), and the dataset of Syafrizal, Bretagne, Hamani, Sugiarto, and Moersidik (2014). These datasets provided all reference data needed for population size, travel demand, share of each transport mode in fulfilling transport demand, number of vehicles per transport mode, total area of roads, PM_{10} emissions per transport mode, health effects of PM_{10} emissions, etc.

The model that was developed in this study includes a range of uncertain parameters, functions, and mechanisms, and has a long time horizon. The nature of uncertainty implies that there are many different plausible future scenarios, that each have a distinct system behavior. To assess how different policy options would perform in these different futures, a wide variety of scenarios were generated through Latin Hypercube Sampling of the uncertain variables. Afterwards, the Patient Rule Induction Method (PRIM) statistical data mining technique was employed to identify the set of uncertainties that lead to undesired policy outcomes. PRIM is widely used for scenario discovery because ‘’it is highly interactive, presents multiple options for the choice of scenarios, and provides visualizations that help users balance among the three measures of scenario quality: coverage, density, and interpretability.’’ (Bryant & Lempert, 2010). This kind of uncertainty analysis is in line with previously conducted SD studies (Kovari & Pruyt, 2012; Fakkert, Schwarz, & Pruyt, 2015), and is directed towards understanding the limitations and robustness of policies.

III. THE MODEL

A. Model boundaries

In the conceptualization phase, different decisions were made regarding what variables and structures should be considered, and in what level of detail these should be modeled. **Figure 1** presents the Bull’s-eye diagram, which provides a general overview of the endogenous variables that were modelled thoroughly, the endogenous variables that were modelled superficially, the exogenous variables, and the variables that were deliberately omitted. The discussion in this section focuses on the omitted variables.

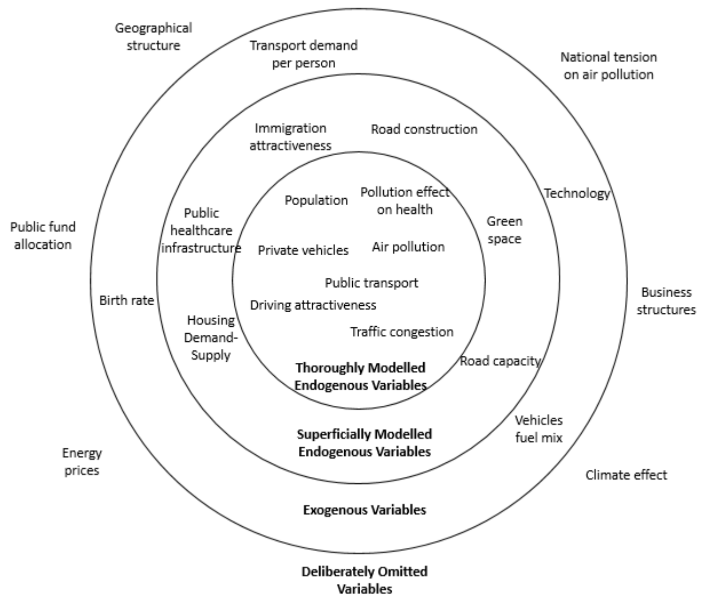


Figure 1. Bull’s-eye diagram.

One of the important exclusions that was made was regarding public fund allocation for road construction, green space development, and housing development. Despite the fact that public fund allocation depicts the prioritization process of the government, we argue that, in order to avoid making the model overly complex, the government has unlimited resources. This means that with regard to road construction, green space development, and housing development, there is only a tension in the context of total land available.

Another variable that was deliberately omitted is national tension on air pollution. Based on the high level observation of air pollution, citizens of Indonesia could engage in social and political events that are aimed towards pressurizing the government, and claiming improvements of the situation. However, these national events and their effects are outside the scope of this study.

In the population subsystem, one of the important variables is migration. In general, migration decreases when there are a lot of health problems in a country, and in parallel, increases when new business structures are being developed. During the conceptualisation phase it was decided to omit the variable business structures, and its effect, as it would make the model too complex, and bring the model outside the original scope.

The price of fuel, and other types of energy, has a direct effect on the choice of commuters with regard to what transport mode to utilize (i.e. private transport attractiveness in our model). However, the effect of several other variables was considered to be larger, and therefore this variable was excluded from the model.

It is genuinely known that emissions from transportation activities contribute to global warming and climate change. In this context, climate change can have an effect on the health of the population, when extreme nature events unfold. However, to what extent the transportation subsystem contributes to climate change, and to what extent climate change has an effect on the population subsystem, is not considered in the model as the model only focuses on regional level of Jakarta province.

B. Main feedback loops

The highly aggregated conceptual model is presented in **Figure 2**. Three indicators are of main importance: traffic congestion, air pollution, and the average health level. Furthermore, the CLD provides an overview of the seven main feedback loops:

(1) Escalating pollution due to delayed effect of pollution on health level - an increase of the population demands more transportation trips, resulting in a higher amount of air pollution, and a decay of the average health level. However, the effect of the average health level on population dynamics has a delay, by which air pollution will escalate.

(2) Traffic jam and road demand – an increase of the population demands more transportation trips, resulting in higher traffic congestion. New roads are developed to balance this, although this is constrained to some extend by the limited available area for road infrastructure.

(3,4,5) Decaying public transportation quality / shifting to public transportation / escalating traffic congestion – Attractiveness of private transportation determines the citizen’s choice of transportation mode, and is affected by traffic congestion and the quality of public transportation. In the current situation, demand will be increasingly fulfilled by public transportation, until public transportation capacity is depleted. Thereafter, the increase of traffic congestion will escalate, as the increase of demand can only be fulfilled by private transportation.

(6, 7) Late green space development / housing boom – The escalation of traffic congestion will lead to an increase of PM_{10} concentration in the air (air pollution), through which the average health level will drop. This initiates pressure from the population towards the government to reduce pollution.

After some delay, the government will develop green space to absorb PM_{10} concentrations. However, the space available for green space competes with the space that should be available for housing.

