A STUDY ON THE IMPACT OF PARAMETER UNCERTAINTY ON THE EMISSION-BASED RANKING OF TRANSPORTATION PROJECTS

Final Report

TranLIVE

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16. Abstract

With the growing concern with air quality levels and, hence, the livability of urban regions in the nation, it has become increasingly common to incorporate vehicular emission considerations in the ranking of transportation projects. Network assignment methods have proven invaluable in the characterization of system level emissions. The estimation of these regional air quality impacts has been typically based on the assumption of determinism. That is, model parameters in network assignment methods are typically assumed to be known with complete certainty. In this research, the assumption of determinism is relaxed and the impact of trip table/ demand uncertainty and road capacity uncertainty is examined. In addition to emissions as the project selection criterion, the classical total system travel time measure is also considered. Based on extensive simulations, our results indicate that the impact of uncertainty is limited. However, at the same time, it is to be emphasized that the findings in this study are preliminary in nature and might not necessarily generalize to other settings than the ones considered in this report.

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EXECUTIVE SUMMARY

With the growing concern with air quality levels and, hence, the livability of urban regions in the nation, it has become increasingly common to incorporate vehicular emission considerations in the ranking of transportation projects. Network assignment methods have proven invaluable in the characterization of system level emissions. The estimation of these regional air quality impacts has been typically based on the assumption of determinism. That is, model parameters in network assignment methods are typically assumed to be known with complete certainty. In this project, the assumption of determinism is relaxed and the impact of trip table/ demand uncertainty and road capacity uncertainty on the selection of road capacity expansion projects to reduce emission and congestion is examined. EPA's MOVES has been used to estimate emissions.

Based on extensive simulations, our results indicate that the impact of uncertainty is surprisingly minimal (the only case where uncertainty was observed to be relevant was in the case of capacity uncertainty, when the goal is to reduce the network travel time), especially in light of findings in previous related work that indicated that uncertainty might lead to the selection of inferior projects. Possible reasons for this discrepancy might include:

- We employed confidence intervals to detect statistical differences, whereas prior only compares mean values.
- Due to the high computational times of MOVES, we necessarily had to limit ourselves to a limited number of samples. As can be seen from our results, in some of the cases, it was not possible to detect a statistically significant difference. A larger sample size would result in excessive computation times.
- Restricted by the computational requirements of MOVES, we only considered the case of triangular distributions in modeling the uncertainties. Other probability distributions might yield different results.

One of the findings did show consistency compared to previous research: Capacity expansion projects to reduce vehicular emissions are not necessarily optimal in terms of congestion

mitigation. Previous work arrived at a similar conclusion, but with EPA's older emission estimation system MOBILE.

As a final note, it has to be emphasized that the findings in this study are preliminary in nature and might not necessarily generalize to other settings than the ones considered in this report.

DESCRIPTION OF PROBLEM

With the growing concern on air quality levels and, hence, the livability of urban regions in the nation, it has become increasingly common to incorporate vehicular emission considerations in the ranking of transportation projects. Network assignment methods have proven invaluable in the characterization of system level emissions. However, the estimation of these regional air quality impacts has been typically based on the assumption of determinism (Ng and Lo, 2013). That is, model parameters in network assignment methods are typically assumed to be known with complete certainty. In this study, the assumption of determinism is relaxed and the impact of trip table/ demand uncertainty and road capacity uncertainty is examined. Moreover, unlike previous related studies, this study employs EPA's MOVES emission software.

As indicated above, traditionally, mean/ expected values of uncertain parameters are simply used as a representative value. This assumes that the *mean network performance is equal to the performance of the network at the expected value of the uncertain parameter*. However, due to the nonlinear nature of traffic, this assumption has been shown to be incorrect (e.g. see Waller et al., 2001), and potentially even misleading. To be correct, expected performance measures should be used to characterize network performance.

The main goal in this study is to investigate whether uncertain parameters can impact the selection of road capacity expansion projects, when lower emission projects are desired. More specifically, we will examine whether project selections based on mean parameter values will result in different project selections than would be the case when the parameter uncertainty is explicitly modeled when using EPA's MOVES emission software. To the best of our knowledge, such a study is non-existent in the currently available literature. In addition to emissions, we shall also examine the impact of uncertainty when the goal is to reduce the system travel time. Comparisons between the two will be made throughout the report.

MOVES (**MO**tor **V**ehicle **E**mission **S**imulator) is developed by EPA's Office of Transportation and Air Quality. This emission modeling system estimates emissions for mobile sources covering a broad range of pollutants and allows multiple scale analysis. EPA continuously collects data and measures vehicle emissions in order to have an up-to-date understanding of mobile source emissions and incorporates this assessment into EPA's mobile source emission models. MOVES is currently the standard in emission estimation.

APPROACH AND METHODOLOGY

In order to investigate the impact of uncertainty on the selection of road capacity expansion projects, these expansion projects are evaluated based on two different approaches.

