CAIT-UTC-NC59

Development of Vehicle Fleet Mix Forecast Models for Life Cycle Cost Forecast for Tunnel Ventilation Systems

FINAL REPORT
August 2020

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TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No. CAIT-UTC-NC59	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Development of Vehicle Fleet Mix Forecast Models for Life Cycle Cost Forecast for Tunnel Ventilation Systems		5. Report Date August 2020 6. Performing Organization Code CAIT/Rutgers University
7. Author(s) Weihong "Grace" Guo, Mohsen A. Jafari, Ghazal Eskandani, Shenghan Guo, and Hooman Parvardeh		8. Performing Organization Report No. CAIT-UTC-NC59
9. Performing Organization Name and Address Center for Advanced Infrastructure and Transportation Rutgers, The State University of New Jersey 100 Brett Road, Piscataway, NJ 08854		10. Work Unit No. 11. Contract or Grant No. DTRT13-G-UTC28
12. Sponsoring Agency Name and Address Center for Advanced Infrastructure and Transportation Rutgers, The State University of New Jersey 100 Brett Road Piscataway, NJ 08854		13. Type of Report and Period Covered Final Report 9/1/2018 – 6/30/2019 14. Sponsoring Agency Code
15. Supplementary Notes U.S. Department of Transportation/OST-R 1200 New Jersey Avenue, SE Washington, DC 20590-0001		

16. Abstract

Tunnel ventilation systems must be able to provide adequate air quality during normal operation in addition to supporting self-evacuation and rescue efforts during emergency incidents. To maintain low or negligible levels of tailpipe emission gases during normal operation, the operational cost of tunnel ventilation systems can be high. As the vehicle emission technology advances rapidly, the vehicle fleet is constantly being renewed. Thus, realistic and practical forecasting of life cycle cost of tunnel ventilation systems must include models that incorporate the ever-changing fleet mix of zero emission, hybrid and combustion vehicles.

The objective of this research project is to provide tunnel ventilation systems owners and the Port Authority of NY & NJ with a vehicle fleet mix forecast model that will:

(1) Enable realistic and practical long-term forecasts of the life cycle costs of tunnel ventilation systems;

(2) Provide recommendations to assist optimizing the performance of tunnel ventilation systems during normal operation and emergency incidents;

(3) Provide a tool to assist in more realistic and practical asset life cycle cost analysis.

17. Key Words Vehicle fleet mix, Forecast, Exhaust emissions, Tunnel, Ventilation systems, Life cycle cost		18. Distribution Statement	
19. Security Classification (of this report) Unclassified	20. Security Classification (of this page) Unclassified	21. No. of Pages 24	22. Price

Form DOT F 1700.7 (8-69)

Acknowledgments

This project would not have been possible without the support from the Rutgers Center for Advanced Infrastructure and Transportation. We would like to thank Dr. Ali Maher, Director of CAIT center and Dr. Patrick Szary, Associate Director of CAIT center for their support. We also would like to thank Mr. Robert Kumapley of The Port Authority of New York and New Jersey for providing the data and domain knowledge. We also would like to acknowledge Qi Tian for his help on conducting many of the data analysis in this study. Finally, we appreciate the support from many CAIT staff members.

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1. DESCRIPTION OF THE PROBLEM

1.1 Background

Tunnel ventilation systems must be able to provide adequate air quality during normal operation in addition to supporting self-evacuation and rescue efforts during emergency incidents. To maintain low or negligible levels of tailpipe emission gases during normal operation, the operational cost of tunnel ventilation systems can be high. As the vehicle emission technology advances rapidly, the vehicle fleet is constantly being renewed. Historical data shown in Figure 1 indicate that since 2004, CO_2 emissions have decreased by 102 g/mile or 22%, and fuel economy has increase by 5.4 mpg or 28% (Source: EPA, “Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends Report”, 2018.) Thus, realistic and practical forecasting of life cycle cost of tunnel ventilation systems must include models that incorporate the ever-changing fleet mix of zero emission, hybrid and combustion vehicles.

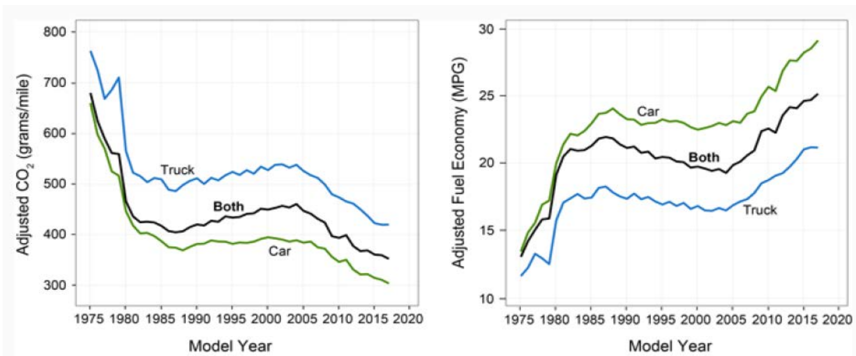


Figure 1. Historical data of CO_2 emission and fuel economy

The vehicle fleet consists of vehicles of different types, different power-train technologies, and different fuel types, as shown in Figure 2. Numerous factors such as fuel economy, vehicle weight, vehicle power, and transformative technology in automotive industry are continuously being improved in such a way that reduces the emission level generated by vehicles. Forecasting the share of different type of vehicles in tunnel transportation is critical in determining the right performance capacity for ventilation system.

Vehicle type	Power-train	Fuel type
• Passengers Car	• Internal combustion engine (ICE)	• Diesel
• Motorcycles	• Full hybrid electric vehicle (HEV)	• Gasoline
• Buses	• Plug-in hybrid electric vehicle (PHEV)	• Natural Gas
• Light Duty Vehicle	• Range extended electric vehicle (REEV)	• Hydrogen
• Heavy Duty Vehicle	• Battery electric vehicle (BEV)	
	• Fuel cell electric vehicle (FCEV)	

Figure 2. Vehicle classification

1.2 Objective

The objective of this research project is to provide tunnel ventilation systems owners and the Port Authority of NY & NJ with a vehicle fleet mix forecast model that will:

(1) Enable realistic and practical long-term forecasts of the life cycle costs of tunnel ventilation systems;
(2) Provide recommendations to assist optimizing the performance of tunnel ventilation systems during normal operation and emergency incidents;
(3) Provide a tool to assist in more realistic and practical asset life cycle cost analysis.

2. APPROACH

Our approach consists of the development of two models. First, the vehicle fleet mix forecast model is developed by integrating traditional time series forecasting methods with electric vehicle (EV) adoption forecasting. Multiple forecast models are developed for different EV adoption scenarios and different forecasting timeframes. Model parameters are estimated using tunnel traffic data. Forecasting vehicle fleet mix helps us to: (1) assess the future capacity needs of the ventilation system, (2) determine the required capacity and MR&R (Maintenance, Rehabilitation and Replacement) process to improve the ventilation system performance and reduce the operation cost, and (3) estimate the required time frame to make improvement in the ventilation system.

Second, the life cycle cost model is developed based on existing models but tailored to the interest of tunnel owners in the NY/NJ area. The life cycle cost, including operating and replacement costs, are analyzed considering the ever-changing vehicle fleet mix. The life cycle cost analysis helps us to monitor and maintain the system condition with respect to the limited financial resources. Two types of information are utilized: information on current condition, provided by facility inspection, and information on cost associated with MR&R. The proposed model has the condition state of the system as a function of various factors including emission level, age, environmental condition, and historical MR&R.

The workplan is designed as follows to consist 7 tasks.

Task 1 – Literature review of relevant models. Review the forecasting methods for life cycle cost of tunnel ventilation systems. Review the forecasting methods for vehicle fleet mix. Review vehicle emission technology advancements, vehicle fleet information, and emission laws.

Task 2 – Review of the Port Authority's current cost model and asset management report. Interview tunnel ventilation systems owners as necessary.

Task 3 – Data collection and processing. Data on emission technology, EV sales, census, demographics, etc. have been collected from various sources. Port Authority (PA) provided E-Zpass summary and NY Green Pass data. All PA's data are processed to correlate with EV data. Empirical data models have been built based on historical data.

Task 4 – Development of vehicle fleet mix forecasting models. Theoretical models have been developed to forecast vehicle fleet mix, considering different EV adoption scenarios. An interactive dashboard visualization has been developed.

Task 5 – Testing and calibration of vehicle mix forecast models. The developed vehicle fleet mix forecast models have been tested and calibrated using recent tunnel traffic data.

Task 6 – Application and impact assessment of models. The vehicle fleet mix forecast model is incorporated into life cycle cost forecasts for tunnel ventilation systems. Models have been built to forecast CO emission. Emission output is visualized on Dashboard. Life cycle cost analysis has been conducted, comparing the cost before and after EV consideration.

Task 7 – Conclusion and recommendations.