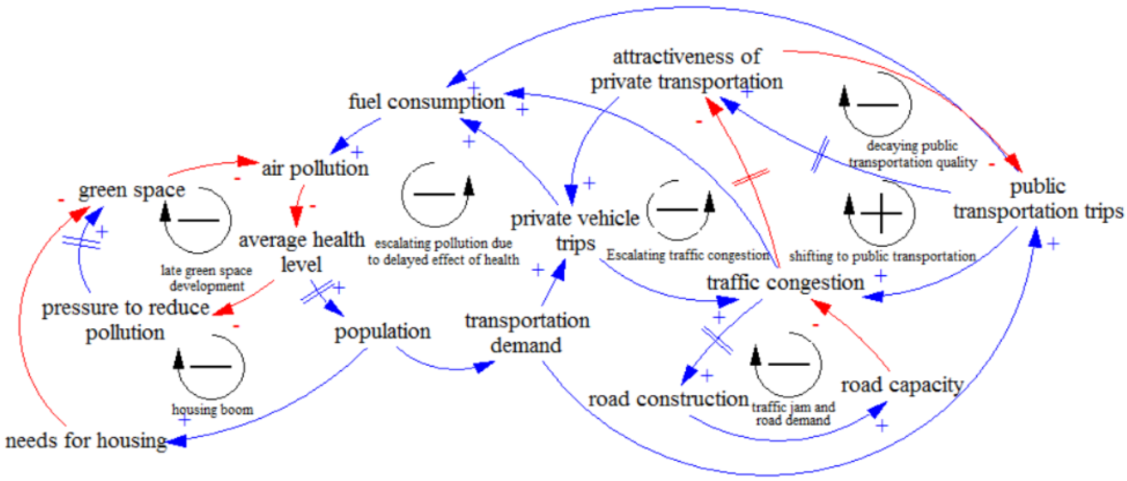


Figure 2: Highly aggregated Causal Loop Diagram.

C. Simulation model and subsystems

Figure 3 presents the simplified SFD of the three subsystems: transportation, population, and built-environment.

<u>Transportation subsystem</u>

As mentioned in section III.B, total transportation demand is a function of the population. Demand can be fulfilled by either private or public transportation. Private transportation consists of gasoline cars, diesel cars, and motorcycles, whereas public transportation consists of small, medium, and large buses. The percentage of demand that the two categories of transportation fulfil is a direct function of private transportation attractiveness. In this context, the factor that influences the attractiveness the most is traffic congestion (60%), followed by the quality of public transportation (40%). It is assumed that the percentage of transportation demand fulfilled by each mode within the private and public transportation groups stays constant over time (i.e. exogenous).

For private transportation, only supply is modelled, as it is assumed that it will always match to demand. However, for public transportation, a fixed supply is assumed. When demand for public transportation exceeds supply, quality of public transportation will decrease (overcrowded buses). Total transportation trips times the average distance per trip is equal to the total distance travelled. Hence, an average distance per trip is assumed for all modes of transportation. Total emissions are derived from the total distance travelled, and the PM_{10} emissions per km travelled, which is specified for each mode of transport. Traffic congestion is represented as the fraction of total transportation trips over the total area of roads. Higher congestion leads to lower private transportation attractiveness, whereas lower quality of public transportation leads to higher private transportation attractiveness. The higher the traffic congestion, the higher the road construction rate will be, until the total area of roads reaches 10% of total Jakarta land occupied; in that case, no construction will occur anymore.

Population subsystem

Population increases by births, and decreases by normal/natural death, death due to air pollution, and migration. Healthy children and adults can become respiratory ill, and die accordingly. However, they can also be cured, and flow to the healthy stocks. Net migration depends on the public health issue perception in the context of accumulating pollution, the traffic congestion influence on migration attractiveness, and the influence of other unknown factors. The flows death through pollution depend on the excess pollution, which are derived from the built environment subsystem.

Built-environment subsystem

Pollution increases by emissions from transportation activities, and decreases by pollution absorption from green space. A comparison of the pollution stock and the World Health Organisation standard on PM_{10} concentration in the air, provides an indication of excess pollution, which influences the death through pollution flows. When there are more deaths due to air pollution, the public pressure on pollution eradication increases, so that green space is developed faster. However, the total area of Jakarta that can be used for green space is limited, and competes with the area that should be available for housing. An increase of the housing demand/supply ratio means that there is more tension on housing demand fulfilment, such that the increase of green space will be slowed down.

IV. KPIs, POLICIES, UNCERTAINTIES

A. Key performance indicators of the model

This model compromises three types of Key Performance Indicators (KPIs): pollution concentration, number of sick population, and traffic congestion. The reasons for choosing these three distinguished, though interconnected KPIs are to (i) consider the three different subsystems, to (ii) inform decision makers regarding the tradeoffs of each indicator and to (iii) applying the notion of multiplism which suggests that a problem should be measured in different ways (Dunn, 2016). Pollution concentration represents the Built Environment subsystem, sick population represents the Population subsystem, while traffic congestion represents the transportation subsystem.

B. Policies

Though there are numerous popular options regarding measures to reduce air pollution in urban setting, this study considers three notions in determining the analyzed policies. Firstly, the interconnectedness of the subsystems prohibits deriving policies from only one driver of the system, since the leverage point of the system may exist in any part of the system. Secondly, this study considers two types of policy, namely one-time static policies and adaptive policies. Further discussions regarding this categorization can be found in (Pruyt & Hamarat, 2010). Lastly, this study also considers popular policies which are under discussion in Indonesia. Since the simulation run is assumed to start in 2010, all policies are activated after 5 years of the run.

