**Do Special Bike Programs Promote Public Health? A case study of New York City's Citi Bike bike sharing program**

*or*

**Investigating the Health Effect of the Citi Bike Bike-sharing Program in New York City Using the ITHIM Health Assessment Tool**

Center for Transportation, Environment, and Community Health
Final Report

*by*

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**ABSTRACT**
Bike travel is often considered as a healthy and environmentally friendly mode of travel and promoted by cities. Bike sharing, as a bike usage boosting program, invigorates these advantages. However, as usage of it rises, so do the adverse effects on cyclists' physical well-being, such as hazardous air exposure and bicycle involved accidents. The net health benefits of bike-sharing programs are therefore not clear cut and are worthy of studying case by case. This paper focuses on the Citi Bike Bike-sharing program in New York City. We evaluate the health effect of it using a modified Integrated Transport Health Impact Model (ITHIM) by assessing and comparing the risks of two proposed scenarios: with-Citi bike scenario (baseline) and without-Citi bike scenario (hypothetical). The baseline scenario corresponds to the actual traffic and health condition in 2017, while we split the Citi Bike trips to other modes according to the NYC travel survey data to construct the hypothetical scenario. For each scenario, we investigate the overall health effects of the Citi Bike from three pathways: Physical Activity (PA), Hazardous air exposure (mainly consider Particle Matters (PM 2.5)), and Road Traffic Injuries. The result indicates that the implementation of Citi Bike plays a positive role in improving the public health. By conducting a sensitivity analysis, we delves into the potential benefits of the Citi Bike under some possible policy outcomes. Finally, we discuss the strength and limitation of the study and the modified model, and provide the future study directions.
**Keywords:** ITHIM, Public Health, Citi Bike, bike sharing, DALYs, Burden of Disease

## INTRODUCTION

Cycling, as a form of Active transportation (e.g., walking and biking) (*1*), is a very healthy travel mode that produces incidental Physical Activities (PA) while riding and easily adhered into the daily routine (*1–3*). Especially, cycling has been found to achieve the necessary intensity to qualify for moderate-intensity activity (*4–6*), and has potentials to meet the recommended weekly levels of PA (*3*, *7*) that proposed by World Health Organization (WHO) (*8*) to keep a healthy condition. However, in today's automobile dominated travel culture, driving or riding cars is usually the first choice for people to travel. These choices result in shaping sedentary lifestyles, which raises the risk of causing many Non-communicable diseases (NCDs) (*9*), such as breast and colon cancer, type 2 diabetes (*10*), and cardiovascular diseases (CVD) (*11*).

There are many ways to motivate people to use bicycles. An existing health study (*1*), for example, recommends infrastructures and facilities shall be reintroduced or redesigned to make walking and biking easy and inexpensive (*12*) to engage in their daily activity. One such a case occurs in New York City (NYC) (*13*). In 2013, NYC implemented a bike-sharing program called Citi Bike (*14*). Citi Bike works as the short-term bicycle rentals, and allow users to share the usage of the same bicycle at different periods among dock stations with a small expense. It thereby attracts riders to use for their daily travel(*15*), which reduce traffic and pollution, and encourage physical activities accordingly (*1*, *16*, *17*).

Although Citi Bike has potentials of improving public health for NYC, with the growth usage of the Citi Bike, it can have higher exposure to pollutants and risks of injury than other methods of travel (*17*). For example, riders are exposed to the open air while riding bicycles, and the polluted air would be harmful to their respiratory tract and cardiovascular system (*18*). Further, the more time cycling means the higher chance of involving the bike accidents. In consequence, the net health benefit of using Citi Bike is ambiguous. There are two existing studies (*19*, *20*) analyzed the Citi Bike health impact from a singular traffic injury aspect. However, to investigate the net health impact, it is essential to quantify the health-related changes through multiple aspects that cover both positive and negative facets. Up to now, there is no comprehensive health effect study quantifying the NYC Citi Bike program.

To fill this gap, in this paper, we modify and apply the Integrated Transport and Health Impact Modelling (ITHIM) tool to quantify the net health impact of the Citi Bike bike sharing program. ITHIM is a health assessment tool (*21*) that estimates health impacts in Burden of Disease (BD) (*22*) from PA, hazardous air exposure, and Roadway Traffic Injuries (RTI) three aspects of a proposed transportation scenario. In fact, ITHIM has been successfully applied in many studies. In 2009, a study (*21*) considers PA, hazardous air pollution exposure, and risk of road traffic injuries to evaluate the health effect in Disability Adjusted Life Years (DALYs) changes of alternative transportation scenarios for London, UK, and Delhi, India. Based on that study(*21*), the ITHIM (*23*) framework was developed and settled. In 2013, ITHIM was used to quantify the benefits of the transportation strategies with aiming to have low carbon emission and high physical activity in San Francisco Bay Area, California (*24*). In 2014, another application of ITHIM (*25*) evaluated the health impact of London's bike-sharing program. (*26*) later assessed the preferred scenarios on carbon reductions of California regional transportation plans by applying ITHIM. This paper focuses on the NYC Citi Bike Bike-sharing program. We, therefore, gather the Citi Bike trips data as well as several data sources from physical activity, hazardous air exposure, and road traffic injury pathways. In order to study the public health changes brought about by the implementation of Citi Bike, we propose a with-Citi Bike scenario (baseline) and a without-Citi Bike scenario (hypothetical). The baseline scenario correspond to the traffic and health condition in 2017, and the hypothetical scenario corresponds to a hypothetical scenario that we split the Citi Bike trips to other modes to presume the Citi Bike program did not exist in 2017. By comparing these two proposed scenarios, we are able to look into the changes of Burden of Disease (BD)(*27*) that brought about by the Citi Bike program.

The rest of this paper is organized as follows. In the next section, we introduce the data sources and scenario setting of with-Citi Bike scenario (baseline) and the without-Citi Bike scenario (hypothetical). The methodology section proposed the customized ITHIM model according to our study goal and proposed scenario settings. In the results section, we present the evaluation outcomes in overall and every aspect. In the discussion section, we explain the assessment results and delve into the potential health benefits that Citi Bike may conduct. The conclusions of this research are discussed in the concluding remarks section.

## DATA SOURCES AND SCENARIO SETTINGS

ITHIM applies the Comparative Risk Assessment (CRA) as the key conceptual basis. CRA is defined as the systematic evaluation of the study objective by comparing the health outcomes of the same population in different scenarios with different exposures of risk factors. In ITHIM, the study objective is usually transportation plan(s) or particular transportation project(s). For the scenarios setting, there are one baseline scenario and one or more alternative scenarios. The baseline scenario generally refers to the existing or no-action condition. On the other hand, the alternative scenarios corresponds to the health and traffic condition that caused by the study objective (*28*).

In a general CRA, the alternative scenarios are usually introduced as the with-action conditions and compare it with the baseline scenario (e.g., existing or no-action condition) to obtain the healthy changes of the population that is associated with the exposures. Different from the general study setting, in this paper, since we are evaluating a transportation infrastructure that has been built, then the condition with action (i.e. the condition with the implementation of the Citi Bike) is being selected as the baseline scenario. The hypothetical scenario, on the other hand, corresponds to the condition that we assume the Citi Bike does not exist by splitting the Citi Bike trips to other modes.