***Approach 1: Sampling*.** For a given road network (four different networks have been examined in this study), a pair of links (link 1 and link 2, say) is selected randomly for capacity expansion. Temporarily, *b* units of capacity are then added to link 1. To model uncertainty, we assume a probability distribution. We then sample from this distribution, and solve a static traffic assignment problem for each sample. The link flows for each sample are used as input in the MOVES software, and the total hourly emission is estimated. By looping through all samples and averaging the estimated emissions, the expected emission level for the road network, assuming that link 1 is expanded, can then be calculated. This procedure is then repeated, assuming that link 2 is expanded with *b* units of capacity instead. Since sampling is involved, we then construct a 95% confidence interval for the difference in the sample means to determine whether the two capacity expansion projects indeed yield statistically significant mean emission values: If this confidence interval does not contain 0, it can be concluded that at the 95% confidence level, one expansion is superior over the other. On the other hand, if the confidence interval contains 0, nothing can be said about the ranking of the projects in terms of average emissions (Law, 2007). As average emissions (rather than emissions at average system behavior) have been recognized as the correct performance measure (e.g. see Waller et al., 2001), the project rankings resulting from this sampling approach give the correct ordering of the projects.

***Approach 2: Mean values*.** For the same pair of links as above, we also evaluate the emission when we use the mean values of the parameters under consideration. As above, the resulting link flows are then used as input in MOVES to estimate the total emission. The emissions from the two projects (expanding capacity of link 1 versus link 2) are then compared and the link whose expansion leads to lower emission values is designated as superior. As noted earlier, while this approach appears to be the state-of-the-practice, such an approach has been criticized in the literature as it might lead to incorrect project rankings when the goal is to minimize the overall travel time in a traffic network (Waller et al., 2001).

In addition to the different project ranking criterion in the two approaches, another critical difference between the two approaches is the computational requirement. In Approach 1, the traffic assignment problem is solved multiple times (depending on the sample size) for each proposed capacity expansion project (leading to a much higher computational burden), whereas in Approach 2 one only needs to solve the traffic assignment problem once for each capacity expansion project. Hence, to summarize the above: whereas Approach 1 is the preferred approach (in terms of correctness), its drawback is that it is much more computationally intensive than Approach 2, which might give misleading project rankings. Motivated by this observation, the central question in this study is whether mean values (Approach 2) can be used for planning purposes, i.e. how different the project rankings will be between the two approaches when one is interested in the average emissions.

To alleviate the high computational requirements in Approach 1, common random numbers (CRN) have been used in this study. CRN is a variance reduction technique that can be used to compare two or more alternative system configurations (Law, 2007). Mathematically, suppose that one wants to compare two alternative configurations with (random) performance measures X and Y (in our case, X would be the emission level resulting from project 1 ("expanding the capacity of link 1"), whereas Y would be the emission level resulting from project 2 ("expanding the capacity of link 2")). More specifically, suppose that one would like to rank their mean performances, denoted as E(X) and E(Y). Let X_k and Y_k denote the k-th sample of X and Y, respectively (k = 1, 2,…,n) and define $Z_k = X_k - Y_k$, the mean difference E(X) – E(Y), can then be estimated with:

$$\overline{Z}(n) \equiv \frac{1}{n}\sum_{k=1}^{n} Z_k$$

which has a variance of

$$Var[\overline{Z}(n)] = \frac{Var(X_k) + Var(Y_k) - 2Cov(X_k, Y_k)}{n}$$

If X_k and Y_k are uncorrelated, then Cov(X_k, Y_k) = 0. However, if common random numbers are used, positive correlative potentially exist between X_k and Y_k, and as a result, the variance of the estimator is reduced. Equivalently, fewer samples are needed in order to obtain a given confidence level. In our context, CRN amounts to using the same samples (e.g. for the capacity and demand values) when evaluating the mean emission levels.

In this study, four real-world test networks have been extracted from the road network in the City of Virginia Beach, Virginia. These networks are discussed below and shown in Figure 1 to Figure 4.

Network 1: Network 1 has 30 links (i.e. roadway segments), 21 nodes (i.e. intersections) and consists of arterial roadways with level terrain. The free flow speeds for the links are either 32, 34 or 38 mph. The capacities of the links are either 650, 850 or 900 vehicles per hour. For this network, the hypothetical capacity increase *b* was chosen to be 650 units.

Network 2: Network 2 consists of arterial roadways with level terrain and contains 14 links and 11 nodes. The speed for all the links is 45 mph. All links have a capacity of 1000 vehicles per hour. A capacity increase of *b*=1000 has been used for Network 2.

Network 3: Network 3 has 26 links and 14 nodes and consists of local and arterial roadways with level terrain. The speeds for all the local links are 26 mph and the arterial links have a speed of either 36, 38, 40 or 45 mph. The capacity of the links are either 450, 700, 800, 1050, 1900 or 2100 vehicles per hour. A capacity increase of *b*=450 vehicles per hour has been used for Network 3.

Network 4: Network 4 consists of 36 links, of which 13 links are freeways and the rest are arterial roads. The speed for all the freeway links are 57 mph. The speed for the arterial streets is either 30 or 34 mph. The capacity of the links are 600, 900, 1200, 1700, 1800, 1900, 2550 and 5700 vehicles per hour. A capacity increase of 600 vehicles per hour has been used to study Network 4.