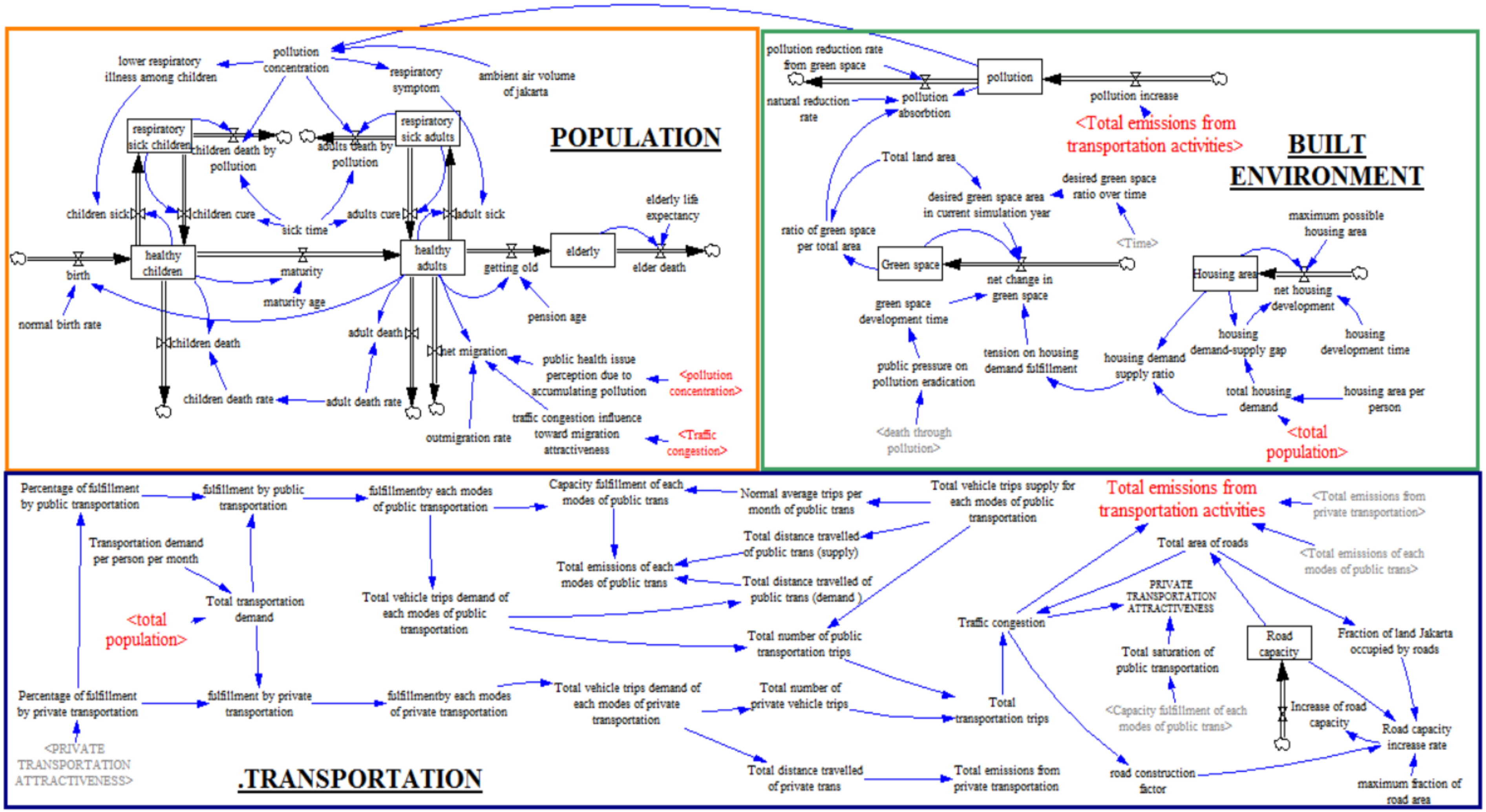


Figure 3. Simplified Stock and Flow Diagram.

The three considerations above generate four policies. The first policy is a static policy of modifying the pollution concentration standard of Jakarta. Currently, the pollution concentration standard for PM10 is 150 µg / m3 PM10 (Schwela et al., 2012). This policy reduces the PM10 standard so that it complies with WHO standard of 50 µg / m3 (WHO, 2006). In the beginning of the simulation run, the PM10 concentration in Jakarta is 48.88 µg/m3 (Firdaus, 2013), which is almost as high as the WHO pollution standard. Decreasing pollution standard is expected to prompt the citizen to leave Jakarta, since the air condition is deemed to be not safe anymore.

The second policy is derived from the popularly debated issue in Indonesia, which tries to tackle the Built Environment subsystem: *conversion to Natural Gas-based fuel Vehicle (NGV).* Using NGV instead of diesel or petrol fuel can reduce the emission from vehicles by up to 24% (Edwards, 2011). Though around 2 million cars, which account for 25% of the whole nation's private cars, reside in Jakarta, the number of NGV had not even exceeded 5000 units by 2010 (Mahendra, Kartohardjono, & Muharam, 2013). Due to the low penetration of NGV, this static policy assumes that by each month, only 0.3% of the private transportation and 0.4% of the public transportation is converted into NGV. The conversion rate of public transportation is slightly higher, as the government can implement direct interventions for this means of transportation. Once converted, all vehicles are assumed to have 25% lower PM_{10} emission.

The third policy concerns the population subsystem, and tries to reduce the population birth rate through reinforcement of the *'family planning' program,* and specifically by adding another measure to the program, which is *banning more than two children per family.* The family planning program is a national program since the 1960s, that aims to control the number of births in families through promotion of contraception methods, and providence of public clinic consultancy services to Indonesian families (Shiffman, 2004). The program has faced ups and downs in Jakarta. The most recent promotion happened in March 2015, where the Vice Governor of Jakarta re-launched the family planning program (Pratiwi, 2015). In this study, it is assumed that activation of this policy will reduce the birth rate of Jakarta population by 25%. This assumption is based on the low effectiveness of the family planning program. This adaptive policy will be activated every time that the population density of Jakarta exceeds 20.000 people / km^2, which is far higher than the 2010 condition of 14.501 people / km^2 (Jakarta Healthcare Agency, 2013). Due to the nature of this long-debated policy, it is also assumed that the policy will take place 5 years after the ''activation condition'' is fulfilled.

The last policy confronts the transportation subsystem, by *increasing the tax for private vehicle purchases in Jakarta*. It aims to dis-incentivize people from using private transportation, so they shift their mode to public transportation. This policy has been proven successful in various regions and countries, such as US, EU, China, India, and Hong Kong (ICCT, 2014). While the current tax rate of private vehicle purchase in Jakarta is 10% (Jakarta Taxes Agency, 2010), this study assumes that the tax will raise to 30%. Moreover, it is assumed that higher private vehicles tax will reduce the attractiveness of private transportation by 21%. Since this number is uncertain, it will be considered as one of the parameter uncertainties in the next chapter.

C. Uncertainties

The developed model so far incorporates several uncertain variables. These variables are uncertain either because of (i) that they are actually uncertain in nature, (ii) that there are different parameterizations from different sources, or (iii) that there is no data available regarding the variable. For instance, a 1997 edition World Bank report (Shah, 1997) provides different numbers of PM_{10} emission per km travelled with the one studied by (Soleiman, 2008). The natural PM_{10} absorption rate by the environment and the saturation threshold of traffic congestion are examples of variables that are uncertain in their nature. Average distance trip for each mode of transportation and average time to build new roads are examples of variables of which data is not documented by any agency. To couple these issues, this study takes a wide range of parameterization possibilities of those variables into account. This results in parameters uncertainty as shown in **Table 1**.

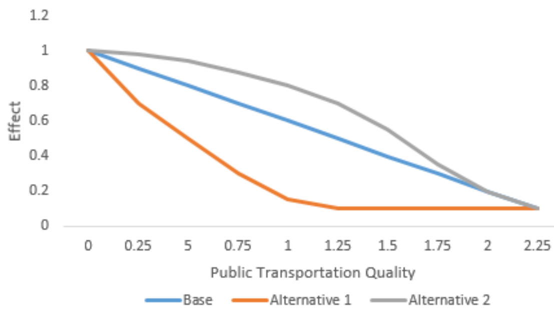


Figure 4. Effect of quality of public transportation on private transportation attractiveness.