ITHIM takes Burden of Disease ($BD$) as the measurement of health effects and $PAF$ as the fraction to calculate the health variation $\Delta BD$ between baseline and an alternative scenario (e.g., the hypothetical scenario in this study) as formulated in **Equation 1**

$$\Delta BD = PAF \cdot BD^{(B)} \tag{1}$$

The superscript (B) represents the baseline scenario. The PAF is calculated by: one minus the ratio of the hypothetical performance to the baseline performance. Each scenario demands data from PA , hazardous air exposure, and RTI aspects, and both terms (BD and PAF) require many data sources to determine. Therefore, we introduce the scenarios from four aspects: Health, physical activity, hazardous air quality, and road traffic injury.

For the study selection, it is preferable to select the current year or a year closest to the current year in order to observe the health impact on current or close to current health conditions and provide insights for the Citi Bike operation or planning in the future. According to the availability of various data sources, we select 2017 as the study year (see **Figure 1** for the bike station distribution), and the following section will introduce the selected data sources and scenarios settings for the baseline and the hypothetical scenarios respectively. This helps to understand the ITHIM modeling process that will be described later.

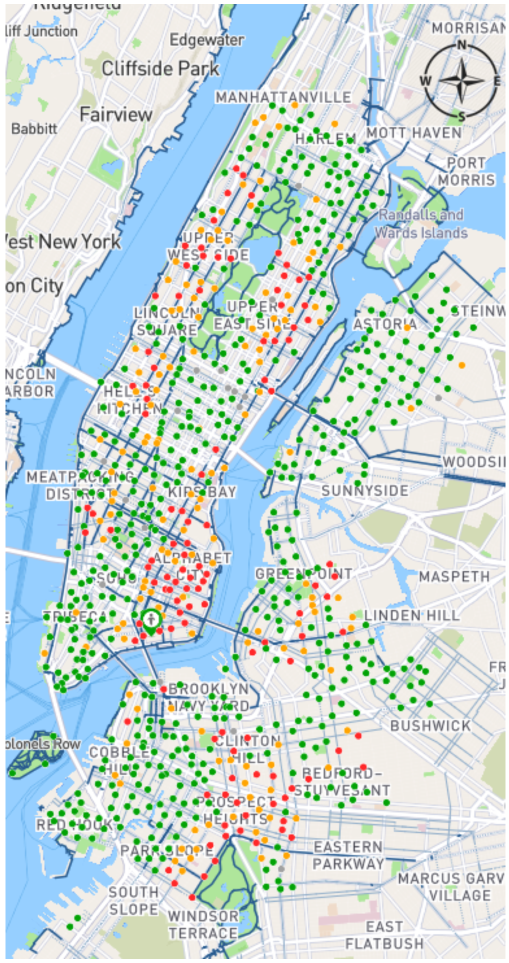


**FIGURE 1 The Citi Bike bike station distribution in 2017**

**Baseline scenario**

*Baseline Health data*

ITHIM takes Burden of Disease (BD) as the measurement of health effects. BD is a concept that used to describe death or loss of health due to diseases or injuries (e.g., traffic accident injuries) for all regions of the world. It is measured in unit of DALYs (*29*) or deaths, and numerically queryable from Global Burden of Disease (GBD) health dataset (*27*) on regional and yearly basis. We select diseases that associated with three aspects (i.e., PA, hazardous air exposure, and RTI) for the health assessment. In order to facilitate the reader's understanding, we will introduce them in each corresponding session below.

We pick BD data of the New York state in 2017 (the most recent available GBD year) as the baseline health data. However, since we focus on NYC area where the Citi Bike bikes are mostly distributed, we refer to the 2017 NYC demographic (*30*) and 2017 NY state demographic data (*31*) to scale down the value of the NY state BD data from statewide into citywide. ITHIM distinguishes different ages and genders for health analysis, so we process the GBD data to match all age (0–4, 5–14, 15–29, 30–44, 45–59, 60–69, 70–79, and greater than 80) and gender (male and female) groups required by the ITHIM framework.

*Physical Activity (PA) data*

The physical activity is quantified as the sum of the travel activities and the non-travel activities in the units of the metabolic equivalent task (MET) hours(*4*). Walking and cycling are classified as the travel activities (*1*). Except for walking and cycling, other activities (e.g., fitness, jogging, or home recreations) are classified as non-travel activities. To maintain the consistency with BD data, we collected 2017 Citi Bike operation data (*14*) and 2017 NYC mobility survey (*32*) to identity Citi Bike cycling trips, other mode trips (e.g., walking, vehicle, and public transit trips(see **Figure 2**), and the number of trips per week for an ordinary citizen. Accordingly, we estimate MET-hours of the travel activities for NYC citizens by these data. On the other hand, because it is difficult to find relevant available non-travel activity data of NYC, we refer to the model settings from another similar metropolitan area health study of the United States: a bay area health study (*24*) for non-travel activity estimation.

For the 2017 New York Citi Bike operation data, there are 12.7 million Citi Bike trip records over different age and gender groups from 1/1/2017 to 12/31/2017. These trip-records are contributed by the so-called “Customer” for 24-hour or 7-day pass users and “Subscriber” for annual members. Because of the price difference between daily pass ($12/day) and annual pass ($14.95/ month with an annual commitment), we assume the local users would choose to have an annual pass, and tourists, on the other hand, would choose a 24-hour or 7-day pass for their economical riding option. We thereby use the trip records of ”subscriber” (90% of the total trips) to proceed with the PA estimation because we are more interested in the benefit or damage on PA that produced by the Citi Bike program to NYC people. Moreover, 2017 NYC mobility survey (*32*) also provides the number of the normal cycling trips (including Citi Bike trips), we, therefore, apply the Citi Bike trips data and the survey data to determine the proportion of trips generated by Citi Bike and the private bike (Not Citi Bike trips).

For diseases of PA aspect, there are many studies (*33–37*) prove that some causes have strong correlation with physical activity and hazardous air exposure. By referring to these study, the ”Preventing Non-Communicable Diseases and Injuries” report(*38*), and some existing health impact evaluation researches (*21*, *24*, *25*, *39*), we select leading death causes: cardiovascular disease (CVD), breast cancer, colon cancer, dementia, depression, diabetes. We use these causes to explore the changes of BD between baseline and hypothetical scenarios.

*Hazardous Air Exposure (PM 2.5) data*

The evaluation of hazardous air exposure impacts requires the knowledge of background air quality information. There are many pollutants that compose hazardous air, such as PM 2.5, CO, NO2, and etc. PM 2.5 is defined as the tiny particles that have two and one-half microns or less in width in the air. The size of PM 2.5 enables this kind of particle a deep travel into the respiratory tract and lungs. This may affect lung functions and result in respiratory diseases, such as asthma and heart diseases(*18*). According to the severe damage to people’s health, we mainly consider PM 2.5 as hazardous air exposure in this study.