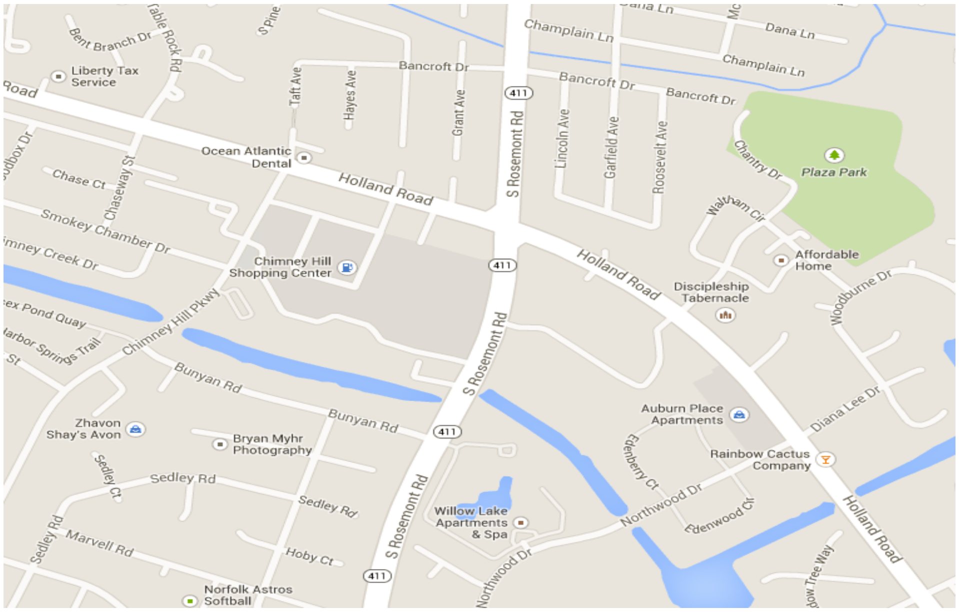

Figure 1: Test Network 1 (Source: www.maps.google.com).

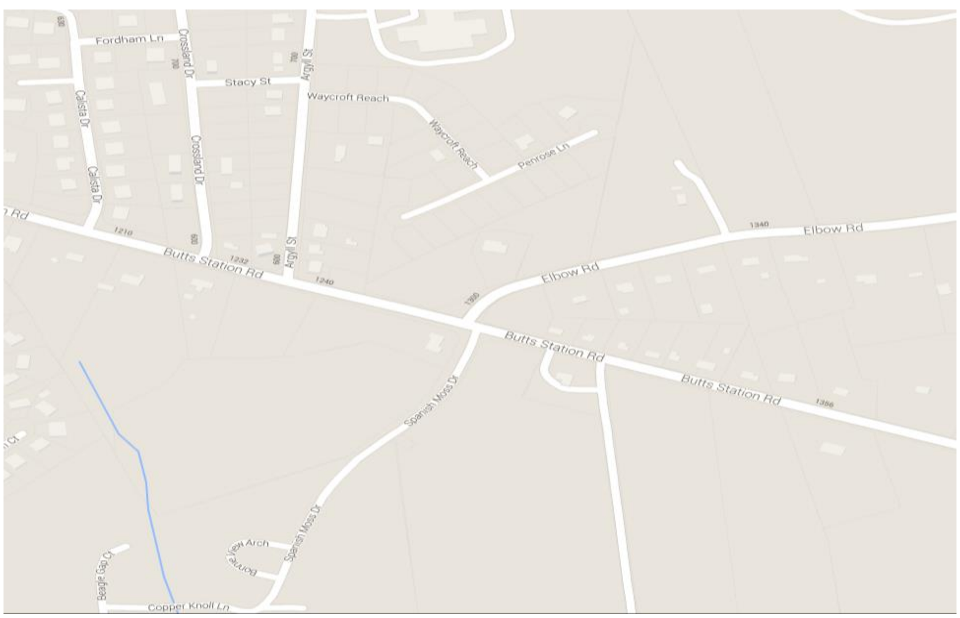

Figure 2: Test Network 2 (Source: www.maps.google.com).

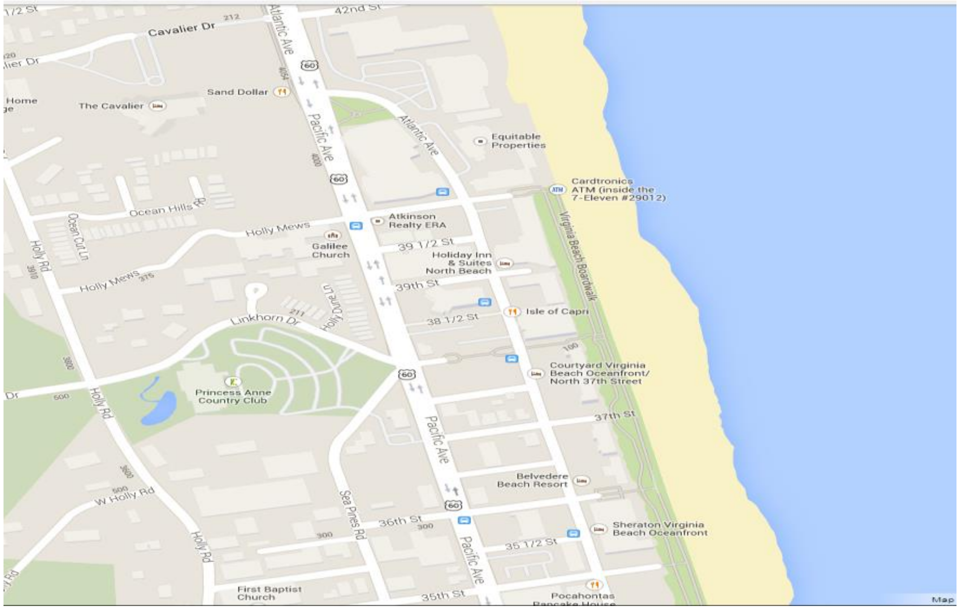

Figure 3: Test Network 3 (Source: www.maps.google.com).