3. METHODOLOGY

3.1 Forecasting Vehicle Fleet Mix and CO Emission

3.1.1 Method Overview

Figure 3 illustrates the major steps in forecasting vehicle fleet mix and CO emission. We focus on the Holland Tunnel. To forecast vehicle fleet mix, we need to forecast the EV traffic volume in Holland Tunnel (HT) and the total traffic volume in HT. To forecast the EV traffic volume in HT, we take the historical data of EV adoption as input. We then forecast the NY & NJ EV adoption by studying regulations and inferring from national level EV adoption trends. Since HT is only one of the tunnels/bridges connecting NY & NJ, we multiply the forecasted EV adoption by a ratio to obtain the EV traffic volume in HT. To forecast the total traffic volume in HT, we consider historical HT E-ZPass data. The mix forecast is then projected into CO emission by forecasting the CO emission factor.

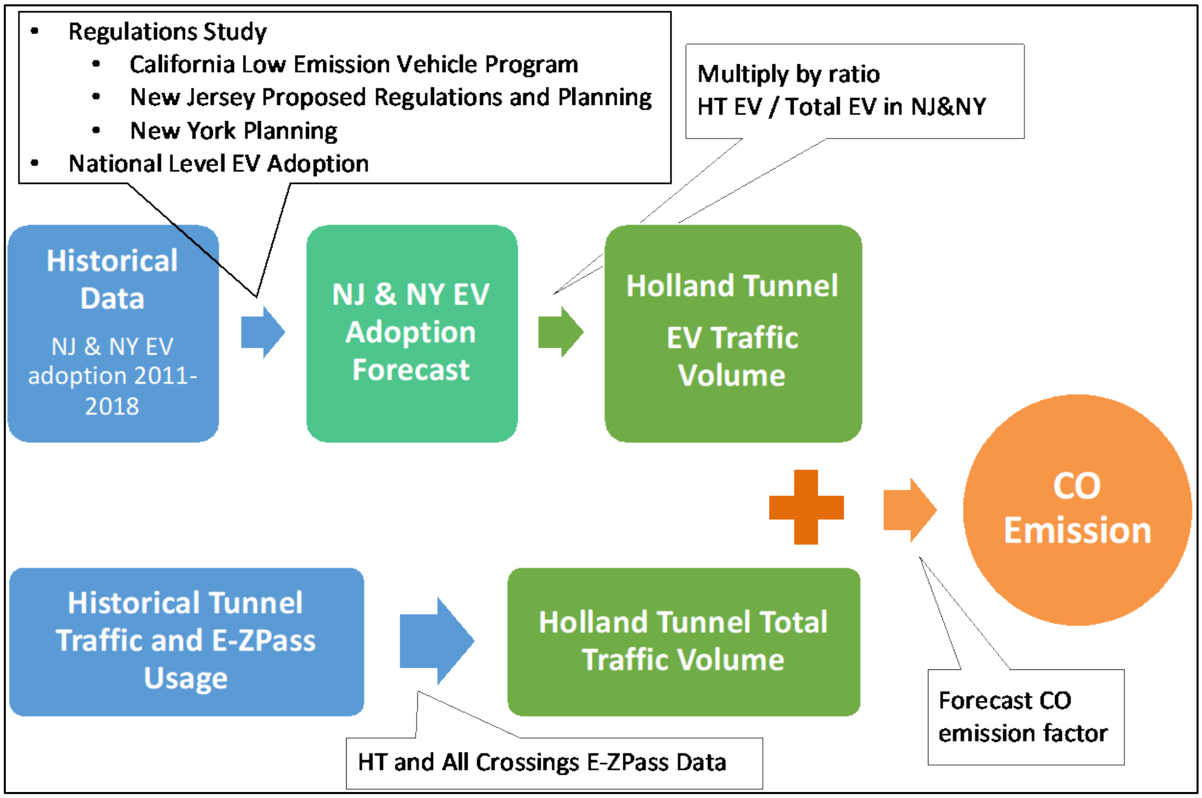


Figure 3. Method overview of forecasting vehicle fleet mix and CO emission

3.1.2 Forecasting EV Traffic Volume in Holland Tunnel

Available historical data for New Jersey and New York suggest increasing EV adoption, as shown in Figure 4 (data sources: DriveClean.NJ.Gov and NYSERDA.NY.GOV).

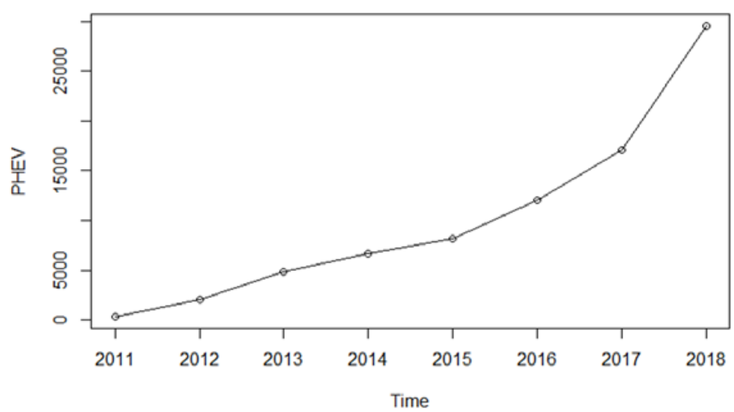


Figure 4. Historical data of PHEV adoption in NJ & NY

To forecast the EV demand in NJ & NY, we refer to 3 regulations and the national adoption trend.

First, California is the leading state in promoting zero to low emission vehicles. New York and New Jersey are already committed to implementing the California Low Emission Vehicle Program. Both states set goals and incentives to increase the PEV sales.

Second, the New Jersey Proposed Regulations and Planning state the following targets:

- By 2021:
  - o 600 fast charging for public
  - o 1000 level 2 chargers should be available
- By Dec 2025:
  - o 25% of multi-family residential properties shall equipped with chargers
  - o 25% of overnight lodging should equipped with EV charging stations
- By Dec 2030:
  - o 50% of multifamily residential properties and 50% of overnight lodging shall equipped with chargers
- By Dec 2035:
  - o 50% of all places of employment shall provide parking with EV charging

Third, the New York Planning regulations give the following guidelines:

- Increasing infrastructure planning and investments and encourage fleet ZEV deployment to create a stable ZEV market
- Reforming regulations at the State and local level to facilitate EV charging
- Educating consumers and policymakers about the benefits of EVs
- Using the State fleet to test advanced EV technologies and demonstrating their benefits to the public

All the current states regulations and intentions may lead adoption rates in both states converge to the National Level rate. National data has been studied to estimate the monthly adoption rate. We apply the National Level adoption rate on the NJ and NY market potential to forecast number of PEV up to 2048, under different scenarios: Conservative and Aggressive, as shown in Figure 5.

The Bass diffusion model is used to estimate rate of adoptions by innovators (early adopters) and imitators (those who wait to learn about market reaction to the product). In the conservative EV adoption scenario, we assume that each household adopts only one PEV, and we only consider the number of highly educated single owned residential properties and multi-family rental properties that have been occupied with highly educated residents (assuming that highly educated people are more likely to adopt EV early). In the aggressive EV adoption scenario, we follow the NJ Assembly's suggestion on the number of EVs to be adopted by 2035, and we estimate the NY EV number by multiplying the NY conservative potential by a percentage increase. Further, we add a Moderate adoption scenario to reflect an EV adoption level between the Conservative and Aggressive scenarios.

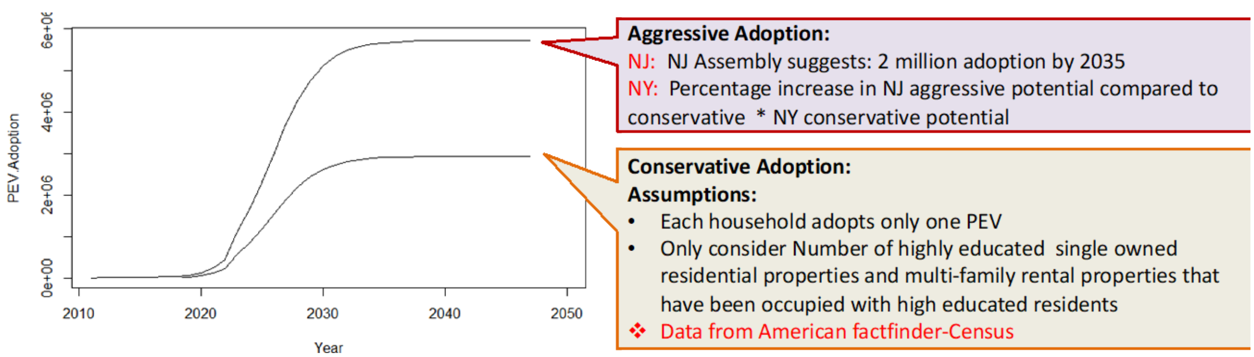


Figure 5. Aggressive and conservative EV adoption in NJ & NY

The number of PEV in Holland Tunnel can be estimated from the forecasted EV adoption for NJ & NJ. We need to estimate the ratio of the registered PEV that pass through the Tunnel to the total of registered PEV. The 2017 NY Green Pass data are used to estimate the tunnel monthly ratio of total registered EV that pass through the tunnel:

$$\text{Average monthly ratio} = \frac{\text{Monthly Average of Green Pass in Tunnel}}{\text{Total Registered PEV in Both States}}. \quad (1)$$

Figure 6 shows the forecasted monthly average EV in Holland Tunnel.