There are three PM 2.5 monitoring stations in the area where the Citi Bike is implemented, two of which are in the downtown area and the remaining one is in the uptown area. The PM 2.5 data are records every hour in the unit of micrograms per cubic meter air ($\mu g/m^3$) (*40*). We

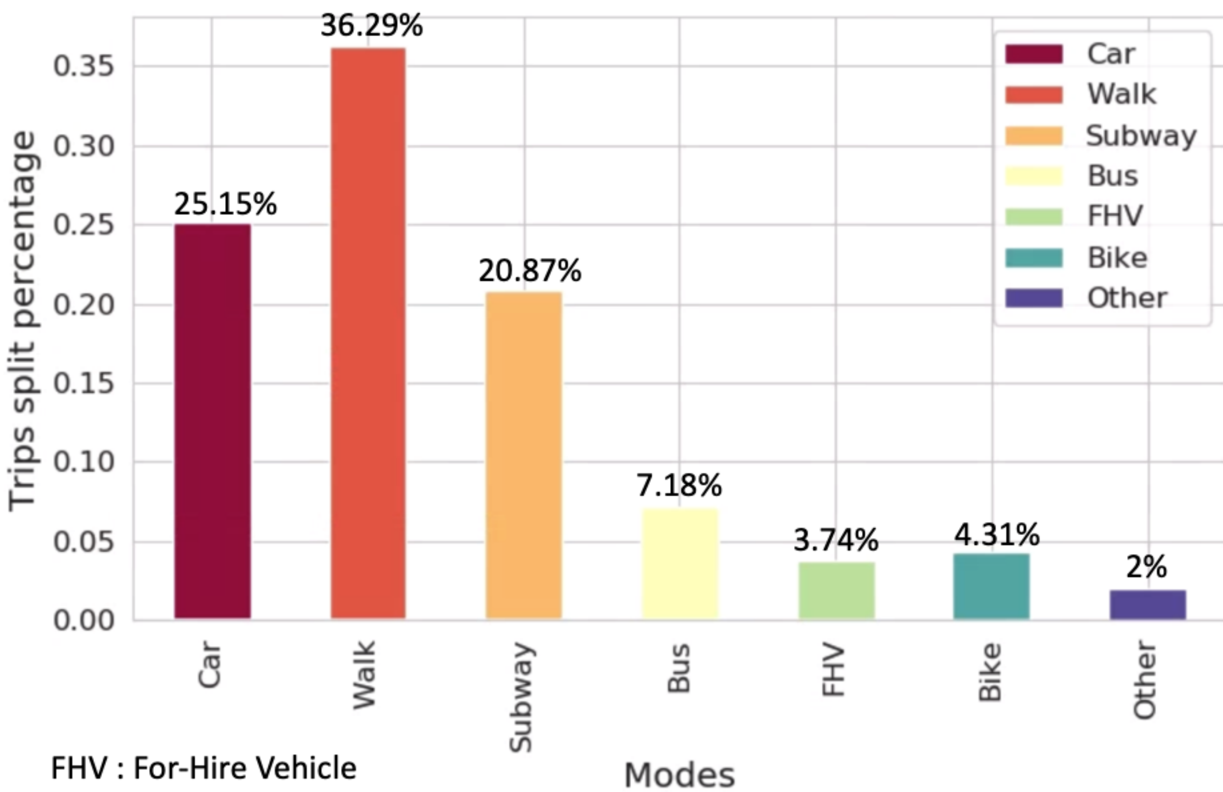


**FIGURE 2 The trips split for baseline scenario**

download the whole year data of 2017, and calculate the average value of the three monitoring detection readings for the health study.

For diseases of PM 2.5 aspect, we also refer to the pieces of literature that are introduced in the PA session and select leading death causes associated with PM 2.5 exposure: Lung Cancer, Cardiovascular Disease(CVD), Acute Respiratory Infection(ARI).

*Road Traffic Injury (RTI) data*

Any on-roads, single- and multi-party collisions that caused injuries or fatalities are defined as RTI. We, therefore, extracted the traffic injury data for the NYC area from (*41*) for the whole year of 2017. The data includes the accident location, contribution of the accident, the types of injury or death, and the number of the injury or death. We, therefore, can derive the strike and victim information from this database.

For the RTI aspect, Different causes from PA and PM 2.5, GBD provides BD information through injuries or fatalities instead of diseases. We, therefore, choose any injuries or fatalities that are associated with Walking accidents, cycling accidents, motorist accidents to investigate the BD changes on RTI.

**Hypothetical scenario**

As mentioned above, we assign the 2017 Citi Bike trips to other modes according to the mode trips breakdown from 2017 NYC mobility survey (*32*) to construct the hypothetical scenario. This setting is to be able to create a scenario that assumes the Citi Bike never been implemented in

NYC in 2017. To have a fair comparison, we keep the health data the same as it of the baseline, but the change of the mode trips distribution would accordingly affect the scenario setting of the three pathways (PA, PM 2.5, and RTI).

First, as following the mode trips breakdown from the 2017 NYC mobility survey, we assign the Citi Bike trips to other travel modes. The hypothetical mode trips distribution, therefore, would be different from that of the baseline scenario. This assignment convert travel activity(e.g., Citi Bike trips) to both non-travel (e.g., motorist and public transit) and travel activity (e.g., walking), and the change thereby has direct impacts on the magnitude of PA. Since bus and subway are operated under fixed capacity and fixed route, we assume the increment of this two ridership would not contribute to any of the three study aspects. Thus, we merge subway and bus with other modes(e.g., skateboarding, segway) into the new "other" mode. On the other hand, we treat For-hire vehicle (FHV) as motorist, since the raising of FHV trips affect every aspect of health study, we therefore merge FHV with Car into the new "car" mode. See **Figure 3** for the hypothetical scenario mode trips split distribution.