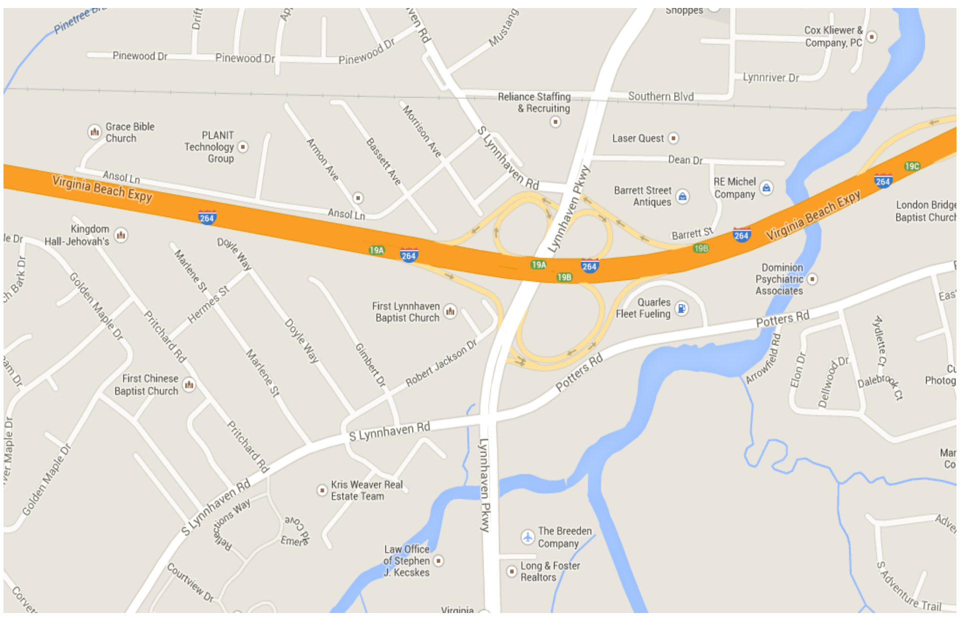

Figure 4: Test Network 4 (Source: www.maps.google.com).

To calculate emissions, default values for the vehicle age distribution, fuel properties and meteorological data provided in MOVES have been used. Nitrogen Oxides (NOx) and

Carbon Monoxide (CO) emissions for gasoline passenger cars were calculated for the time period of 7:00 to 8:00 am on a weekday in the month of July, 2009.

For all test networks, 10 pairs of different project selections are evaluated to examine the impact of parameter uncertainty on capacity expansion project selection.

FINDINGS; CONCLUSIONS; RECOMMENDATIONS

Impact Capacity Uncertainty

To account for capacity uncertainty, it is assumed that capacity values follow a triangular distribution where the mode of the distribution is equal to the design capacity of the roadway, the smallest possible capacity value is 15% below the mode/ design capacity, and the highest possible capacity value is 10% higher than the mode/ design capacity. Because of the high computational requirements, 20 samples have been used in our analysis.

Expected emission levels and emission levels at expected capacity values for 10 pairs of different project selections are evaluated to examine the impact of capacity uncertainty on capacity expansion project selection. Tables 1, 2, 3 and 4 show the results for Networks 1, 2, 3 and 4, respectively. The first columns in the tables indicate the project pairs under consideration. For example, project pair 1 comprises of "project 1" – providing capacity expansion to link (7, 10) – and "project 2" – adding capacity to link (10, 15). The column "E(Emission)" gives the preferred project when the expected emission level is used as a selection criterion (a dash "-" indicates that the difference in average emissions between the two projects were not statistically different for the sample size used), whereas the column "Emission(E(C))" indicates the preferred project when emissions at expected capacity values are used as the measure of comparison. The column titled "Same selection by E(Emission) and Emission at E(C)?" summarizes whether the project selections are the same based on the two different selection criteria. For instance, row 1 in Table 1 indicates that Project 2 (expanding link (10,15)) is superior based on both the expected emission level criterion as well as when examining the emissions at expected capacity values.

We have repeated the above analysis when the goal is to reduce the network's total system travel time (TSTT). Analogous to above, the columns E(TSTT) and TSTT(E(C)) indicate the project selection based on the expected TSTT and TSTT at expected capacity values, respectively. The column "Same selection by E(TSTT) & TSTT(E(C))?" summarizes whether the project selections are the same. As an example, row 1 in Table 1 indicates that

Project 2 is selected as the preferred project based on both the expected TSTT and TSTT at expected capacity. (It is interesting to note that for TSTT in Table 1, statistical significance could be ensured for all project pairs, whereas for emissions, a sample size of 20 was not sufficient to distinguish between the projects in 3 of the cases.)