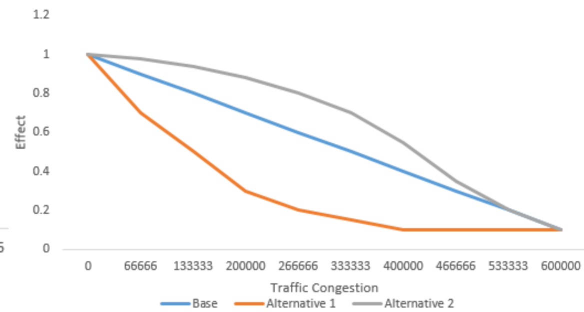


Figure 5. Effect of traffic congestion on private transportation attractiveness.

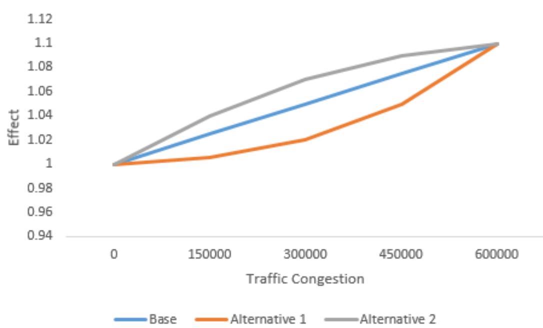


Figure 6. Effect of traffic congestion on transportation emissions.

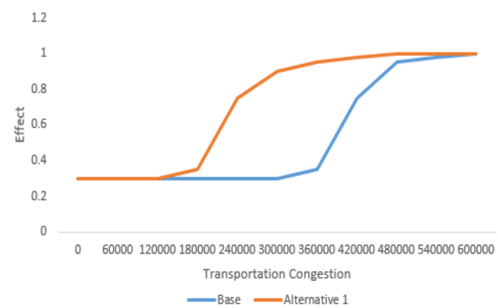


Figure 7. Effect of traffic congestion on road construction factor.

Besides parameters uncertainty, this study faces problem in determining the relationship between variables which are depicted as graphical function in the model. Therefore, this study also considers different shapes of graphical functions as depicted in **Figure 4 to 7**. In general, the graphical function can take a form of either linear relationship, non-linear concave relationship or non-linear convex relationship.

V. BASE CASE AND POLICIES RESULT

Figure 8 to 10 compare the result of different policies for each KPI. Eventually, some policies cause backfire to some KPIs itself, instead of making the situation better. It supports the notion of counterintuitive behavior of social system where the multiple feedback loops in the system deceive the logical reasoning of policy makers (Forrester, 1971).

By reducing the pollution standard (Policy 1), it is expected that people will be aware that the air condition in Jakarta is considered bad thus increasing the emigration flow of the citizen. This results in lower population, which in turn reduces the transportation demand and air pollution. However, it should be noted that the behavior over time of the system is still the same, though the magnitudes of all KPIs and the steepness of all KPIs' increase are lower. After some time, the performance of all KPIs will eventually reach the base case condition of the system.

Table 1. Uncertain Variables List.

No	Variable	Base	Min	Max	Source
1	Average distance per trip private transportation	2.27	1	5	Wismadi et al. (2013)
2	Average distance per trip public transportation	2.27	1	5	Wismadi et al. (2013)
3	Average time building new roads	60	24	84	Assumed
4	Death multiplier due to pollution	0.096	0.0192	0.1728	Firdaus (2013)
5	Delay of private transportation attractiveness on percentage of transportation demand fulfilled by private transportation	3	0.6	5.4	Assumed
6	Delay time traffic congestion	3	0.6	5.4	Assumed
7	Emergency room visit due to pollution	0.0002354	4.708E-05	0.0004237	Firdaus (2013)
8	Housing development time	12	9	20	Assumed
9	Natural reduction rate	0.15	0.1	0.2	Assumed
10	Normal green space development time	36	12	60	Assumed
11	Other factors influence	0.5	0.3	0.7	Assumed
12	PM emissions per km of each modes of private transportation[GasolineCars]	0.2	0.1	0.4	Syafrizal et al. (2014)
13	PM emissions per km of each modes of private transportation[DieselCars]	0.6	0.4	1	Syafrizal et al. (2014)
14	PM emissions per km of each modes of private transportation[Motorcycles]	0.05	0.02	0.1	Syafrizal et al. (2014)
15	PM emissions per km of each modes of public transportation[LargeBuses]	2	1	3.5	Syafrizal et al. (2014)
16	PM emissions per km of each modes of public transportation[MediumBuses]	1.45	0.8	2	Syafrizal et al. (2014)
17	PM emissions per km of each modes of public transportation[SmallBuses]	0.9	0.4	1.5	Syafrizal et al. (2014)
18	PM emissions per km of each modes of public transportation[Taxis]	0.2	0.1	0.4	Syafrizal et al. (2014)
19	Pollution impact toward respiratory illness among children	0.00169	0.000338	0.003042	Firdaus (2013)
20	Respiratory hospital admission due to pollution	0.000012	0.0000024	0.0000216	Firdaus (2013)
21	Saturation of traffic congestion	100000	20000	180000	Wismadi et al. (2013)
22	Sick time	3	0.6	5.4	Assumed
23	Tolerable population density	20000	4000	36000	Assumed
24	Total trips per day of each modes of public transportation	3	2	6	Wismadi et al. (2013)

Conversion to NGV (Policy 2) as predicted reduces the pollution concentration of PM_{10} in Jakarta, which leads to lower sick population. Interestingly, the traffic congestion performance gets worsen compared to the base case condition. The lower pollution concentration reduces the outflow rates of population, which in this case are death through pollution and outmigration rate. As a result, the number of population gets higher, thus increasing the transportation demand and traffic congestion in the city.

Birth control (Policy 3) is the most promising policy since it is the only policy that alters the behavior over time of all KPIs. The mechanism behind this is straightforward: reducing the inflow of the population automatically leads to lower transportation demand. Next, the number of operating vehicles, either public or private, is declining, which means that the level of PM_{10} emission is also falling. This adaptive policy prevents Jakarta from overpopulation. Since number of population is under control, excess pollution can be prevented.

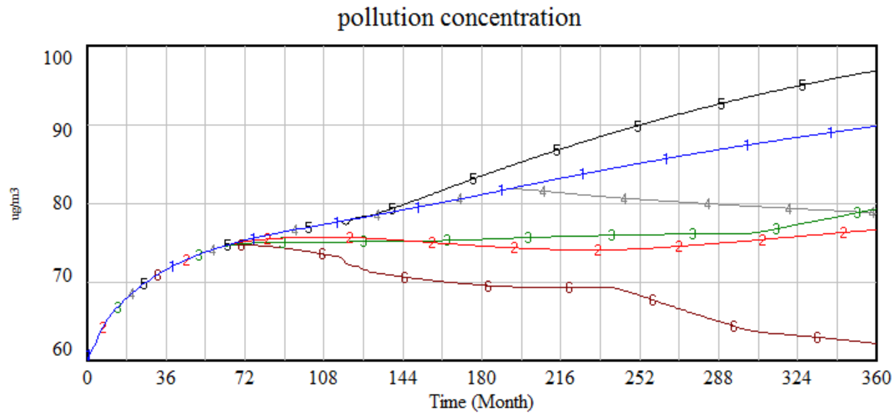


Figure 8. Pollution Concentration Single Run Policy Results.