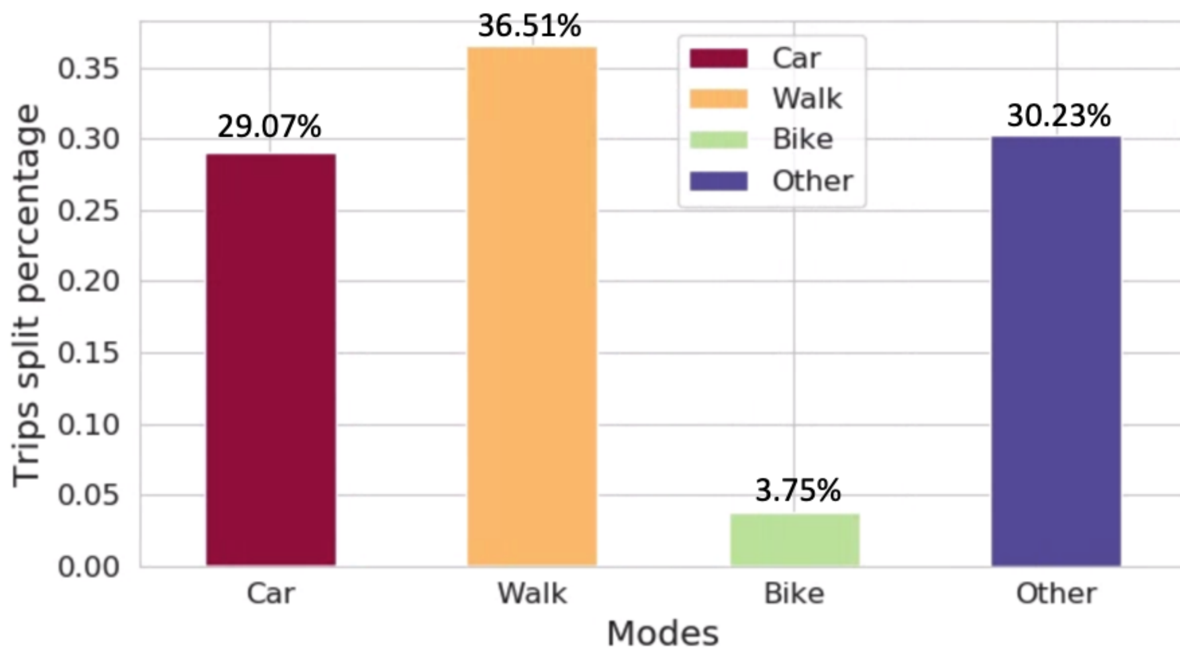


**FIGURE 3 The trips split for hypothetical scenario**

Second, the adjustment of the mode trips' distribution of the hypothetical scenario directly affect the total Vehicle Miles Travel (VMT), and influence the PM 2.5 emission level accordingly. Since ITHIM assumes a high correlation between VMT and vehicle emission concentration, we need to understand the VMT changes to predict the PM 2.5 concentration in the hypothetical scenario.To have the VMT of the hypothetical scenario, we acquire the Citi Bike trips' distance information from the Citi Bike operation data (*14*) and assign the Citi Bike trips to other modes according to the percentage of the corresponding mode trips breakdown from the survey (*32*), the VMT, therefore, equals to the baseline VMT plus the converted "Car" VMT. To explore the PM 2.5 level of the hypothetical scenario, the Bay area health impact study (*24*) built a linear model on PM 2.5 difference and percentage of VMT changes to predict the PM 2.5 concentration of the evaluation year. We refer to this method and collected the urbanized area VMT data in the New York state from Daily Vehicle Miles of Travel dataset (*42*) and PM 2.5 concentration data from Environmental Protection Agency (EPA) (*43*) for NYC from 2000 to 2016, and fit a linear model for the annually PM 2.5 concentration prediction for the hypothetical scenario. Therefore, the hypothetical PM 2.5 concentration can be estimated by applying the hypothetical VMT into the fitted linear model.

Third, the adjustment of the mode trips distribution of the hypothetical scenario affects not only the VMT but also miles travel of other travel modes of the hypothetical scenario. In the RTI analysis, ITHIM assumes that a mode accident rates is highly correlated with the miles-traveled of the corresponding mode. Therefore, we extract the VMT change information in the PM 2.5 emission prediction process, and apply the same method for estimation of walk and Bike, so as to have the miles-traveled of car, walk, bike, and Citi Bike bikes.

**Scenario summary**

The description of the study scenarios is summarized in **Table 1**.

nevertheless, because the ITHIM is not an off-the-shelf software, it requires necessary modeling according to the specific health evaluation objects, proposed scenarios, and parameters that describe regional transportation or health conditions. In this section, we covered the introduction of scenarios' settings for the Citi Bike program health evaluation. The next section will focus on the introduction of the procedure of building the Citi Bike's health evaluation model and the associated health-related parameters according to our proposed scenarios.

**Citi Bike Health Impact Modeling**

In our model, we use death and DALYs as the measurement unit of disease burden (DB). Accordingly, the total change of death or DALYs of the study population is the summation of death or DALYs of every aspect.

$$\Delta BD_{total} = \sum_i PAF_i \cdot BD_i^{(B)},\ BD \in \{death, DALYs\} \tag{2}$$

where $i$ denote the study aspect, i.e., physical activities (PA), PM 2.5 and road traffic injuries (RTI). The superscript $(B)$ represents the baseline scenario.The BD of the PA and PM 2.5 are measured through a serial of diseases that are introduced in the previous section, and the PAF of PA or PM 2.5 aspect, therefore, can be formulated as:

$$PAF_{PA/PM2.5} = 1 - \frac{\int RR(x)P^{(H)}(x)}{\int RR(x)P^{(B)}(x)}, \tag{3}$$

where the superscripts represents baseline (B) and hypothetical (H), $P$ is the population distributions to exposure level $x$ (e.g. $x$ MET-hours of all physical activities), and $RR(x)$ is the relative risk at exposure level $x$. The relative risk (RR) of a disease is defined as the ratio of the probability of exposure-related unhealthy outcomes occurring in the exposed population over the unexposed population (*44*). Relative risks of the selected diseases are based on existing relation $R_{disease}$ between disease and its exposure (*45–50*), described as

$$RR_{i,d} = R_d^{f(x_i)}, \tag{4}$$

**TABLE 1 Description of the Baseline and Hypothetical scenarios**

| Sessions | Data Sources | Causes | Scenario Baseline | Scenario Hypothetical |
|---|---|---|---|---|
| Health Data | 2017 New York City DALYs and Deaths data from Global Burden of Disease (GBD) database;<br>Citi Bike operation data in 2017;<br>2017 New York State demographic data;<br>2017 New York city demographic data. | N/A | To have a fairly comparison, the two comparing scenarios have the same health data. | |
| Physical Activity | New York City Mobility survey in 2017 and Citi Bike operation data in 2017. | Breast cancer, colon cancer, cardiovascular disease (CVD), dementia, depression, diabetes. | Car 28.90%, Walk 36.29%, Bike 4.31%, Others 30.50%. | Car 29.08%, Walk 36.52%, Bike 3.75%, Others 30.65%. |
| Particle Matters 2.5 | PM 2.5 concentration data from EPA and Citi Bike operation data in 2017. | Lung Cancer, Cardiovascular Disease (CVD), Acute Respiratory Infection (ARI) | PM 2.5[a]:<br>15 $\mu g/m^3$ | PM 2.5[a]:<br>15.27 $\mu g/m^3$ |
| Road Traffic Injury | Road traffic crash data in 2017 (NYPD);<br>New York City Mobility survey in 2017;<br>The injury and death data from 2017 GBD database. | Walking crashes, Cycling crashes, Motorists crashes. | VMT[b]:<br>252895 miles | VMT[b]:<br>278562 miles |

[a] Annual average PM 2.5 concentration.
[b] Annual average daily vehicle miles traveled.

where $d$ is disease, $i$ represents the exposure (either PA or PM 2.5). Function $f$ may vary with diseases, with a presumed form of function $f$ is $f(x) = \sqrt{x}$ (*24*, *39*). $x_i$ is the quantity of exposure $i$ (either amount of activity or PM 2.5 index), and the scenario settings provide data to calculate these variables as the model inputs.