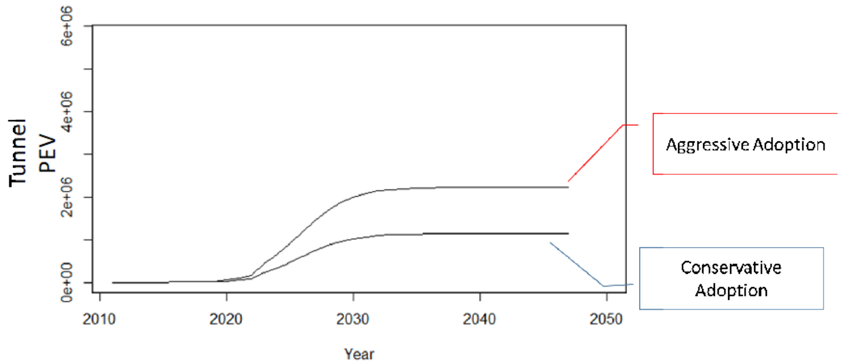


Figure 6. Forecast of EV traffic volume in Holland Tunnel

3.1.3 Forecasting Total Traffic Volume in Holland Tunnel

We develop an ARIMA seasonal model to forecast traffic volume in Holland Tunnel. The ARIMA time series model forecasts the future traffic volume based entirely on its historical trend. The modeling of seasonality is driven by the repeated traffic patterns seen in historical data. The ARIMA model implements differencing to reach unchanged mean and variance over time to effectively handle the observed randomness in mean and variance of data. We implemented data transformation to meet the normality assumption requirement of ARIMA. Two ARIMA models are developed: one for short-term forecast and long-term traffic forecast. The rationale is that the short-term traffic is more dependent on on-going construction works, but the long-term traffic reflects more of the stable traffic behavior.

Model HT (short-term forecast): The ARIMA model for short-term traffic volume forecast is developed based on Holland Tunnel E-ZPass data. Raw data are the monthly E-ZPass Holland Tunnel traffic volume and E-ZPass Usage (%) from 2011 to 2018. We estimate short-term HT traffic volume by

$$\text{HT Traffic Volume} = 2 * \text{Holland Tunnel E-ZPass} / \text{E-ZPass Usage\%}. \tag{2}$$

The horizon of short-term forecasting is 5 years (2019-2023).

Model A (long-term forecast): The ARIMA model for long-term traffic volume forecast is developed based on All Crossings (all tunnels and bridges connecting NY and NJ) E-ZPass data. Raw data are the monthly EZ-Pass Holland Tunnel traffic volume, All-crossing traffic volume, and EZ-Pass percentage from 2011 to 2018. We estimate long-term HT traffic volume by

$$\text{HT Traffic Volume} = 2 * \text{All Crossings E-ZPass} * \text{AVG(HT/All)\%} / \text{E-ZPass Usage\%}. \tag{3}$$

The horizon of long-term forecasting is 30 years (2019-2048).

3.1.4 Forecasting CO Emission in Holland Tunnel

The relationship between EV traffic volume and CO emission depends on a CO emission factor (gram/mile), and this factor needs to be forecasted as well. We take the following three data sources to help us estimate the CO emission factor.

- (D1) Fuel efficiency (mile/gallon) forecast for automobile, truck and bus from EIA (2016-2050) https://www.eia.gov/outlooks/aeo/data/browser/#/?id=7-AEO2018&region=0-0&cases=ref2018&start=2016&end=2050&f=A&linechart=ref2018-d121317a.5-7-AEO2018&sourcekey=1
- (D2) CO2 emission per gallon (8887 gram/gallon) from EPA https://www.epa.gov/greenvehicles/greenhouse-gas-emissions-typical-passenger-vehicle
- (D3) Emission factors for CO and CO_2 (gram/mile) of automobile, truck and bus (2016 & 2036) http://www.dot.ca.gov/hq/tpp/offices/eab/LCBC_Analysis_Model.html

The estimation consists of 3 steps. First, data sources (D1) and (D2) are used together to calculate the CO_2 emission factor (gram/mile), as shown in Figure 7:

$$CO_2 \text{ emission factor (gram/mile)} = 8887 \text{ (gram/gallon)/ fuel efficiency (mile/gallon).} \tag{4}$$

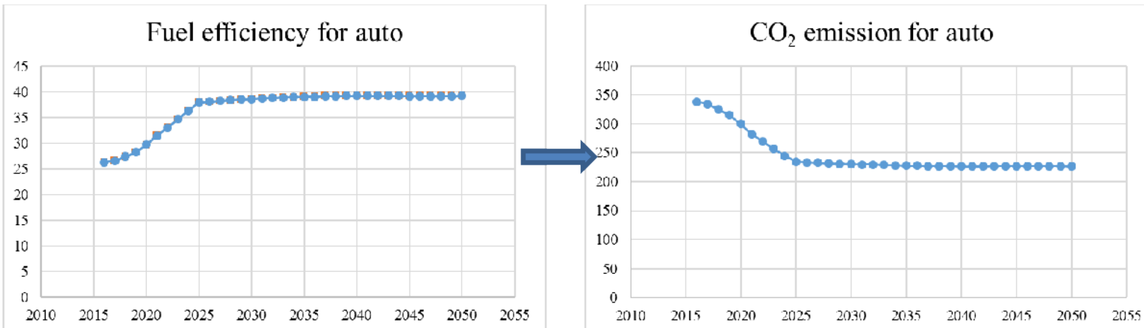


Figure 7. Estimating CO_2 emission factor from fuel efficiency

Second, we find the relationship between CO emission factor and CO_2 emission factor according to data source (D3). It can be seen from Figure 8 that there is a positive linear relationship between CO emission factor and CO_2 emission factor.

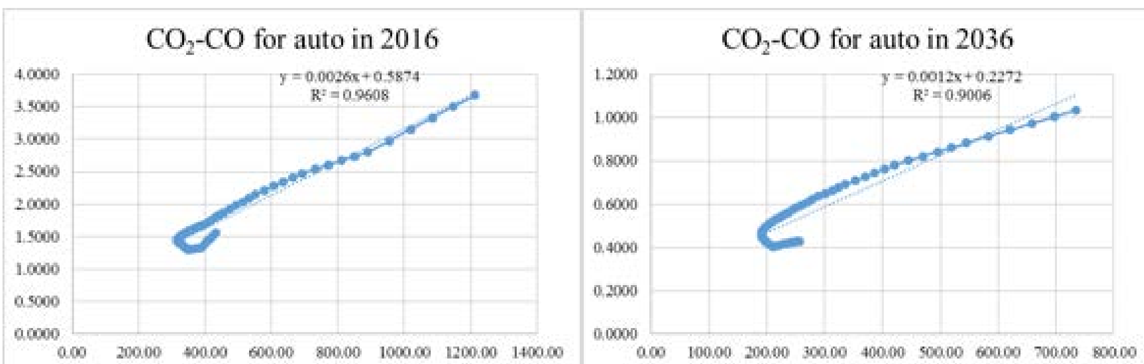


Figure 8. Relationship between CO emission factor and CO_2 emission factor

Third, we use the CO_2 emission factor trend (from step 1) and the CO emission factor in 2016 & 2036 (data source D3) to forecast the CO emission factor by the "max-min" method:

$$\frac{\text{CO emission factor in 2016} - \text{CO emission factor in year } t}{\text{CO emission factor in 2016} - \text{CO emission factor in 2036}} = \frac{CO_2 \text{ emission factor in 2016} - CO_2 \text{ emission factor in year } t}{CO_2 \text{ emission factor in 2016} - CO_2 \text{ emission factor in 2036}}. \tag{5}$$

The CO emission factor forecasts are shown in Figure 9.

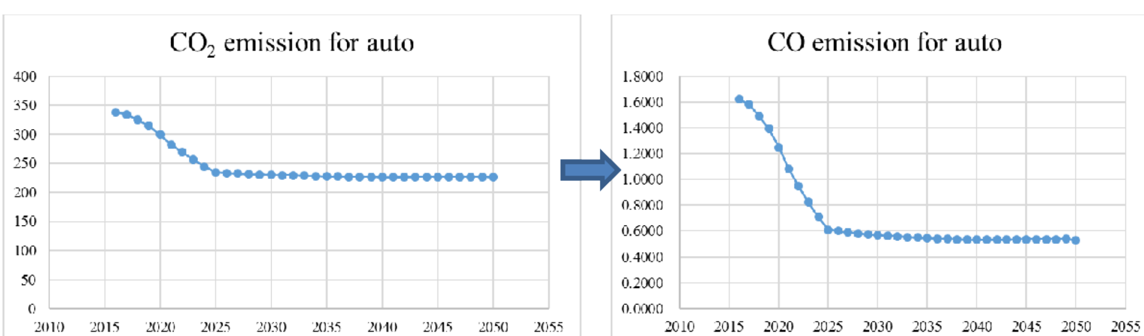


Figure 9. Forecasting CO emission factor

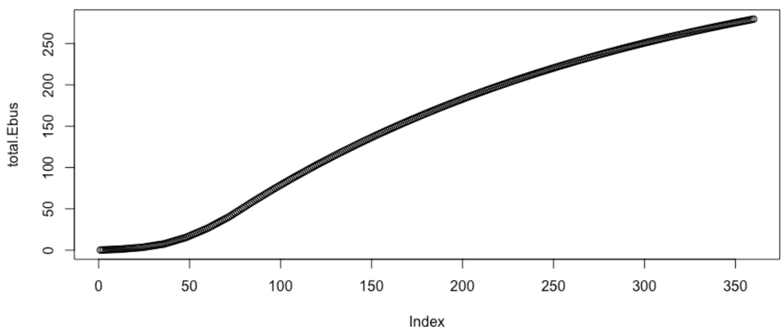
3.1.5 Forecasting Electric Buses and Trucks in the Vehicle Fleet

It is noted that the adoption of electric buses and trucks are different from that of passenger cars. We refer to public data sources to forecast the volume of e-bus and e-truck in the vehicle fleet.