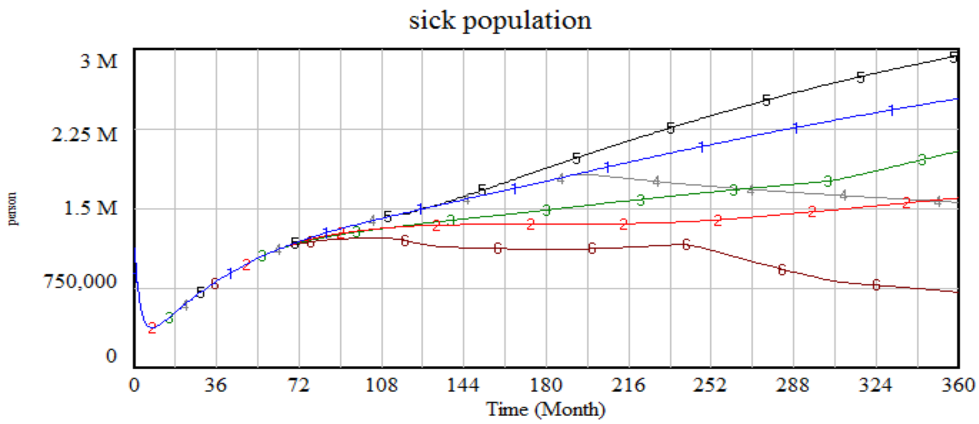


Figure 9. Sick Population Single Run Policy Results.

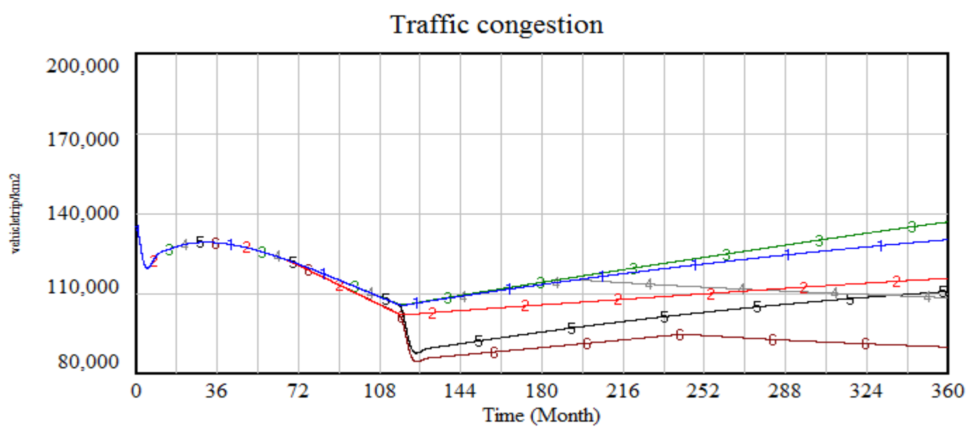
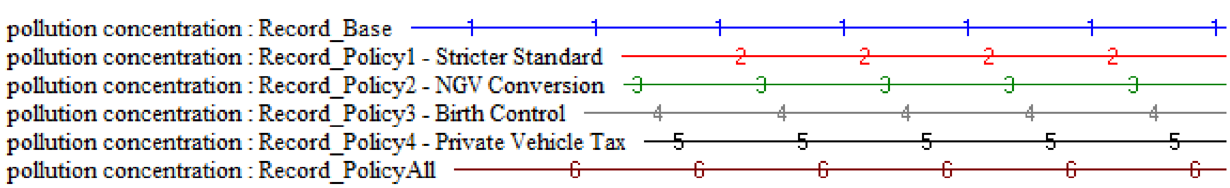


Figure 10. Traffic Congestion Single Run Policy Results.



The additional private vehicle tax policy (Policy 4) succeeds to decrease the attractiveness of private transportation, shifting the transportation demand to public modes. However, while the traffic congestion is greatly reduced, this policy unexpectedly boosts the level of pollution concentration and sick population. This counterintuitive behavior occurs because no matter how the market share mix between public transportation and private transportation, people still need transportation service to conduct their daily activities. Shifting to public transportation increases the number of operating public transportation modes. Since these modes generally have higher emission per kilometer, the level of pollution concentration raises accordingly even though the traffic congestion decreases.

If the government can only select one policy, it is clear that birth control policy is the most assuring one. Applying all policies at once however produces the best outcomes for all KPIs because the magnitudes of all indicators are the lowest and their behavior also shows downward trend.

VI. POLICY TESTING UNDER UNCERTAINTY

A. Ensembles of scenarios for all policies

In total, there are six cases considered in this study: one business as usual (BAU) case, four individual policy cases, and one case where all policies are applied. Each case is simulated 2000 times in order to maximize the vector of all plausible options of uncertain variables, creating ensembles of scenarios where each scenario contains one unique settings of uncertain variables parameterization. As a result, 12000 simulation runs were conducted for this study. Analyses of policies are then based on the robustness of the policy while taking into account the full ensembles of uncertainties.

Figure 11 to 13 show the resulting simulation run of 12000 different scenarios. The upper graph displays the envelopes and simulation runs of the outcomes of each case. From this graph, the minimum and maximum value for a set of runs over the simulation time can be observed. All the 2000 replications for each case fall within these envelopes. In order to compare results between policies, understanding about the distribution on how the KPIs evolve over time is needed. For this purpose, the graphs below each of the behavior over time envelopes graph is developed. These graphs display the kernel density, which plots the density of the value of each indicator during a particular time of the simulation in a density probabilistic graph.

Figure 11 presents the evolution of sick population indicator over time. As clearly seen, the indicator starts to split in the 180th month, with simulations from Policy All case immediately form narrower distribution. It implies that the sick policy indicator immediately responds to Policy All case. The sharper peak also shows that Policy All case cuts down the influence of uncertainties straightaway. During the 270th month Policy 1, 2, and 3 also create a slightly sharper peak of distribution in comparison to Policy 4 and the BAU case. It indicates that Policy 4 does not perform well in this KPI. The kernel density at the terminal value confirms the findings; Policy All is the most robust case to reduce the number of sick population due to air pollution.