The magnitude of PA is quantified in the unit of the metabolic equivalent of task (MET)-hours, where MET of an activity is defined by the ratio of a person's energy consumption during the activity to his or her mass. The unit quantity of MET reflects the intensity, and it varies depending on the type of activity (*51*). In this study, the MET value of cycling is 8 MET, which refer to the values in (*51*), whereas the MET of walking is given by a linear model (*24*) on the walking speed of various age and gender groups, and the average MET value of walking is 3.5 MET.

Different from PA and PM 2.5 that modeled through a serial of diseases, the BD of RTI is modeled through injuries or fatalities of any on-roads, single- and multi-party traffic collisions. Under the ITHIM framework, each accident is caused by both striking and victim sides. For each side, walking, cycling, and motorists are the three modes we mainly consider in the RTI analysis. For accidents with striking mode $u$ and victim mode $v$, the accident rate is modeled (*24*) to be proportional to the square root of multiplication of miles traveled by mode $u$ and by $v$. Assuming the accident rate unchanged across both scenarios, the PAF of RTI part is then calculated by **Equation 5**:

$$PAF_{RTI} = 1 - \left[ \frac{MT_u^{(H)} MT_v^{(H)}}{MT_u^{(B)} MT_v^{(B)}} \right]^{\frac{1}{2}} \tag{5}$$

where $MT_k$ is the total miles traveled of mode $k$. Superscripts $(B)$ and $(H)$ represents the results under baseline and hypothetical scenario, respectively.

**Figure 4** summarizes the overall calculation procedure of the model.

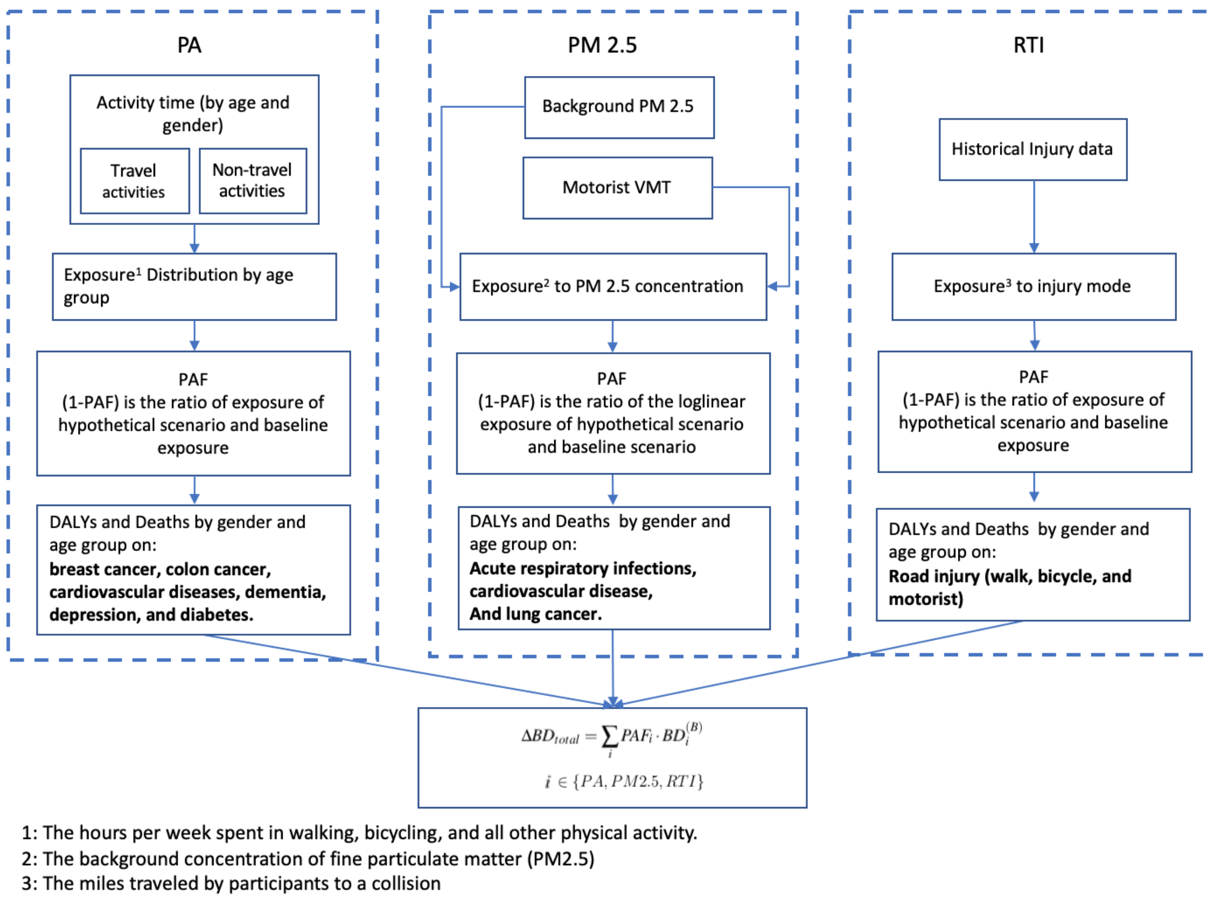


**FIGURE 4 The calculation procedure of the Citi Bike health impact model**

## RESULTS

We found that the implementation of Citi Bike introduces a change of BD (-5744.75 DALYs with -216 deaths), see **Table 2**, **Table 3** and **Figure 5** for details. According to **Equation 3** and **Equation 5**, the PAF is calculated by values of the Baseline scenarios minus values of the hypothetical scenarios. Since DALYs is a measurement that generally describes the number of years lost due to the illness, disability, or early death (*29*), a negative change of BD signifies a health benefit. In this study, the negative change of BD, therefore, indicates that the Citi Bike program produces health benefits to NYC.