Finally, in the last column of the tables, a comparison is made between project selections based on expected TSTT and expected emissions.

A number of interesting observations can be made regarding Tables 1 to 4:

- The project selections based on emissions at expected capacity values are the same, for all distinguishable cases, as the selections based on expected emission levels for all four test networks. Although this might suggest that the expected capacity can be safely used (i.e. uncertainty can be ignored), it is to be emphasized that this finding might not be generalizable to other transportation networks or when the number of project pairs increases. This same word of caution applies to all results below.
- Evaluation of the project selections with the goal of reducing the TSTT indicates that for networks 1, 3 and 4, the expected TSTT and TSTT at expected capacity give the same project selection. However, for network 2, it can be seen that among the 8 distinguishable pairs of projects, 6 project selections were different.
- Network design from the travel time reduction perspective does not necessarily reduce total system emissions. For example, among the 7 distinguishable project pairs in network 1, 5 of the cases were found to be different when the goal is to reduce TSTT versus when the aim is to lower emission levels.

Table 1: Project Selection for Capacity Expansion with Uncertain Capacity for Network 1

Pair	Project 1	Project 2	E(Emission)	Emission(E(C))	Same selection by E(Emission) & Emission(E(C))?	E(TSTT)	TSTT(E(C))	Same selection by E(TSTT) & TSTT(E(C))?	Same selection by E(TSTT) & E(Emission)?
1	7, 10	10, 15	Project 2	Project 2	Yes	Project 2	Project 2	Yes	Yes
2	21, 14	9, 14	-	Project 1	-	Project 1	Project 1	Yes	-
3	21, 14	7, 10	Project 2	Project 2	Yes	Project 1	Project 1	Yes	No
4	18, 16	2, 8	Project 1	Project 1	Yes	Project 2	Project 2	Yes	No
5	14,9	15, 17	Project 2	Project 2	Yes	Project 1	Project 1	Yes	No
6	13, 18	4, 2	Project 2	Project 2	Yes	Project 1	Project 1	Yes	No
7	15, 17	12, 13	Project 1	Project 1	Yes	Project 1	Project 1	Yes	Yes
8	20, 21	19, 20	-	Project 1	-	Project 1	Project 1	Yes	-
9	18, 16	21, 14	-	Project 2	-	Project 2	Project 2	Yes	-
10	13, 18	10, 15	Project 2	Project 2	Yes	Project 1	Project 1	Yes	No

Table 2: Project Selection for Capacity Expansion with Uncertain Capacity for Network 2

Pair	Project 1	Project 2	E(Emission)	Emission(E(C))	Same selection by E(Emission) & Emission(E(C))?	E(TSTT)	TSTT(E(C))	Same selection by E(TSTT) & TSTT(E(C))?	Same selection by E(TSTT) & E(Emission)?
1	2, 1	5, 4	-	Project 2	-	-	Project 2	-	-
2	6, 5	5, 11	-	Project 2	-	Project 1	Project 2	No	-
3	4, 2	8, 7	-	Project 2	-	-	Project 2	-	-
4	9, 8	11, 10	-	Project 1	-	Project 1	Project 2	No	-
5	6, 7	10, 11	Project 2	Project 2	Yes	Project 2	Project 1	No	Yes
6	8, 9	10, 12	-	Project 1	-	Project 1	Project 2	No	-
7	10, 3	5, 6	Project 2	Project 2	Yes	Project 2	Project 2	Yes	Yes
8	1, 2	7, 6	Project 2	Project 2	Yes	Project 2	Project 1	No	Yes
9	4,5	7, 8	Project 2	Project 2	Yes	Project 2	Project 2	Yes	Yes
10	2,4	11, 5	Project 2	Project 2	Yes	Project 2	Project 2	Yes	Yes

Table 3: Project Selection for Capacity Expansion with Uncertain Capacity for Network 3

Pair	Project 1	Project 2	E(Emission)	Emission(E(C))	Same selection by E(Emission) & Emission(E(C))?	E(TSTT)	TSTT(E(C))	Same selection by E(TSTT) & TSTT(E(C))?	Same selection by E(TSTT) & E(Emission)?
1	10,12	3,4	-	Project 1	-	Project 1	Project 1	Yes	-
2	4,7	7,9	-	Project 2	-	Project 2	Project 2	Yes	-
3	10,12	6,1	-	Project 2	-	Project 2	Project 2	Yes	-
4	10,5	9, 7	-	Project 2	-	Project 2	Project 2	Yes	-
5	12, 13	13, 12	-	Project 1	-	Project 1	Project 1	Yes	-
6	9, 8	10, 12	-	Project 2	-	Project 2	Project 2	Yes	-
7	13, 14	1, 6	-	Project 1	-	Project 1	Project 1	Yes	-
8	14, 12	8, 6	-	Project 1	-	Project 1	Project 1	Yes	-
9	2, 3	4, 7	-	Project 1	-	Project 1	Project 1	Yes	-
10	7, 9	9, 13	-	Project 2	-	Project 2	Project 2	Yes	-

Table 4: Project Selection for Capacity Expansion with Uncertain Capacity for Network 4