The evolution of Pollution Concentration indicator between policies as shown in **Figure 12** is less distinguishable than the previous KPI. However, in accordance to the Sick Population's behavior over time, Policy All case produces better result than the other cases. The Pollution

Concentration's kernel density's mode at the end of the simulation run is approximately 60 µg / m^3, while the other cases' modes are around 80-100 µg / m^3. Though only marginal, Policy 4 creates results which are worse than the BAU. Policy 3's results are also slightly better than the other individual policies since Policy 3 case has sharper peak, implying that this case can deal with the uncertainties better.

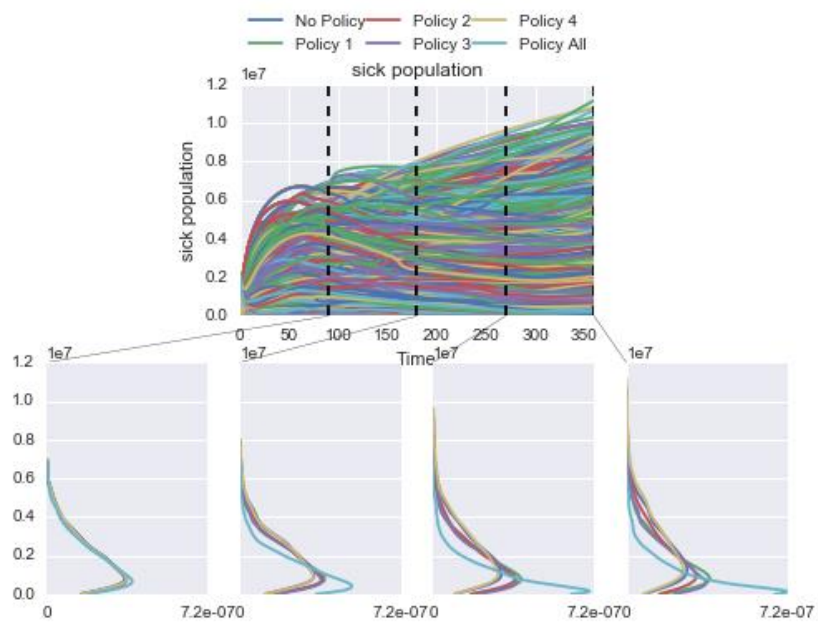


Figure 11. Sick Population Kernel Density Over Time.

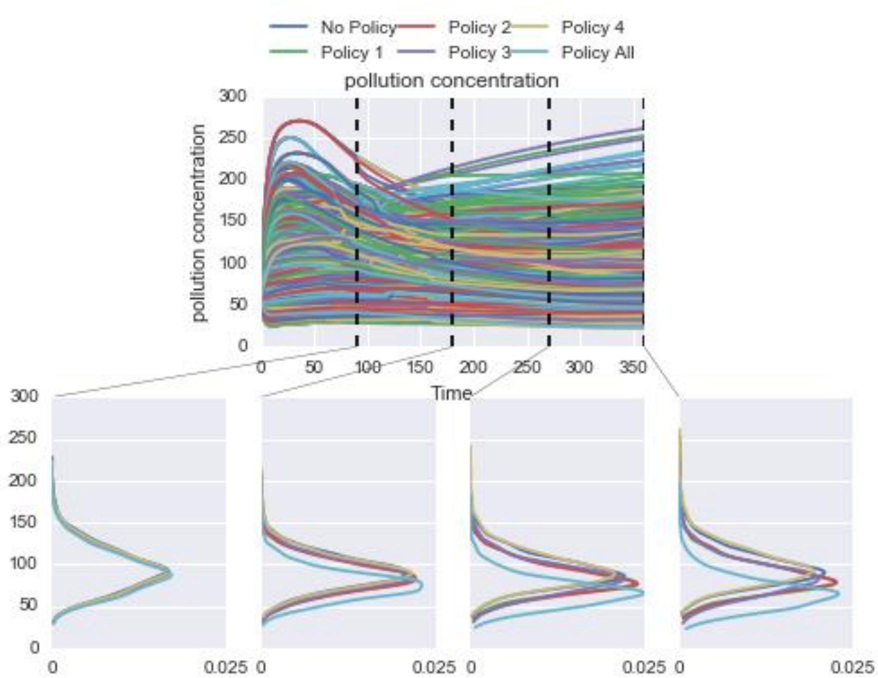


Figure 12. Pollution Concentration Kernel Density Over Time.

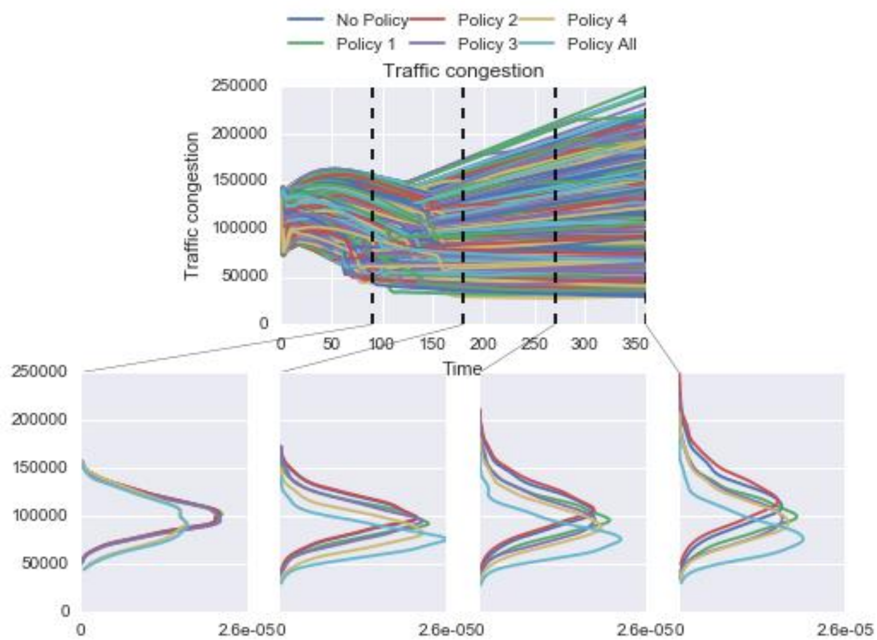


Figure 13. Traffic Congestion Kernel Density Over Time.

The Traffic Congestion KPI shown in **Figure 13** is more dispersed than the other KPIs, though the differences are still marginal. In the 180th month, it can be seen that the Policy All case already starts to outperform the other cases. This fact is further proven by the 270th and the final month of the simulation run. At the end of the simulation run, the kernel density shows that Traffic Congestion responses badly to Policy 2. The distribution of Policy 2 results is slightly higher than the BAU's. The other policies' results are more undifferentiated, implying that any policy will perform similarly under deep uncertainty.