Electric Bus: The United States invested $84 million in electric buses (Forbes). Currently, around 300 electric passenger buses are operating in the US (Reuters). New Jersey announced the percentage of new electric bus purchases as follows: 5% by the end of 2019, 10% by the end of 2020, 20% by the end of 2021, 40% by the end of 2022, 60% by the end of 2023, 80% by the end of 2024, and 100% by the end of 2025.

Electric Truck: High profile companies, such as Tesla and Daimler, are investing in commercial electric trucks. It is expected that Tesla electric trucks will enter the market by the end of 2019 or early 2020.

Since the current age distribution of buses and trucks in the tunnel (or even in states) is unknown, we assume that 5% of the current number of buses and trucks would be replaced every year. We then apply the NJ assembly rates of new E-buses adoption to forecast the number of E-buses (2020-2048). Figure 10 shows the projected number of E-buses and E-trucks, respectively. Since there are not any available approaches that anticipate how E-truck will be introduced to the market and how regulations will promote e-truck adoptions, the same purchase rates as E-bus are considered. We assume E-truck adoption will begin in 2029.



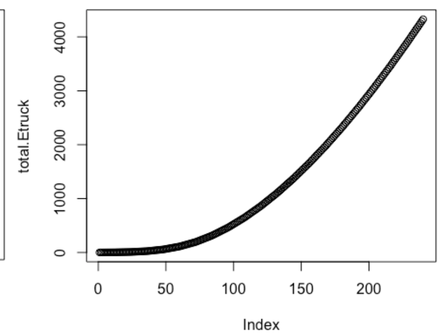


Figure 10. Forecast of E-buses (left) and E-trucks (right)

3.1.6 Dashboard

An interactive dashboard is developed to visualize the forecasting results and provide insights to support decision making. The dashboard is launched as a website that can be easily accessed: http://holland-tunnel.com/. Figures 11~14 below are examples of the dashboard. Users can simply click on the options to see results for automobiles, buses, trucks, or all vehicles. Users can see either short-term (Model HT) or long-term (Model A) forecast results. We also present three EV adoption scenarios: conservative, moderate, and aggressive. The blue bars represent the total traffic volume and the green bars represent the EV traffic volume. The CO emissions are shown in red curves.

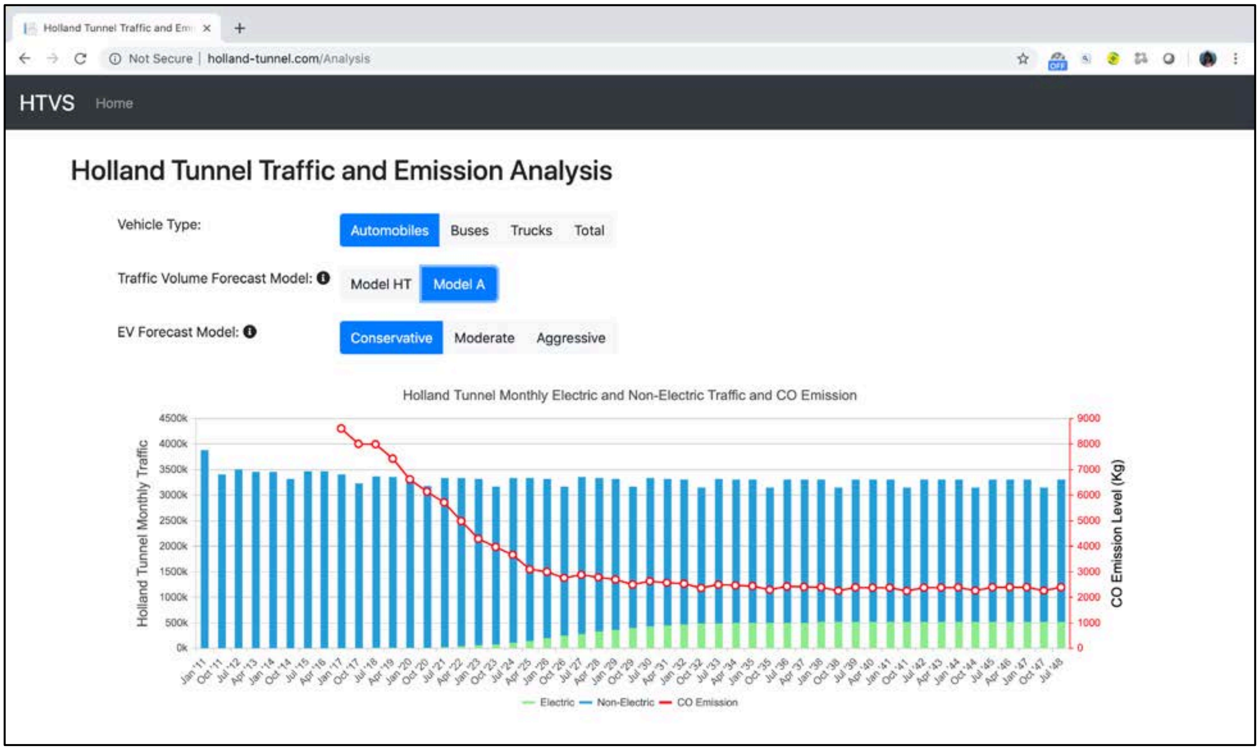


Figure 11. Dashboard showing long-term forecast of automobiles, under conservative EV adoption scenario

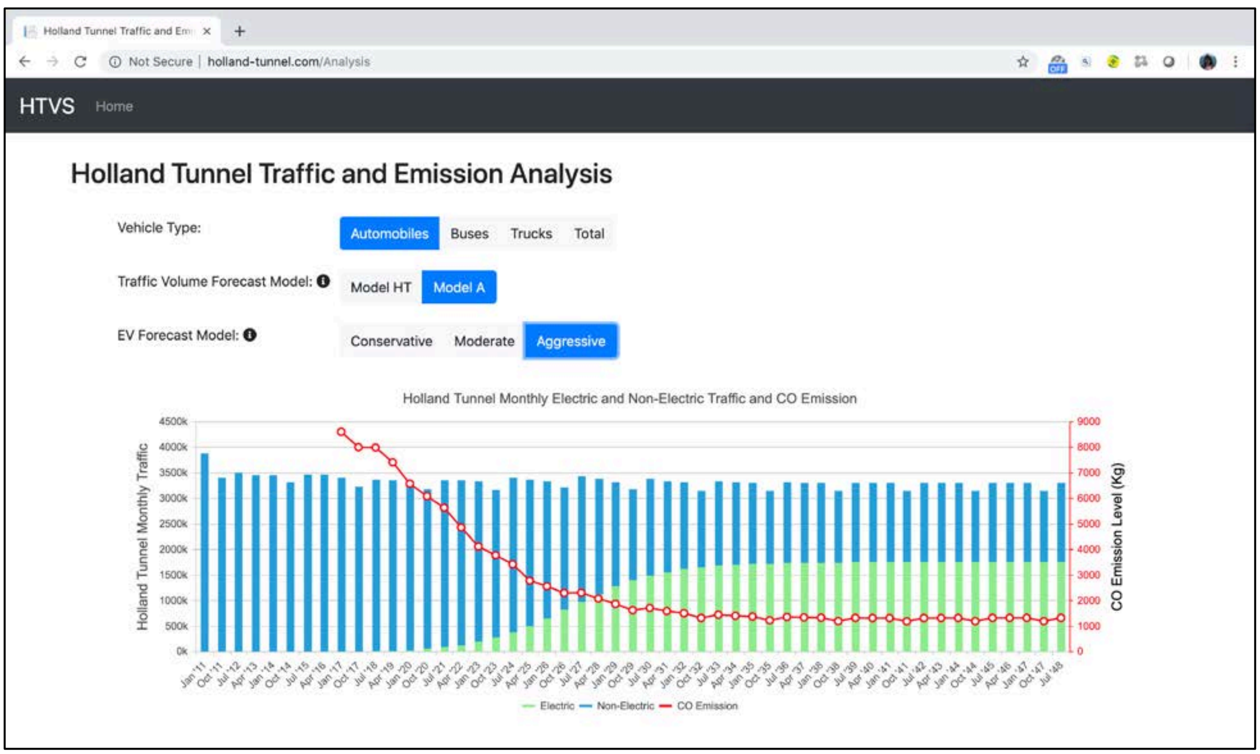


Figure 12. Dashboard showing long-term forecast of automobiles, under aggressive EV adoption scenario