Pair	Project 1	Project 2	E(Emission)	Emission(E(C))	Same selection by E(Emission) & Emission(E(C))?	E(TSTT)	TSTT(E(C))	Same selection by E(TSTT) & TSTT(E(C))?	Same selection by E(TSTT) & E(Emission)?
1	5, 1	1, 2	-	Project 1	-	Project 1	Project 1	Yes	-
2	9, 10	21, 9	Project 1	Project 1	Yes	Project 1	Project 1	Yes	Yes
3	15, 16	20, 10	Project 2	Project 2	Yes	Project 1	Project 1	Yes	No
4	16, 17	20, 10	-	Project 2	-	Project 1	Project 1	Yes	-
5	11, 23	2, 1	-	Project 1	-	Project 1	Project 1	Yes	-
6	15, 21	7, 13	Project 2	Project 2	Yes	Project 2	Project 2	Yes	Yes
7	3, 6	16, 17	-	Project 1	-	Project 2	Project 2	Yes	-
8	4, 11	6, 7	Project 2	Project 2	Yes	Project 2	Project 2	Yes	Yes
9	20, 10	16,19	Project 2	Project 2	Yes	Project 2	Project 2	Yes	Yes
10	14, 5	17, 14	-	Project 1	-	Project 1	Project 1	Yes	-

Impact of Demand Uncertainty

To account for demand uncertainty, it is assumed that demand values follow a triangular distribution where the mode of the distribution is equal to the planning demand of the roadway, the smallest possible demand value is 50% below the mode/ planning demand, and the highest possible demand value is 50% higher than the mode/ planning demand. Because of the high computational requirements, 20 samples have been used in our analysis.

Expected emission and emission at expected demand for 10 pairs of different project selections have been evaluated to examine the impact of demand uncertainty on capacity expansion project selections. (The 10 project pairs considered here are the same 10 pairs that were considered above in the capacity uncertainty analysis.) Table 5, 6, 7, 8 show the results for Network 1, 2, 3 and 4 respectively. The interpretation of the tables is exactly the same as above (cf. Table 1 to 4). The only difference is that now demand (denoted by the letter D in the tables) is the uncertain factor.

A number of interesting observations can be made regarding Tables 5 to 8:

- The project selections based on emissions at expected demand are the same as the selections based on expected emission levels for all the 4 networks for all distinguishable cases. Note that for networks 2 and 3, we were not able to find any statistically different project selections based on our sample size.
- When the goal is to reduce the expected TSTT, using the TSTT at the expected demand level yields the same project selection.
- Network design from travel time optimization perspective does not necessarily reduce total system emissions. For example, for network 1, among the 8 distinguishable project pairs, 5 of the cases were found to be different when the goal is to lower TSTT versus when the aim is to lower emission levels.

Table 5: Project Selection for Capacity Expansion with Demand Uncertainty for Network 1

Pair	Project 1	Project 2	E(Emission)	Emission(E(D))	Same selection by E(Emission) & Emission(E(D))?	E(TSTT)	TSTT(E(D))	Same selection by E(TSTT) & TSTT(E(D))?	Same selection by E(TSTT) & E(Emission)?
1	7, 10	10, 15	Project 2	Project 2	Yes	Project 2	Project 2	Yes	Yes
2	21, 14	9, 14	-	Project 1	-	Project 1	Project 1	Yes	-
3	21, 14	7, 10	Project 2	Project 2	Yes	Project 1	Project 1	Yes	No
4	18, 16	2, 8	Project 1	Project 1	Yes	Project 2	Project 2	Yes	No
5	14,9	15, 17	Project 2	Project 2	Yes	Project 1	Project 1	Yes	No
6	13, 18	4, 2	Project 2	Project 2	Yes	Project 1	Project 1	Yes	No
7	15, 17	12, 13	Project 1	Project 1	Yes	Project 1	Project 1	Yes	Yes
8	20, 21	19, 20	-	Project 1	-	Project 1	Project 1	Yes	-
9	18, 16	21, 14	Project 2	Project 2	Yes	Project 2	Project 2	Yes	Yes
10	13, 18	10, 15	Project 2	Project 2	Yes	Project 1	Project 1	Yes	No

Table 6: Project Selection for Capacity Expansion with Demand Uncertainty for Network 2

Pair	Project 1	Project 2	E(Emission)	Emission(E(D))	Same selection by E(Emission) & Emission(E(D))?	E(TSTT)	TSTT(E(D))	Same selection by E(TSTT) & TSTT(E(D))?	Same selection by E(TSTT) & E(Emission)?
1	2, 1	5, 4	-	Project 2	-	Project 1	Project 1	Yes	-
2	6, 5	5, 11	-	Project 1	-	Project 2	Project 2	Yes	-
3	4, 2	8, 7	-	Project 1	-	Project 2	Project 2	Yes	-
4	9, 8	11, 10	-	Project 1	-	Project 2	Project 2	Yes	-
5	6, 7	10, 11	-	Project 1	-	Project 2	Project 2	Yes	-
6	8, 9	10, 12	-	Project 2	-	Project 2	Project 2	Yes	-
7	10, 3	5, 6	-	Project 2	-	Project 2	Project 2	Yes	-
8	1, 2	7, 6	-	Project 2	-	Project 1	Project 1	Yes	-
9	4,5	7, 8	-	Project 2	-	Project 2	Project 2	Yes	-
10	2,4	11, 5	-	Project 2	-	Project 2	Project 2	Yes	-