The simulation runs across ensembles of scenario explains that none of the policies studied in this paper is robust. There are some permutations of uncertain variables that drive the KPIs relatively higher, which is not desirable in this case. Execution of all policies is also not sufficient to robustly tackle air pollution in Jakarta and its health implication. Nevertheless, the combination of all policies is proven to generate considerably better outcomes.

B. Selection of simulation runs with undesirable outcomes

The analysis so far has shown that even the best case (Policy All) can still produce undesired KPI outcomes in some scenarios. This subchapter tries to illuminate the most prominent sets of uncertainties that influence the undesired outcomes of the policy. For this purpose, this study utilizes the statistical data mining technique PRIM (Patient Rule Induction Method) as proposed in (Lempert, Groves, Popper, & Bankes, 2006). This subchapter will discuss under what circumstances the 'Policy All' case fails to produce the desired outcomes.

As a starting point, the value of each KPI in the single simulation run is used as a threshold in the PRIM analysis. Therefore, PRIM will search for scenario settings where the output of the simulation run is higher than the threshold values, which are 90 µg / m^3 for the pollution concentration, 2.000.000 people for sick population, and 120.000 vehicle trip / km^2 for traffic congestion. **Figure 14 to 16** present the restricted dimension found by PRIM for each of the KPI while the summary of PRIM analysis can be seen in **Table 2**.

The coverage measure in **Table 2** indicates the percentage of cases of interest that reside in the restricted dimensions, while the density measure indicates how much of all cases in the restricted dimensions have the desired cases of interests (Bryant & Lempert, 2010). For instance, 81.3% of simulation runs where the pollution concentration exceeds 90 µg / m^3 exist in the 5 restricted dimension as shown in **Figure 14**. Additionally, out of all cases that exist in the restricted dimension of **Figure 14**, 22.6% of them have pollution concentration beyond the threshold value.

Table 2. PRIM Results Summary from Three Indicators.

	Pollution Concentra-tion	Sick Population	Traffic Congestion
Points of Interest	198	256	178
Coverage	81.3%	83.2%	71.9%
Density	22.6%	29.9%	36.6%
Restricted Dimension	5	7	5

From all the coverage and density values in **Table 2**, it can be seen that PRIM identifies set of uncertain parameters which are the most influential to the undesired outcomes consistently. However, only some of the restricted dimensions shown in **Figure 14 to 16** have significantly small uncertainty ranges. Variables whose uncertainty ranges are very wide, or even covering the whole spectrum of the uncertainty range, can be left out from the analysis since they only give little insight in identifying the vulnerable scenario. For instance, from **Figure 14** we can leave out 'average distance per trip of public transportation[medium bus]' and 'PM emissions per km of public transportation[small bus]' from the analysis since the uncertainty range of these variables cover almost the full spectrum of the line. It is important to emphasize that the undesired region is resulted from the combination of all these ranges of uncertainties at once (high tolerable population density, and not too high pollution impact toward children's health, and not too high death multiplier due to pollution). Taking one of these variables and its range separately will not necessarily lead to the undesired outcomes.

For pollution concentration KPI, there are five restricted dimensions that drive the behavior of this KPI high in Policy All case. Nevertheless, as shown in **Figure 14**, the two last variables can be disregarded since the uncertainty range is too broad. This leaves three important uncertain variables: high tolerable population density, low pollution health impacts toward children, and low death multiplier due to pollution. If the tolerable population density is high, the government will be less responsive in executing the birth control policy. Therefore, the number of Jakarta population will rise, resulting in higher transportation activities and higher air pollution. Interestingly, the pollution concentration will also rise if the pollution health impacts toward children is low (or at least, not too high). This is because in general, children are more prone to health problems rather than adults. Low pollution health impacts toward children will cause less number of ill children and therefore less children death. Consequently, the number of population will be high thus the same logic like tolerable population density variable applies.

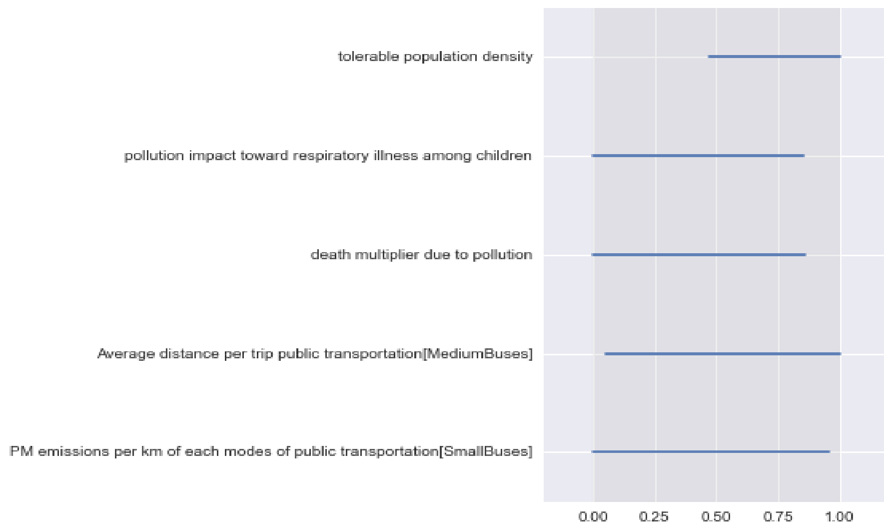


Figure 14. PRIM Result for Pollution Concentration Above 90 µg / m3.

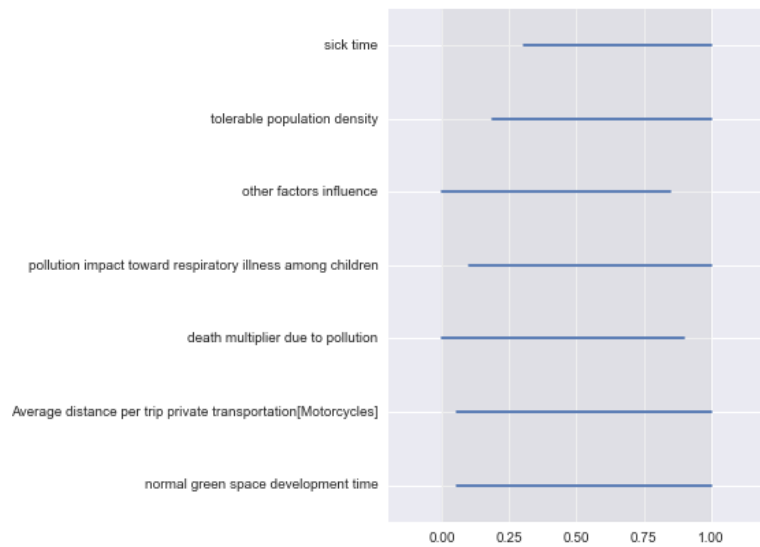


Figure 15. PRIM Result for Sick Population Above 2,000,000 People.