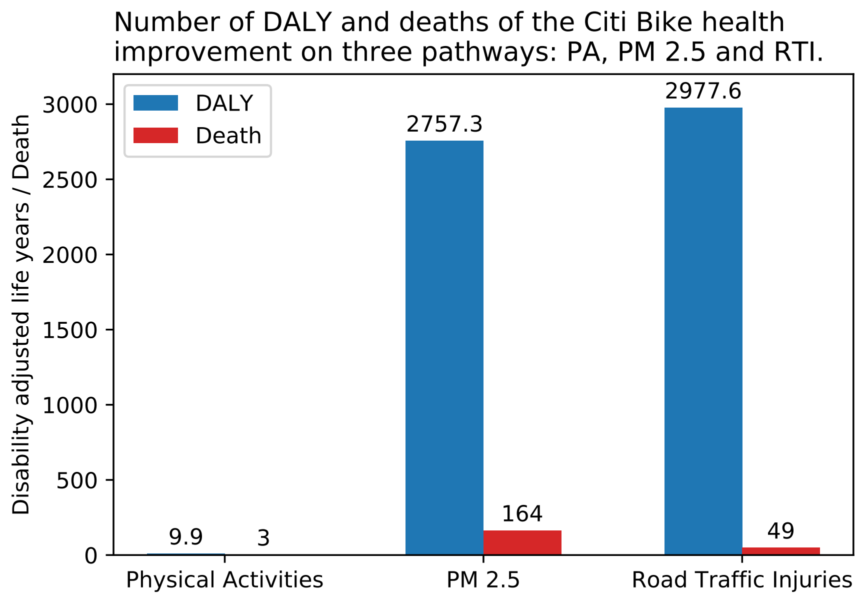


**FIGURE 5 Number of DALY and deaths of the Citi Bike health improvement on three pathways: PA, PM 2.5 and RTI.**

For the PA aspect, there is a change of -9.88 DALYs (with -2.71 deaths) for the population. In particular, there are -0.49 DALYs benefit for breast cancer, 0.05 DALYs for colon cancer, -6.07 DALYs for Cardiovascular disease (CVD), -6.04 DALYs for dementia, 0.21 DALYs for depression, and 2.46 DALYs for diabetes (see **Table 2**). Because the breast cancer morbidity of men is trivial (*52*), we omitted it in our PA analysis. Moreover, only one percent chance that a person could have cancers below 20 years old (*53*) and the DALYs and deaths for these age groups are approximated zeros in the GBD data. Further, by referring to the existing studies (*24*) and (*39*), which only consider the effect of cancers on people who are above 15 years old people, we followed this setting in our PA analysis. Among the six causes we investigated, CVD, Diabetes, and Dementia have the highest negative changes. The outcomes of our analysis are consistent with the results of some existing studies on the health effects of PA (*7*, *54–56*).

For the Hazardous air exposure (PM 2.5) analysis, the daily VMT increases from 252895 (baseline) to 278562 (hypothetical) miles. In other words, the Citi Bike implementation saves 25667 miles VMT per day (9368455 miles VMT in 2017), and produces a small decrease of the PM 2.5 concentration that from $15.27\,\mu g/m^3$ to $15.0\,\mu g/m^3$ in 2017. Among the three diseases we studied, the total benefits for the whole population have a change of -2757.27 DALYs (with -164.13 deaths). CVD, lung cancer, and ARI change DALYs by -2068.67, -681.18, and -7.42 respectively. ARI is a severe infection that prevents normal breathing function and can even result in death (*57*), but because it mostly (approximately 50%) occurs to children whose age is in range of 1 month to 59 months (*57*), and some existing studies (*24*, *39*) applied this metric only to this age group, we thereby followed these settings for ARI analysis in our study. Therefore, the DALYs benefit of ARI is found to be not as significant as CVD and lung cancer in our study.

**TABLE 2 Table of DALYs changes between baseline and hypothetical scenarios**

| Age | Physical Activity | | | | | | | | | | | | PM 2.5 | | | | | | Road Traffic Injuries | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Breast Cancer | | Colon Cancer | | CVD[1] | | Dementia | | Depression | | Diabetes | | CVD[1] | | Lung Cancer | | ARI | | | | |
| | M | F | M | F | M | F | M | F | M | F | M | F | M | F | M | F | M | F | M | F | |
| 0-4 | 0.00 | -0.00 | 0.00 | -0.00 | 0.04 | -0.01 | 0.00 | -0.00 | 0.00 | 0.00 | 0.00 | -0.00 | -1.05 | -1.19 | -0.00 | -0.00 | -3.79 | -3.62 | -20.84 | -19.72 | -50.17 |
| 5-14 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | -1.78 | -2.06 | -0.00 | -0.00 | 0.00 | 0.00 | -51.26 | -37.91 | -92.98 |
| 15-29 | 0.00 | -0.00 | 0.00 | -0.00 | 0.68 | -0.07 | 0.00 | -0.00 | 0.12 | -0.04 | 0.36 | -0.05 | -19.15 | -12.88 | -0.73 | -0.51 | 0.00 | 0.00 | -687.89 | -249.92 | -970.08 |
| 30-44 | 0.00 | -0.03 | 0.01 | -0.00 | 0.88 | -0.14 | 0.00 | -0.00 | 0.08 | -0.04 | 0.56 | -0.12 | -74.04 | -40.55 | -7.59 | -8.08 | 0.00 | 0.00 | -477.77 | -185.52 | -792.36 |
| 45-59 | 0.00 | 0.10 | 0.07 | 0.01 | 5.15 | 0.50 | 0.06 | 0.01 | 0.12 | 0.04 | 3.19 | 0.42 | -267.61 | -135.51 | -92.52 | -79.12 | 0.00 | 0.00 | -408.53 | -201.46 | -1175.08 |
| 60-69 | 0.00 | -0.20 | 0.06 | -0.02 | 4.19 | -1.75 | 0.16 | -0.13 | 0.04 | -0.05 | 2.23 | -1.29 | -293.24 | -166.00 | -128.59 | -101.82 | 0.00 | 0.00 | -206.45 | -123.97 | -1016.84 |
| 70-79 | 0.00 | -0.13 | 0.04 | -0.02 | 3.06 | -2.24 | 0.37 | -0.46 | 0.01 | -0.02 | 1.13 | -0.99 | -253.15 | -199.89 | -95.05 | -86.29 | 0.00 | 0.00 | -105.49 | -83.34 | -822.47 |
| > 80 | -0.00 | -0.23 | -0.04 | -0.05 | -6.13 | -10.24 | -1.64 | -4.42 | -0.02 | -0.04 | -1.25 | -1.74 | -252.27 | -348.29 | -39.69 | -41.19 | 0.00 | 0.00 | -55.85 | -61.68 | -824.76 |
| Total | 0.01 | -0.50 | 0.14 | -0.08 | 7.88 | -13.94 | -1.05 | -4.99 | 0.36 | -0.15 | 6.22 | -3.76 | -1162.29 | -906.38 | -364.18 | -317.01 | -3.79 | -3.62 | -2014.08 | -963.52 | -5744.75 |
| | -0.49 | | 0.05 | | -6.07 | | -6.04 | | 0.21 | | 2.46 | | -2068.67 | | -681.18 | | -7.42 | | -2977.60 | | |

M=Male, F=Female, CVD=Cardiovascular disease, ARI=Acute respiratory infections.
DALYs are computed by baseline minus hypothetical scenario results. Negative values means baseline (with-Citibike) is better.
1. CVD is affected by both physical activity and PM 2.5 parts.