Table 7: Project Selection for Capacity Expansion with Demand Uncertainty for Network 3

Pair	Project 1	Project 2	E(Emission)	Emission(E(D))	Same selection by E(Emission) & Emission(E(D))?	E(TSTT)	TSTT(E(D))	Same selection by E(TSTT) & TSTT(E(D))?	Same selection by E(TSTT) & E(Emission)?
1	10,12	3,4	-	Project 1	-	Project 1	Project 1	Yes	-
2	4,7	7,9	-	Project 2	-	Project 2	Project 2	Yes	-
3	10,12	6,1	-	Project 2	-	Project 2	Project 2	Yes	-
4	10,5	9, 7	-	Project 2	-	Project 2	Project 2	Yes	-
5	12, 13	13, 12	-	Project 1	-	Project 1	Project 1	Yes	-
6	9, 8	10, 12	-	Project 2	-	Project 2	Project 2	Yes	-
7	13, 14	1, 6	-	Project 1	-	Project 1	Project 1	Yes	-
8	14, 12	8, 6	-	Project 1	-	Project 1	Project 1	Yes	-
9	2, 3	4, 7	-	Project 1	-	project 1	Project 1	Yes	-
10	7, 9	9, 13	-	Project 2	-	Project 2	Project 2	Yes	-

Table 8: Project Selection for Capacity Expansion with Demand Uncertainty for Network 4

Pair	Project 1	Project 2	E(Emission)	Emission(E(D))	Same selection by E(Emission) & Emission(E(D))?	E(TSTT)	TSTT(E(D))	Same selection by E(TSTT) & TSTT(E(D))?	Same selection by E(TSTT) & E(Emission)?
1	5, 1	1, 2	-	Project 1	-	Project 1	Project 1	Yes	-
2	9, 10	21, 9	-	Project 2	-	Project 1	Project 1	Yes	-
3	15, 16	20, 10	Project 2	Project 2	Yes	Project 2	Project 2	Yes	Yes
4	16, 17	20, 10	-	Project 2	-	Project 1	Project 1	Yes	-
5	11, 23	2, 1	-	Project 1	-	Project 1	Project 1	Yes	-
6	15, 21	7, 13	Project 2	Project 2	Yes	Project 2	Project 2	Yes	Yes
7	3, 6	16, 17	-	Project 1	-	Project 2	Project 2	Yes	-
8	4, 11	6, 7	-	Project 1	-	Project 2	Project 2	Yes	-
9	20, 10	16,19	Project 1	Project 1	Yes	Project 1	Project 1	Yes	Yes
10	14, 5	17, 14	-	Project 1	-	Project 1	Project 1	Yes	-

Impact Joint Capacity and Demand Uncertainty

To investigate the joint impact of capacity and demand uncertainty, it is now assumed that both the capacity and demand values follow their respective triangular distribution, as described above. Again, 20 samples have been used in our analysis. From the results, shown in Tables 9 to 12, it can be observed that:

- The project selections based on expected capacity and demand values are the same, for all distinguishable cases, as the selections based on expected emission levels for all four test networks.
- When the goal is to reduce the expected TSTT, using expected values gives the same project selection as when uncertainty is explicitly accounted for.
- Network design from the travel time optimization perspective does not necessarily reduce total system emissions. For example, for network 1, among the 8 distinguishable project pairs, only 5 of the cases were found to be different.

Concluding Remarks

In this research, the impact of demand and capacity uncertainty on the network assignment-based ranking of capacity expansion projects was examined. Based on extensive simulations, our results indicate that the impact is surprisingly minimal (the only case where uncertainty was observed to be relevant was in the case of capacity uncertainty, when the goal is to reduce the network travel time), especially in light of findings in previous related work that indicated that uncertainty might lead to the selection of inferior projects (e.g. see Waller et al., 2001). Possible reasons for this discrepancy might include:

- We employed confidence intervals to detect statistical differences, whereas prior only compares mean values.
- Due to the high computational times of MOVES, we necessarily had to limit ourselves to a limited number of samples. To illustrate, the computation time in MOVES for Network 2 (which is the smallest of all the networks with 18 links) ***for one sample*** was already 2.45 minutes on a standard computer with a

2.67 GHz processor and 8 GB RAM. For Network 4, with 36 links, the execution time was 6.10 minutes for one sample. This slow execution speed has been identified as a drawback of the MOVES software (EPA, 2014). As a result, in some of the cases, it was not possible for us to detect a statistically significant difference.

- Restricted by the computational requirements of MOVES, we only considered the case of triangular distributions in modeling the uncertainties. Other probability distributions might yield different results.

One finding was consistent with previous research: Capacity expansion projects to reduce vehicular emissions are not necessarily optimal in terms of congestion mitigation. Ferguson et al. (2010) arrived at a similar conclusion, but with EPA's older emission estimation system MOBILE.

We conclude by emphasizing that the findings in this study are preliminary in nature and might not necessarily generalize to other settings than the ones considered in this report.