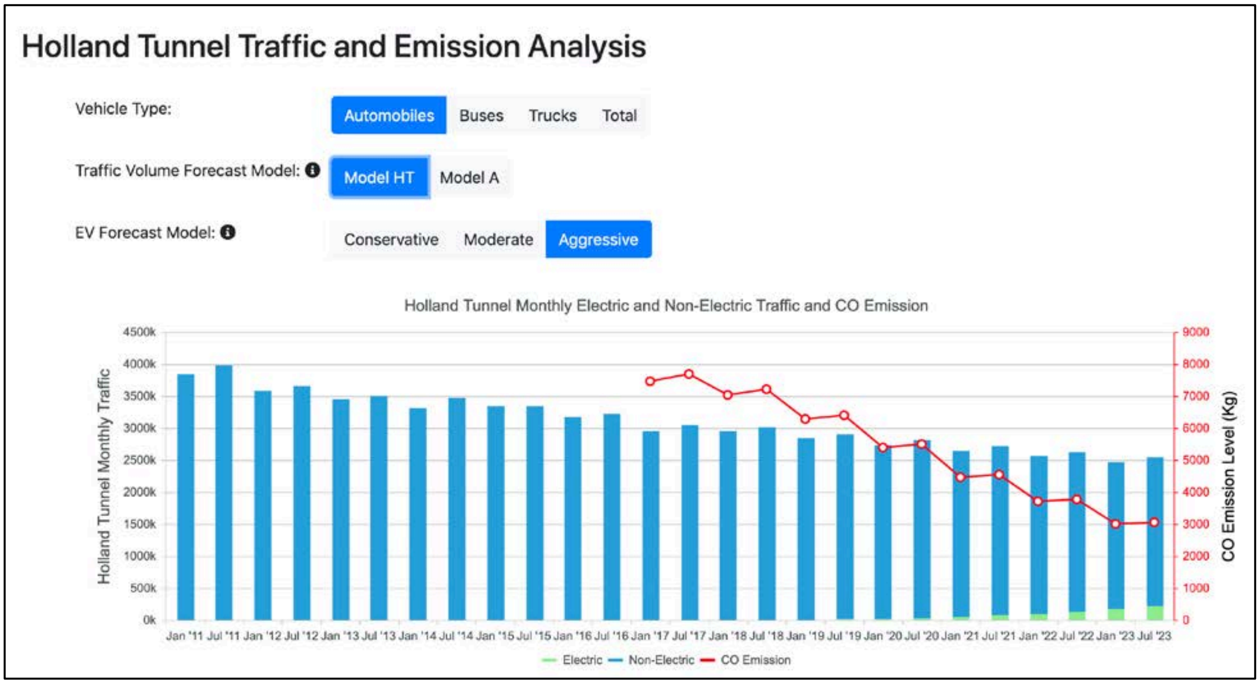


Figure 13. Dashboard showing short-term forecast of automobiles, under aggressive EV adoption scenario

3.2 Life Cycle Cost Analysis

3.2.1 Life Cycle Cost Model

The PA provided us with an asset management report ("PANYNJ report"). The report contains the following information.

- 420 assets are in Excellent condition with more than 75% of remaining life
- Useful life information
  - Only consider Blower and Exhaust
    - Motors
    - Dampers
    - Damper Actuators
    - Starting Cabinets
  - With useful life of 25 years
  - The rest of the assets have more than 30 years of useful life
- Capital Cost for 2018, 2034, 2037-2041, 2044
- Corrective and Preventive Maintenance cost
- Only consider labor cost

In the life cycle cost model, we aim to estimate the total ownership cost as the sum of capital cost, maintenance cost, and operation cost.

$$\text{Total Ownership Cost} = \text{Capital Cost} + \text{Maintenance Cost} + \text{Operation Cost}. \tag{6}$$

The **capital cost** includes rehabilitation cost (for ducts) and replacement cost (for others). The ages for ducts are 100 years, for fans are 75 years, for others are 25 years. The capital cost also considers the influences of CO emission level on the age of assets. Age for others is assumed to be 25 (current scenario) → 52 (conservative)→ 63 (moderate)→ 86 (aggressive). As shown in the left figure of Figure 14, the decay curves in the PANYNJ report assumed a linear trend, which is not realistic. We modify the decay curves by considering the more realistic situation that degradation starts at lower rate and speed up over time, therefore failure rate is increasing over time. The decay rate is calculated by Eq. (7).

$$\text{Decay. Rate} = 1 - \left(\frac{\text{t. current}}{\text{useful. life}}\right)^3. \tag{7}$$

As shown in Eq. (7), the age of asset is the deterministic factor of the decay process. Operation hours only extend the useful life of assets. Our analysis requires historical operation and maintenance data.

After developing the modified decay curve, we obtain our forecast considering CO emission reduction, as shown in the right figure of Figure 14. The different colored lines in Figure 14 correspond to different EV adoption scenarios. As can be seen in our forecast in Figure 14, there is no need to replace other assets before 2048. The capital costs in our model are shown in Figure 15.

The **maintenance cost** includes preventive maintenance (PM) cost, corrective maintenance (CM), and emergency maintenance (EM) cost. Only labor cost is considered. The effect of CO emission level is not considered in maintenance. Our forecast of the maintenance cost is the same as that calculated in the PANYNJ report (Figure 16).

The **operation cost** depends on the operating hours of the blower fans. So, we determine the operation cost according to the following estimations (Figure 17).

- Operation cost per year = 2*42*365 * fan's energy consumption * fan's operating time per day * energy price
- Fans' energy consumption: 25-80 kw/hour, set as 52.5 kw/hour
- Current: fans' operating time per day: 6-8 hours, set as 7 hours
- **With our forecast: operating time is proportional to CO emission**
- Energy price: electric price from EIA, considering inflation rate (2.6%)

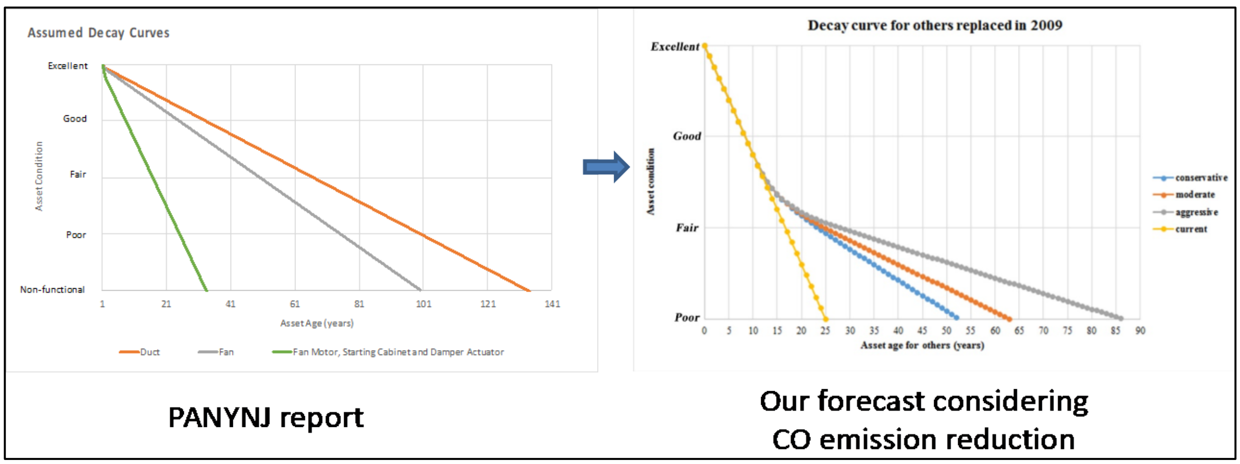


Figure 14. Decay curves in PANYNJ report (left) and our forecast (right)

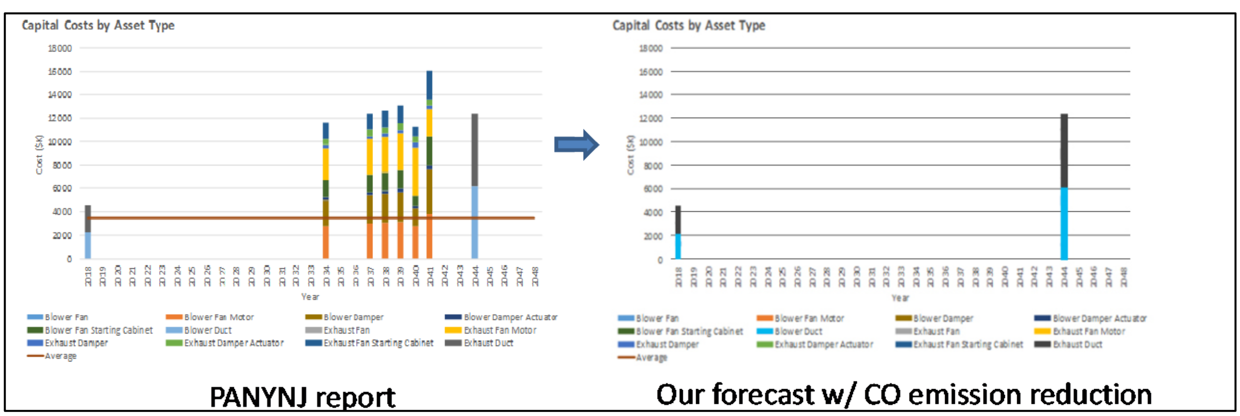


Figure 15. Capital costs in PANYNJ report (left) and our forecast (right)