**TABLE 3 Table of death changes between baseline and hypothetical scenarios**

| Age | Physical Activity | | | | | | | | | | | | PM 2.5 | | | | | | Road Traffic Injuries | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Breast Cancer | | Colon Cancer | | CVD[1] | | Dementia | | Depression | | Diabetes | | CVD[1] | | Lung Cancer | | ARI | | | | |
| | M | F | M | F | M | F | M | F | M | F | M | F | M | F | M | F | M | F | M | F | |
| 0-4 | 0.00 | -0.00 | 0.00 | -0.00 | 0.00 | -0.00 | 0.00 | -0.00 | 0.00 | 0.00 | 0.00 | -0.00 | -0.01 | -0.01 | -0.00 | -0.00 | -0.01 | -0.01 | -0.24 | -0.23 | -0.51 |
| 5-14 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | -0.01 | -0.01 | -0.00 | -0.00 | 0.00 | 0.00 | -0.55 | -0.42 | -1.01 |
| 15-29 | 0.00 | -0.00 | 0.00 | -0.00 | 0.01 | -0.00 | 0.00 | -0.00 | 0.00 | -0.00 | 0.00 | -0.00 | -0.26 | -0.14 | -0.01 | -0.01 | 0.00 | 0.00 | -9.66 | -3.25 | -13.32 |
| 30-44 | 0.00 | -0.00 | 0.00 | -0.00 | 0.02 | -0.00 | 0.00 | -0.00 | 0.00 | -0.00 | 0.00 | -0.00 | -1.35 | -0.62 | -0.16 | -0.17 | 0.00 | 0.00 | -6.96 | -2.21 | -11.46 |
| 45-59 | 0.00 | 0.00 | 0.00 | 0.00 | 0.13 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.03 | 0.00 | -6.91 | -3.10 | -2.69 | -2.28 | 0.00 | 0.00 | -6.56 | -2.60 | -23.96 |
| 60-69 | 0.00 | -0.01 | 0.00 | -0.00 | 0.15 | -0.06 | 0.01 | -0.00 | 0.00 | -0.00 | 0.03 | -0.01 | -10.36 | -5.38 | -5.19 | -4.12 | 0.00 | 0.00 | -4.04 | -2.02 | -31.00 |
| 70-79 | 0.00 | -0.01 | 0.00 | -0.00 | 0.16 | -0.11 | 0.02 | -0.03 | 0.00 | -0.00 | 0.02 | -0.02 | -13.31 | -10.09 | -5.74 | -5.24 | 0.00 | 0.00 | -2.85 | -1.98 | -39.17 |
| $>80$ | -0.00 | -0.02 | -0.00 | -0.01 | -0.73 | -1.38 | -0.19 | -0.59 | -0.00 | -0.00 | -0.05 | -0.08 | -30.23 | -47.09 | -4.61 | -4.99 | 0.00 | 0.00 | -2.79 | -2.62 | -95.39 |
| Total | 0.00 | -0.04 | 0.00 | -0.01 | -0.27 | -1.55 | -0.17 | -0.62 | 0.00 | 0.00 | 0.03 | -0.10 | -62.45 | -66.44 | -18.40 | -16.81 | -0.01 | -0.01 | -33.66 | -15.33 | -215.83 |
| | -0.04 | | -0.01 | | -1.81 | | -0.78 | | 0.00 | | -0.08 | | -128.89 | | -35.21 | | -0.03 | | -48.99 | | |

M=Male, F=Female, CVD=Cardiovascular disease, ARI=Acute respiratory infections.
DALYs are computed by baseline minus hypothetical scenario results. Negative values means baseline (with-Citibike) is better.
1. CVD is affected by both physical activity and PM 2.5 parts.

For the RTI aspect, Citi Bike obtains -2977.60 DALYs (with -48.99 deaths) for the whole population. It is noted that the change of trips from hypothetical to baseline scenarios are trips that comes from the other modes to the Citi Bike mode, and the source of Citi Bike trips are dominated by walking trips (36.3%) and motorist trips (25.2%). Thus, these shifted trips cause a larger amount of walking and motorist accidents reduction than the amount of cycling accidents increase, which xplains how Citi Bike brings benefits to the RTI.

## DISCUSSION

### Discussion on results

As the evaluation result has shown, Citi Bike plays a positive role in improving public health of NYC. Although the magnitude of change (-5744.75 DALYs) in the overall BD (the summation of the BD from three aspects) is not very big for the 2.7 million people (0.0021 DALYs per person) in the study area in 2017, the implementation saves 216 lives. Further, consider that there are only 136 thousand Citi Bike users who produce these health benefits, the health benefit created by each user is nonnegligible. Compared the Citi Bike's health impact (-2112 DALYs per million people) with some results from existing health impact studies:

- In the California Bay Area low carbon and high physical activity goal evaluation, there are -5169 DALYs per million people health benefit. (*24*)
- In the London Santanders Bike sharing program, there are -1901 DALYs per million benefit. (*25*)
- In the 2030 Walking and Cycling project for England and Wales, there are -3774 DALYs per million benefit. (*39*)
- In the carbon reductions of preferred scenarios of California regional transportation plans, there are -444 DALYs per million benefit. (*26*)

The implementation of Citi Bike can be deemed as a successful case of an attempt on improving public health improvement. In particular, NYC has already maintained a healthy travel pattern that 36.3% of trips in New York in 2017 is accomplished by walking. This fact further illustrates the Citi Bike program has a significant contribution to public health, considering the small percentage of trips that been made by Citi Bike. Meanwhile, this fact may also explain why Citi Bike has limited health benefits from PA facet. Although the direct physical health effect of using Citi Bike is mild, the reduction in VMT and PM 2.5 produces considerable health benefits. Notably, only 0.27 $\mu g/m^3$ reduction of annual average PM 2.5 cut down 2757.3 DALYs and 164 deaths. This change shows that the implementation of Citi Bike has perceptible potentials, and it is also worth studying in-depth.

### Sensitivity study on the market share of Citi Bike

To explore these potentials, we perform a sensitivity study on the Citi Bike market share below. Due to the lack of travel mode choice model or travel behavior survey, it is hard to predict the traveler's mode choices on the changes of Citi Bike market share from specific transportation policies, and accordingly, estimate the health effect results. However, we can still infer the marginal effect of increasing Citi bike shares on the overall health if we assume that Citi bike takes away a small portion of other traffic modes' market shares proportionally.

Since the change of the number of trips in "other" mode does not affect any of the three