Out of seven restricted dimension for sick population above 2,000,000 shown in **Figure 15**, three of them (tolerable population density, pollution health impacts toward children, and death multiplier due to pollution) are the equivalent with the pollution concentration's restricted dimensions. In addition, high sick time and low other factors' influence toward outmigration decision are also responsible for this problem. The high number of sick time holds the people in the sick population stocks and subsequently keeps the number of sick population high. In reality, the sick time is not purely exogenous. For instance, the government can influence it by rising healthcare delivery quality standard. Since this is out of this paper's scope, this finding might be useful for sending message to the government regarding the importance of healthcare service quality. If the other factors' influence toward outmigration decision is low, less people will leave Jakarta. The same logic then pertains like the tolerable population density variable. Eventually, the concentration of air pollutants rises, causing illness to more people.

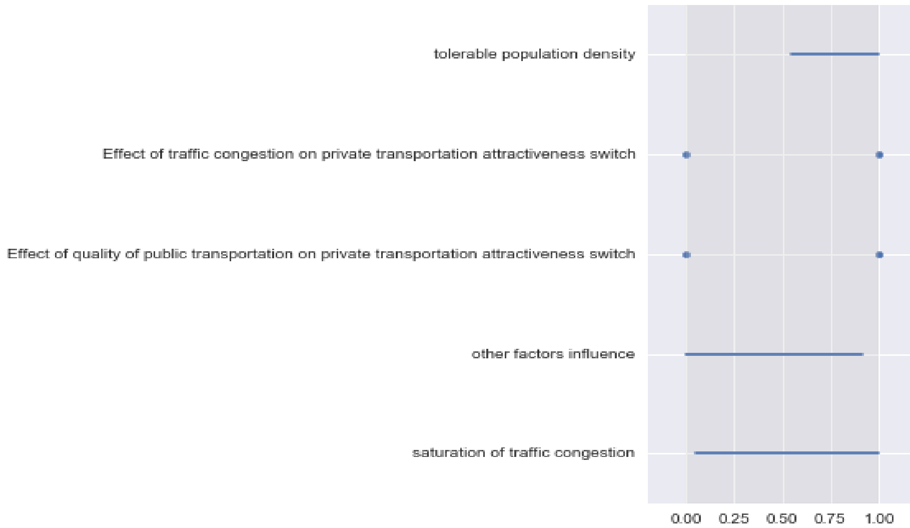


Figure 16. PRIM Result for Traffic Congestion Above 110.000 Vehicle Trip / Km2.

The traffic congestion threshold produces five restricted dimension as displayed in **Figure 16**. High tolerable density appears for the third time in this analysis, with the same causal effect logic persists similar to the two other thresholds. Moreover, the uncertain relations between traffic congestion and public transportation quality toward private transportation attractiveness are also the determinants of the high traffic congestion. In this case, the base relation and alternative relation proposed in **Figure 4 and 5** result in traffic congestion above the threshold. In other words, only if the relations form an exponential decay curve that the traffic congestion can stay below the threshold value. This signals the importance of further research in identifying a more accurate information regarding the relation between these variables, thus the policy analysis discussion can become richer. Nevertheless, since in reality this relation cannot be influenced by the government, it might also be wiser to focus the research on finding other alternatives to tackle the problem.

It is important to emphasize that there are some combinations of uncertainties that cannot be countered by even executing all policies. The number of points of interest for any threshold falls around 200 simulation runs as shown in **Table 2**. It means that out of the 2000 simulation runs from Policy All case, around 10% of them have undesired outcomes.

Another important finding is that the tolerable population density, which acts as a signal for the government to initiate the birth control policy, is an important uncertain variable as it appears in all the three PRIM analyses. Reflecting to reality, the value of this variable is contested. Proponents of urbanization, economic growth, and inequality eradication usually support a high tolerable population density. The main argument is that Jakarta is the most urbanized city and is promising better welfare for poor people. Advancement of urban planning should be able to extend the capacity of Jakarta itself, raising the tolerable density. On the other hand, environmentalists and urban planners are against this. The tolerable population density should be kept low to ensure the livability of the city. Though the debate over this issue is continuing, the exemplar selection analysis has shown that the number of tolerable population density should be kept low.

VII. CONCLUSION AND RECOMMENDATIONS

The purpose of this study was to analyze policies to tackle air pollution and its health impact in Jakarta. The analysis has shown that the population subsystem is the most important aspect in tackling air pollution and its health impact. As long as the population remains large, transportation demand will be high, which is bad for traffic, environment, and - given fossil fuels - health.

As thoroughly analyzed in this study, the traditional debated policies fail to solve the interconnected air pollution, its health implication, and traffic congestion issues. Some policies, such as promoting conversion to NGV and increasing tax for private vehicle purchases, even worsen some of the indicators. Our model can be used to convey the message of this counterintuitive behavior to policy makers, so they can make higher quality decisions to solve Jakarta's problem.

Nevertheless, this study has managed to shade a light on how the currently debated policies to tackle air pollution and its health implication in Jakarta perform upon the three selected indicators, taking into account deep uncertainties. A general bottom line from the analysis is that the system reacts strongly to uncertainties. Even the combination of all policies will still perform badly in some circumstances. The currently debated appropriate value of tolerable population density is proven to be an influential uncertain parameter that may drive the outcomes significantly.

Moreover, Lower Respiratory Infections (LRI) have been addressed as the third highest cause of Years of Life Lost (YLL) in Indonesia. Jakarta is the main contributor of LRI in Indonesia, due to its devastating air pollution. While currently, the number of people that suffer from LRI is estimated to be around 1 million, in the worst case scenario this can increase to even higher than 5 million. Though not extensively assessed in this study, this overwhelming number intuitively leads to even a larger amount of YLL, and disability-adjusted life years. This fact, in combination with the main findings of this study, provide an urgent message to the government to extend the debate and research regarding effective measures to decouple air pollution in Jakarta.

Further research may add to the discussion of more promising alternatives, by identifying better adaptive policies. For instance, a policy with regard to the improvement of the public healthcare performance, in order to reduce the impact of air pollution, might be considered. Moreover, additional structure can be added to the model in order to incorporate shifts of market share for each vehicle mode within the public and private transportation. Interactive model building with experts and stakeholders can also be conducted in order to improve the acceptance and reliability of the analyses. Finally, various calibration techniques such as Markov Chain Monte Carlo or Simulated Annealing can be utilized to limit the range of the uncertain variables, in order to prevent the shooting up behavior at the beginning of the simulation runs in the scope of policy testing under uncertainty.

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