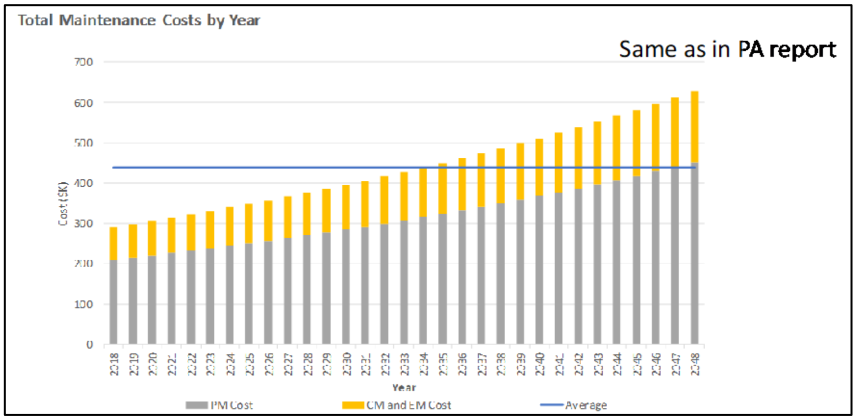


Figure 16. Maintenance costs in our forecast

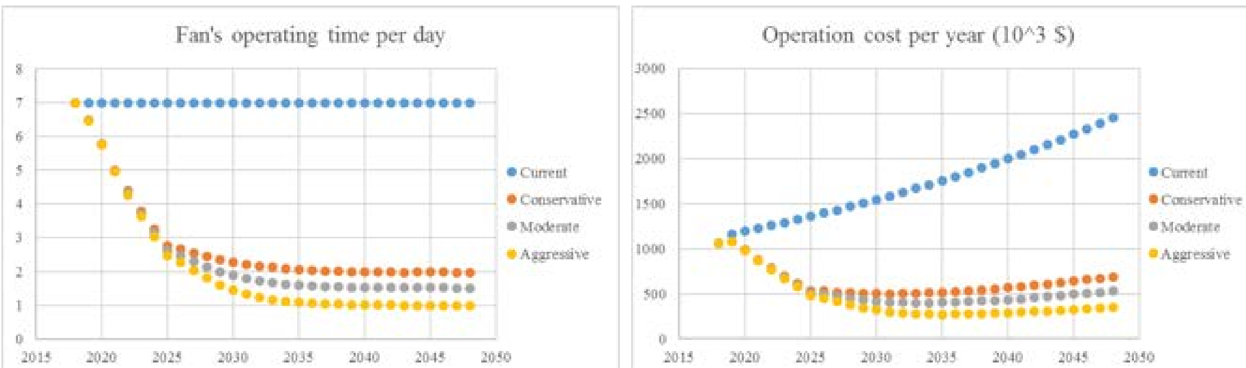


Figure 17. Fan operating time and operation cost in our forecast

Following the calculations above, the **Total Ownership Cost (TOC)** in different EV adoption scenarios is summarized in Table 1. The current scenario is consistent with that in the PA's report. The conservative, moderate, and aggressive scenarios correspond to the EV adoption strategies presented in Section 3.1.

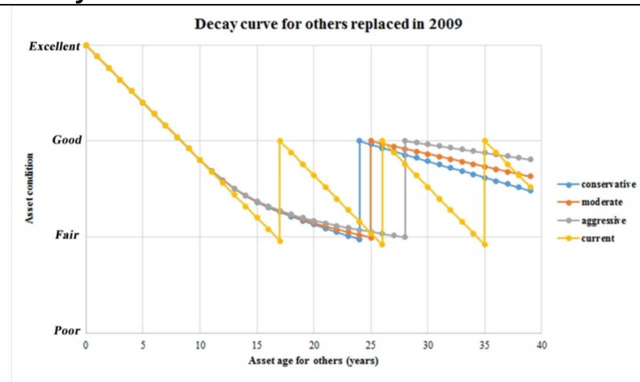
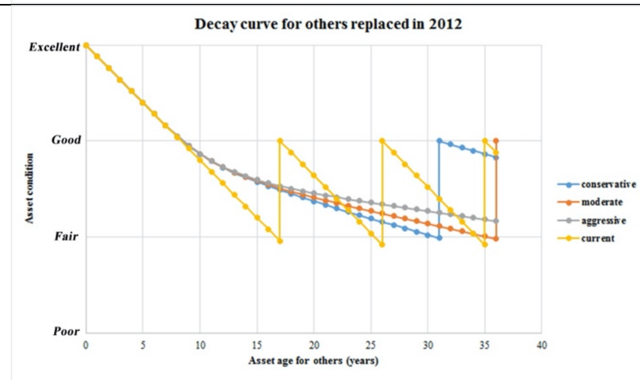
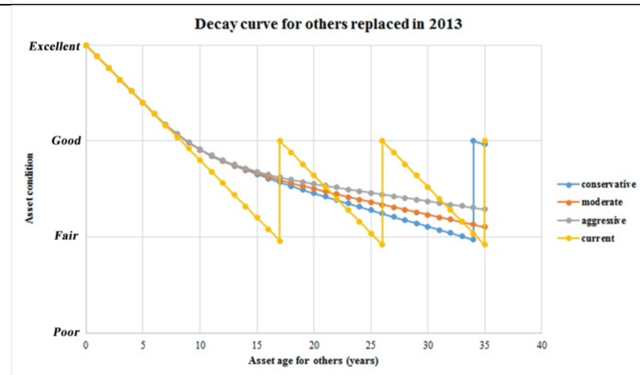
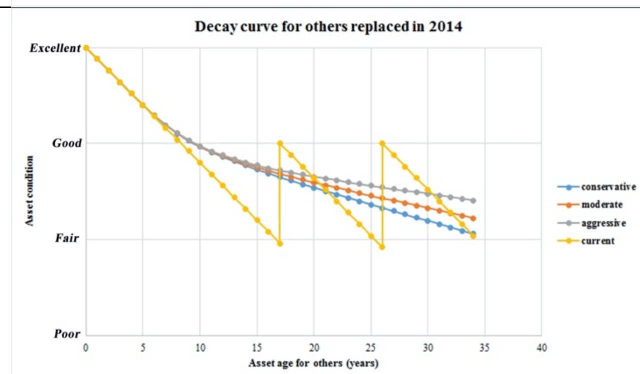
Table 1. Life cycle cost in current, conservative, moderate, and aggressive scenarios

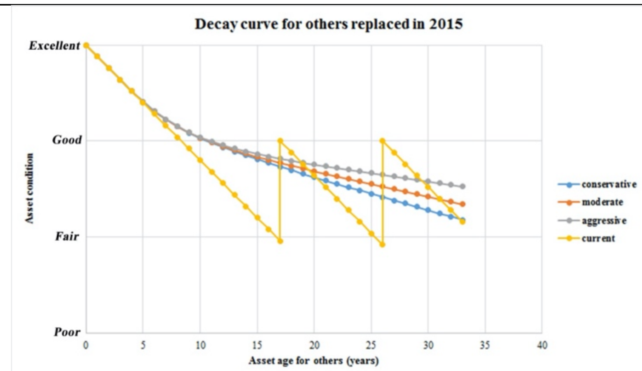
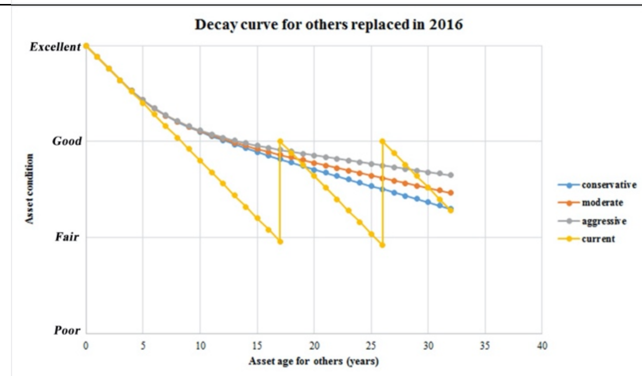
Cost factor	Current (10^3 $)	Conservative (10^3 $)	Moderate (10^3 $)	Aggressive (10^3 $)
Capital Cost	93,239	17,137 (82% ↓)	17,137(82% ↓)	17,137 (82% ↓)
Maintenance Cost	13,660	13,660	13,660	13,660
Operation Cost	53,004	19,523 (63% ↓)	16,814 (68% ↓)	13,770 (74% ↓)
TOC	159,903	50,320 (69% ↓)	47,611 (70% ↓)	44,567 (72% ↓)

3.2.2 Life Cycle Cost Model with Another Strategy for Capital Cost (Rehabilitation Only)

Another strategy for estimating the capital cost for life cycle cost is developed by assuming that parts do not get replaced. This assumption is more realistic depending on the overall business strategy and budget considerations. In this strategy, we assume that the tunnel ventilation systems do rehabilitation instead of replacement for the other assets. Specifically, when their condition comes to fair, by doing rehabilitation, their condition will go back to good; for assets replaced in different years, they have different decay curves (Table 2). The replacements of "other assets" in 2009 and 2012-2016 are given in the PANYNJ report. Maintenance cost and operation cost remain unchanged.