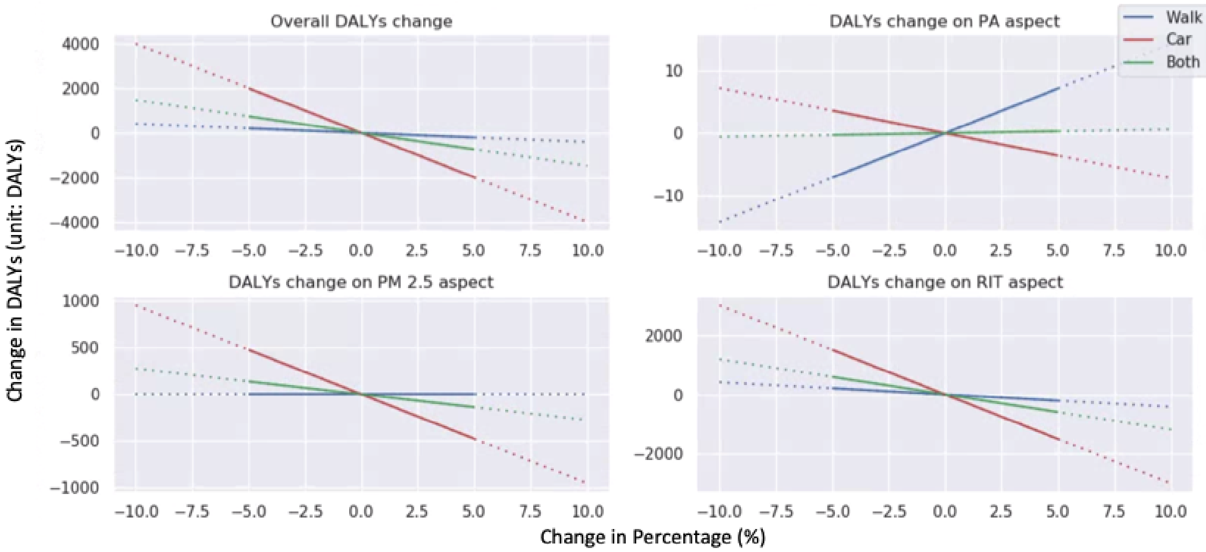


**FIGURE 6 Sensitive analysis on Citi Bike, walk, and car market changes from three pathways: PA, PM 2.5 and RTI.**

study aspects (PA, PM 2.5, and RTI) in the model, we will adjust the mode split percentage of Citi Bike, walk, and car in this analysis. Further, we are interested in the health consequences of changing Citi Bike market share, we thus propose three study groups: Citi Bike versus walk, Citi Bike versus car, and Citi Bike versus walk and car. We adjust the market share of the Citi Bike from -5% to 5% with 1% increment in each group. For example, for the Citi Bike versus walk group at 5% change, we increase the existing Citi Bike trips by 5%, and subtract the associated walking trips due to the increased bicycle trips based upon the mode trips breakdown from 2017 NYC mobility survey (*32*). By following the adjustment of each group, we can observe the DALYs changes.

As the **Figure 6** has shown, the curve that shifting trips from car to Citi Bike (car curve) drops fast. Then, the curve that shifting trips from both (wc curve) drops the second fastest, and the curve of shifting trips from walk (walk curve) descends the slowest. With a 1% increase on Citi Bike trips, the car curve has -393 DALYS, the walk curve has -35 DALYs, and the wc curve has -142 DALYs benefits. Further, as the market share of the Citi Bike increases, the advantages also increase. At +5% change, the car curve has -1990 DALYs averted, the walk is -199 DALYs, and the wc curve has -731 DALYs. This big advantage can be explained as the trips shifted from car mainly changes the VMT and affects the PM 2.5 concentration accordingly, but no VMT is changed when shift trips from walk to the Citi Bike use. Therefore, policies can achieve relatively good results if it can shift trips from the car travel to the Citi Bike travel only.

It is noted that in the PA aspect, the walk curve slopes upward. The more added trips shifting from walk makes the DALYs changes from PA aspect worse, although walk is also a type of active transportation providing incidental exercises. The MET of walk (3.75 MET on average) is smaller than that of Cycling (8 MET), walking however may spend more time than cycling on the same length trip, so the total amount of exercise of walk may happen to be higher than that of cycling. Therefore, if the trips only shifted from walk would make the DALYs worse in the PA aspect but the magnitude is slim. To sum up, the car curve has dominated advantages in three aspects and could benefit public health the most. Therefore, any policies are advocated if they promote motorists or riders from For-Hire Vehicles (FHV) to use Citi Bike. However, with concerns on the effect of policy implementation, it is necessary to make an effort to avoid attracting people who originally traveled by walk to travel by Citi Bike. Because switching from walking to Citi bikes would not help to improve the health benefit from PM and RTI aspects, and lead to adverse health effects of PA.

**Strength and limitation**

This study evaluates an existing bike sharing system: the NYC Citi Bike program. The proposed modified ITHIM is a ready-to-use health impact assessment model for any existing bike-sharing program. Nonetheless, there are also limitations that could be improved in the evaluation to make the evaluation outcome more precise. First of all, according to the lack of travel mode choice (normal bike or bike sharing involved) model in NYC, We apply the mode trips breakdown from the 2017 NYC mobility survey to construct the hypothetical mode trips distribution instead. This handling method allows us to have meaningful estimation and prediction. However, it is desired to have the travel mode choice data or model to have insights on the travelers' decisions while the market share of the Citi Bike changes. Second, with the current ITHIM, the performance of PM 2.5 highly relies on the VMT changes. Some studies explore correlation between PM 2.5 concentration and the climate change (*58*, *59*) or economic change (*60*, *61*). These factors can also be integrated into ITHIM in order to have a more precise health impact study from the PM 2.5 aspect since the health outcomes of PM 2.5 exposure is susceptible to the PM 2.5 concentration changes. Third, as mentioned in **Equation 5**, ITHIM assumes the accident rate unchanged across all the proposed scenarios. This is a feasible method but may cause estimation bias. The prediction can be more accurate if there is a separate model to describe the relation between the accident rate and mode split.

## CONCLUSIONS

In this paper, we build a modified ITHIM based on the proposed Citi Bike study scenarios and utilizes this model to evaluate the health effect of the Citi Bike program in 2017. we find out that the implementation of Citi Bike produces a significant health benefit (-5744.75 DALYs changes in 2017), which indicates that the Citi Bike plays a positive role in improving the population health of NYC. By comparing with some existing studies that evaluates public health promotion strategies, Citi Bike can be deemed as a successful case. Through the analysis of PA, PM 2.5, and RTI three aspects, the affection of the Citi Bike program on PA is beneficial but moderate. This fact could be the reason that NYC has already maintained a healthy travel pattern that 35.4% of trips were accomplished by walking in 2017. However, the implementation of Citi Bike contributes -2757.3 DALYs and -2977.6 DALYs health benefits in PM 2.5 and RTI aspects respectively. Especially, from the outcome of PM 2.5 study, only $0.25\,\mu g/m^3$ of PM 2.5 concentration reduction results in a change of -22757.3 DALYs. Undoubtedly, Citi Bike has a considerable potential to improve population health by reducing NYC air pollution. The role of policymakers in facilitating such potential advancement is critical (*62*, *63*). We thus conduct a sensitivity study on the possible policy outcomes by adjusting the mode split distribution. The result suggests that attracting motorists or car riders to use Citi Bike can benefit public health the most, but also requires some necessary measures to avoid attracting travelers from walk.

The modified ITHIM is helpful for the evaluation of the Citi Bike bike sharing program, and can be extended to the applications of other bike sharing program health impact evaluation. However, there are still some places that can be further improved to have a more accurate the prediction. For example, first, adding the travel mode choice model to predict the traveler's choice while the market share of Citi Bike is changed in the hypothetical scenario. Second, the PM 2.5 part of the ITHIM could introduce climate or economic changes as factors in predicting the hypothetical PM 2.5 concentration. Third, adding a separate model to describe the relationship between the accident rate and mode split. Improving these limitations are interesting and considerable in the future work for more accurate quantification. All in all, this study applies the modified ITHIM to assess the health effects of an existing transportation facility, and provide insights for the Citi Bike operation or planning according to the potential benefits analysis. However, conventional transportation planning does not pay enough attention to the health aspects of transportation. We hope that this study provides another motivating example for planners to include public health metrics in today's transportation planning process.

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