Table 2. Asset replacement and the corresponding decay curves

<table>
<tr><th>Asset replacement</th><th>Decay curves</th></tr>
<tr><td>For “other assets” replaced in 2009
➢ Current scenario: 3 rehabilitations in 2026, 2035, 2044
➢ Conservative scenario: 1 rehabilitation in 2033
➢ Moderate scenario: 1 rehabilitation in 2034
➢ Aggressive scenario: 1 rehabilitation in 2037</td><td>
</td></tr>
<tr><td>For “other assets” replaced in 2012
➢ Current scenario: 3 rehabilitations in 2029, 2038, 2047
➢ Conservative scenario: 1 rehabilitation in 2043
➢ Moderate scenario: 1 rehabilitation in 2048
➢ Aggressive scenario: 0 rehabilitation before 2048</td><td>
</td></tr>
<tr><td>For “other assets” replaced in 2013
➢ Current scenario: 3 rehabilitations in 2030, 2039, 2048
➢ Conservative scenario: 1 rehabilitation in 2047
➢ Moderate scenario: 0 rehabilitation before 2048
➢ Aggressive scenario: 0 rehabilitation before 2048</td><td>
</td></tr>
<tr><td>For “other assets” replaced in 2014
➢ Current scenario: 2 rehabilitations in 2031, 2040
➢ Conservative scenario: 0 rehabilitation before 2048
➢ Moderate scenario: 0 rehabilitation before 2048
➢ Aggressive scenario: 0 rehabilitation before 2048</td><td>
</td></tr>
</table>

For “other assets” replaced in 2015 ➢ Current scenario: 2 rehabilitations in 2032, 2041 ➢ Conservative scenario: 0 rehabilitation before 2048 ➢ Moderate scenario: 0 rehabilitation before 2048 ➢ Aggressive scenario: 0 rehabilitation before 2048	
For “other assets” replaced in 2016 ➢ Current scenario: 2 rehabilitations in 2033, 2042 ➢ Conservative scenario: 0 rehabilitation before 2048 ➢ Moderate scenario: 0 rehabilitation before 2048 ➢ Aggressive scenario: 0 rehabilitation before 2048	

The **capital costs** under current, conservative, moderate, and aggressive scenarios are shown in Figures 24~27, respectively. The rehabilitation cost is assumed as 1/3 of the corresponding replacement cost of the assets. For all other assets replaced in 2009, 2012-2016, they have the following rehabilitations.

- ➢ Current scenario: 15 rehabilitations in 2026, 2029, 2030-2033, 2035, 2038-2042, 2044, 2047-2048
- ➢ Conservative scenario: 3 rehabilitations in 2033, 2043, 2047
- ➢ Moderate scenario: 2 rehabilitations in 2034, 2048
- ➢ Aggressive scenario: 1 rehabilitation in 2037

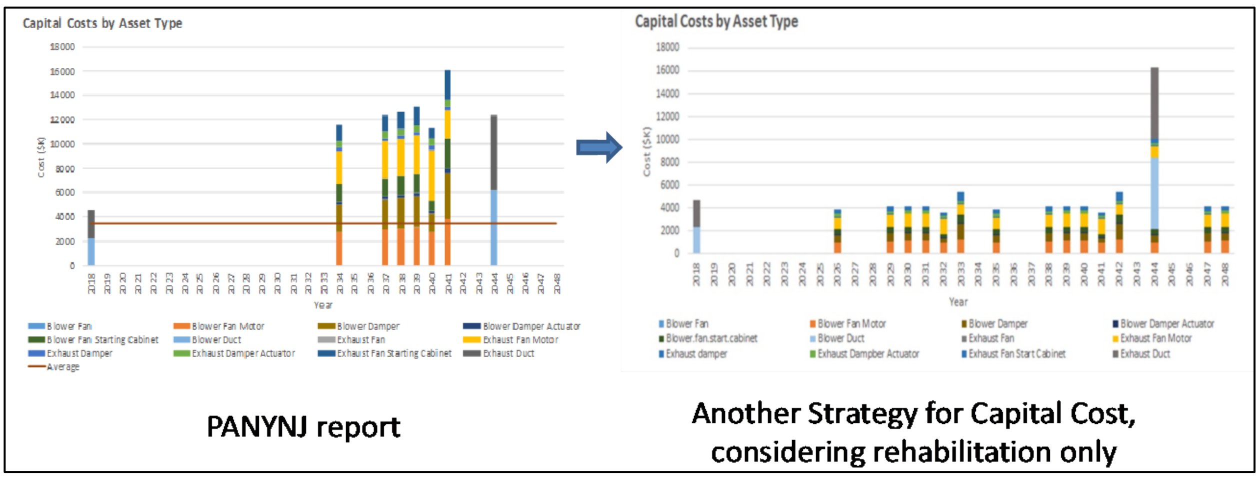


Figure 18. Capital costs (rehabilitation only) in the current scenario

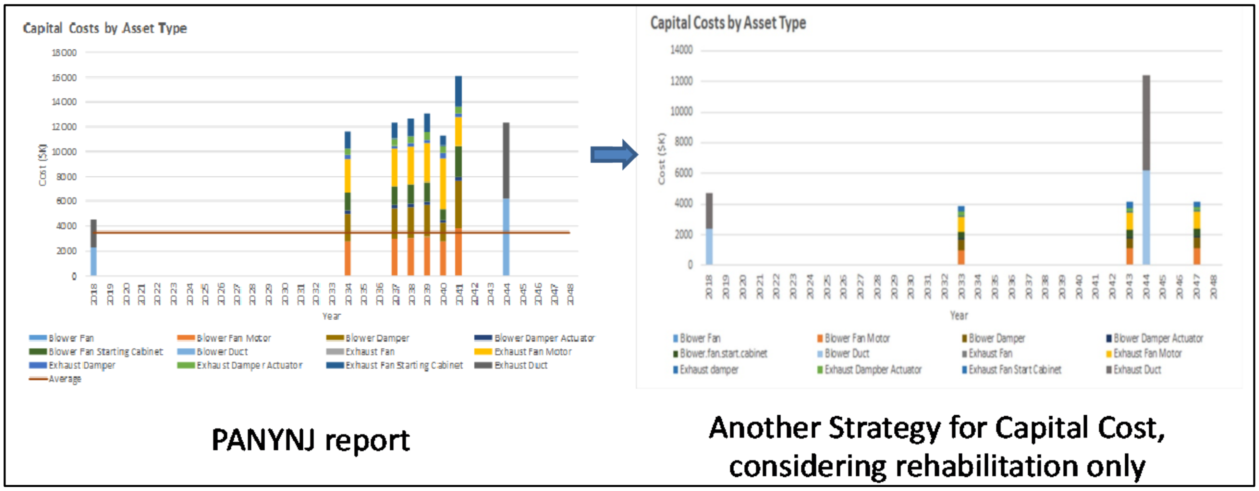


Figure 19. Capital costs (rehabilitation only) in the conservative scenario

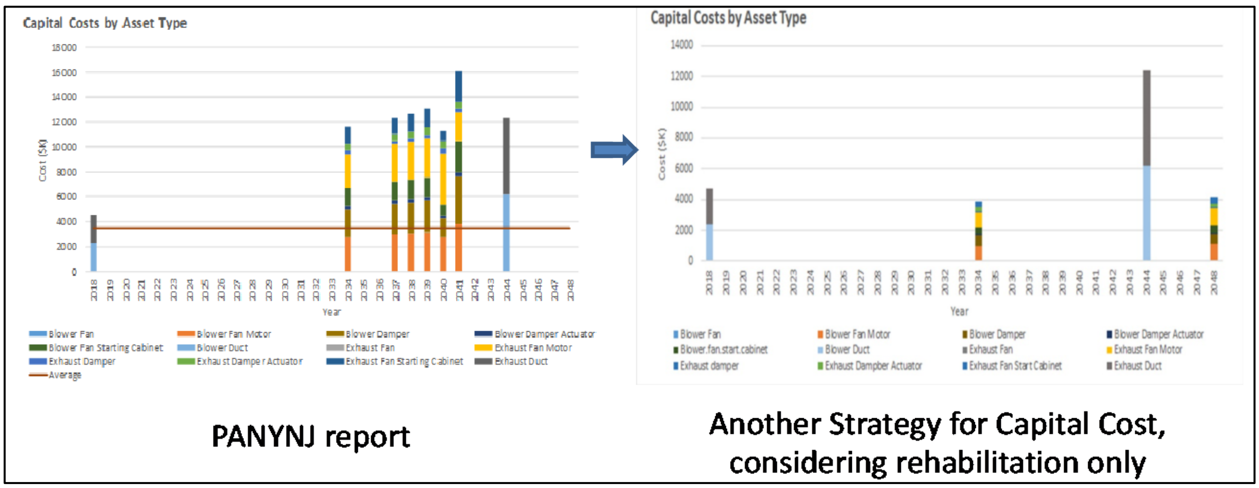


Figure 20. Capital costs (rehabilitation only) in the moderate scenario

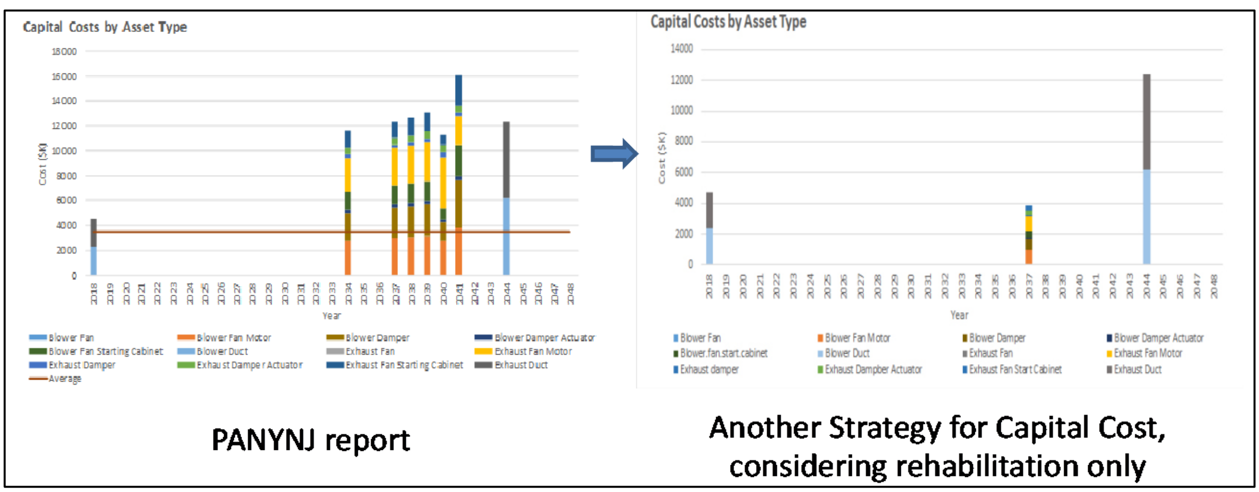


Figure 21. Capital costs (rehabilitation only) in the aggressive scenario

Following the calculations above, the **Total Ownership Cost (TOC)** (when capital cost considers rehabilitation only) is summarized in Table 3. The conservative, moderate, and aggressive scenarios correspond to the EV adoption strategies presented in Section 3.1.

Table 3. Life cycle cost if capital cost only considers rehabilitation

Cost factor	Current (10^3 $)	Conservative (10^3 $)	Moderate (10^3 $)	Aggressive (10^3 $)
Capital Cost	80,072	29,337 (63%⬇)	25,148 (68%⬇)	21,026 (73% ⬇)
Maintenance Cost	13,660	13,660	13,660	13,660
Operation Cost	53,004	19,523 (63%⬇)	16,814 (68%⬇)	13,770 (74%⬇)
TOC	146,736	62,520 (57%⬇)	55,622 (62%⬇)	48,456 (67% ⬇)

4. FINDINGS

The proposed research provided a much need realistic and practical forecast models on the vehicle fleet mix, exhaust emission, and life cycle costs for tunnel ventilation systems. Comparing our forecasts with the sustainability policy developed by PANYNJ in June 2019 (Figure 22), our forecast (Table 4) shows a relatively conservative forecast for EV number and a relatively aggressive forecast for CO emission reduction. But more importantly, our model considers the different EV adoption scenarios, thus providing tangible managerial insights to tunnel ventilation system owners.

Table 4. Summary of EV traffic volume and CO emission forecast

Scenario	PANYNJ	Conservative	Moderate	Aggressive (based on NJ assembly)
EV% in 2025	50%	4.78%	9.63%	14.98%
EV% in 2030	100%	13.36%	27.58%	43.33%
CO reduction% in 2025	35%	56.51%	57.76%	66.52%
CO reduction% in 2050	80%	73.04%	78.64%	84.93%

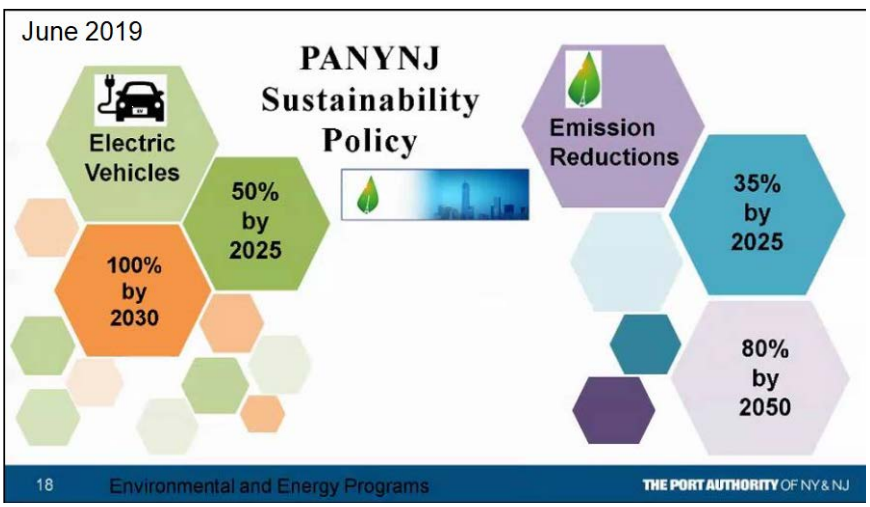


Figure 22. PANYNJ sustainability policy (June 2019)

Table 5. Summary of life cycle cost analysis

(a) Capital cost includes rehabilitation cost for ducts and replacement cost for other assets

Cost factor	Current (10^3 $)	Conservative (10^3 $)	Moderate (10^3 $)	Aggressive (10^3 $)
Capital Cost	93,239	17,137 (82% ⬇)	17,137(82% ⬇)	17,137 (82% ⬇)
Maintenance Cost	13,660	13,660	13,660	13,660
Operation Cost	53,004	19,523 (63% ⬇)	16,814 (68% ⬇)	13,770 (74% ⬇)
TOC	159,903	50,320 (69% ⬇)	47,611 (70% ⬇)	44,567 (72% ⬇)

(b) Capital cost only considers rehabilitation cost

Cost factor	Current	Conservative	Moderate	Aggressive
Capital Cost (rehabilitation only)	80,072	29,337 (63%⬇)	25,148 (68%⬇)	21,026 (73% ⬇)
Maintenance Cost and Operation Cost same as above				
TOC	146,736	62,520 (57%⬇)	55,622 (62%⬇)	48,456 (67% ⬇)

Our life cycle cost analysis models (Table 5) reveal the cost reductions considering different rehabilitation and replacement strategies, under different EV adoption scenarios. These findings will potentially advise how tunnel ventilation system components should be maintained, replaces, and rehabilitated to accommodate the ever-changing vehicle fleet mix in tunnels. These findings will also potentially help to optimize the operations of tunnel ventilation systems, pointing towards a smart ventilation system. Port Authority personnel can be trained on the deployment of the developed models on other tunnels and bridges. The models developed here may also bring changes to the existing tunnel operations.

5. CONCLUSIONS

Owners of tunnel ventilation systems are often faced with forecasting life cycle costs for their assets, which includes but are not limited to operating and replacement costs over long time horizons such as 10 years, 20 years or 30 years. Within such a time horizon, vehicle emission technology changes with the continuing growth of zero- or low-emission and hybrid vehicles and the declining growth of combustion vehicles fleet in the mix that use tunnels. This study investigated the future operation needs of tunnel ventilation systems considering the increase of EVs, the adoption rate of EVs, and various rehabilitation and replacement strategies. Time series models are incorporated with EV regulations to estimate EV adoption. Both short-term and long-term forecasting models are developed to account for the impact of short-term construction works on tunnel traffic and the long-term increase of overall traffic. Our forecasts considered conservative, moderate, and aggressive EV adoptions, as well as their impact on overall fleet mix and life cycle cost. Our life cycle cost model quantified the capital cost, maintenance cost, and operation cost of tunnel ventilation systems and suggest significant cost reduction if the ventilation system can be operated considering emission reduced brought by the increasing number of EVs.

This research could potentially benefit tunnel ventilation systems owners with more realistic and practical forecasts of vehicle emissions and life cycle costs, which will guide the decisions on resource allocation and capacity planning. For example, a drastic increase in zero emission and hybrid vehicles in the fleet mix that uses a tunnel will significantly reduce the operational costs of tunnel ventilation systems. Thus, savings from reduced emission as a result of reduced need for tunnel ventilation can free up money needed for other critical need especially in constrained budget situations. Furthermore, during replacement, the vehicle fleet mix forecast model can also be used to guide the capacity planning for normal operation and emergency incidents.

Future research can be conducted along the following directions:

1) Fine-tune the forecasting models with more detailed tunnel traffic data;
2) Design condition-based maintenance and repair for tunnel ventilation systems;
3) Smart controls of tunnel ventilation systems considering traffic patterns and EV increase.

6. RECOMMENDATIONS

The results of this research suggest:

1) The increase of EVs in tunnel traffic has a huge impact on exhaust emission and the life cycle cost of tunnel ventilation systems.
2) The developed forecasting models provide a much needed concreate analysis of how EV traffic volume would change in the next 30 years, providing a foundation for optimal control of tunnel ventilation systems.
3) We encourage the Port Authority and tunnel ventilation systems owners to design smart controls of tunnel ventilation systems considering the emission reduction brought by the changing fleet mix, leading to a more sustainable tunnel ventilation system.