Table 9: Project Selection for Capacity Expansion with Joint Capacity and Demand Uncertainty for Network 1

Pair	Project 1	Project 2	E(Emission)	Emission(E(C, D))	Same selection by E(Emission) & Emission(E(C,D))?	E(TSTT)	TSTT(E(C, D))	Same selection by E(TSTT) & TSTT(E(C,D))?	Same selection by E(TSTT) & E(Emission)?
1	7, 10	10, 15	Project 2	Project 2	Yes	Project 2	Project 2	Yes	Yes
2	21, 14	9, 14	-	Project 1	-	Project 1	Project 1	Yes	-
3	21, 14	7, 10	Project 2	Project 2	Yes	Project 1	Project 1	Yes	No
4	18, 16	2, 8	Project 1	Project 1	Yes	Project 2	Project 2	Yes	No
5	14,9	15, 17	Project 2	Project 2	Yes	Project 1	Project 1	Yes	No
6	13, 18	4, 2	Project 2	Project 2	Yes	Project 1	Project 1	Yes	No
7	15, 17	12, 13	Project 1	Project 1	Yes	Project 1	Project 1	Yes	Yes
8	20, 21	19, 20	-	Project 1	-	Project 1	Project 1	Yes	-
9	18, 16	21, 14	Project 2	Project 2	Yes	Project 2	Project 2	Yes	Yes
10	13, 18	10, 15	Project 2	Project 2	Yes	Project 1	Project 1	Yes	No

Table 10: Project Selection for Capacity Expansion with Joint Capacity and Demand Uncertainty for Network 2

Pair	Project 1	Project 2	E(Emission)	Emission(E(C,D))	Same selection by E(Emission) & Emission(E(C,D))?	E(TSTT)	TSTT(E(C, D))	Same selection by E(TSTT) & TSTT(E(C,D))?	Same selection by E(TSTT) & E(Emission)?
1	2, 1	5, 4	-	Project 1	-	Project 1	Project 1	Yes	-
2	6, 5	5, 11	Project 1	Project 1	Yes	Project 2	Project 2	Yes	No
3	4, 2	8, 7	-	Project 1	-	Project 2	Project 2	Yes	-
4	9, 8	11, 10	-	Project 1	-	Project 2	Project 2	Yes	-
5	6, 7	10, 11	-	Project 2	-	Project 2	Project 2	Yes	-
6	8, 9	10, 12	-	Project 2	-	Project 2	Project 2	Yes	-
7	10, 3	5, 6	Project 2	Project 2	Yes	Project 2	Project 2	Yes	Yes
8	1, 2	7, 6	-	Project 1	-	Project 1	Project 1	Yes	-
9	4,5	7, 8	-	Project 1	-	Project 2	Project 2	Yes	-
10	2,4	11, 5	-	Project 2	-	Project 2	Project 2	Yes	-

Table 11: Project Selection for Capacity Expansion with Joint Capacity and Demand Uncertainty for Network 3

Pair	Project 1	Project 2	E(Emission)	Emission(E(C, D))	Same selection by E(Emission) & Emission(E(C,D))?	E(TSTT)	TSTT(E(C, D))	Same selection by E(TSTT) & TSTT(E(C,D))?	Same selection by E(TSTT) & E(Emission)?
1	10,12	3,4	-	Project 1	-	Project 1	Project 1	Yes	-
2	4,7	7,9	-	Project 2	-	Project 2	Project 2	Yes	-
3	10,12	6,1	-	Project 2	-	Project 2	Project 2	Yes	-
4	10,5	9, 7	-	Project 2	-	Project 2	Project 2	Yes	-
5	12, 13	13, 12	-	Project 1	-	Project 1	Project 1	Yes	-
6	9, 8	10, 12	-	Project 2	-	Project 2	Project 2	Yes	-
7	13, 14	1, 6	-	Project 1	-	Project 1	Project 1	Yes	-
8	14, 12	8, 6	-	Project 1	-	Project 1	Project 1	Yes	-
9	2, 3	4, 7	-	Project 1	-	Project 1	Project 1	Yes	-
10	7, 9	9, 13	-	Project 2	-	Project 2	Project 2	Yes	-

Table 12: Project Selection for Capacity Expansion with Joint Capacity and Demand Uncertainty for Network 4

Pair	Project 1	Project 2	E(Emission)	Emission(E(C, D))	Same selection by E(Emission) & Emission(E(C,D))?	E(TSTT)	TSTT(E(C, D))	Same selection by E(TSTT) & TSTT(E(C,D))?	Same selection by E(TSTT) & E(Emission)?
1	5, 1	1, 2	-	Project 1	-	Project 1	Project 1	Yes	-
2	9, 10	21, 9	Project 1	Project 1	Yes	Project 1	Project 1	Yes	Yes
3	15, 16	20, 10	Project 2	Project 2	Yes	Project 1	Project 1	Yes	No
4	16, 17	20, 10	-	Project 2	-	Project 1	Project 1	Yes	-
5	11, 23	2, 1	-	Project 1	-	Project 1	Project 1	Yes	-
6	15, 21	7, 13	Project 2	Project 2	Yes	Project 2	Project 2	Yes	Yes
7	3, 6	16, 17	-	Project 1	-	Project 2	Project 2	Yes	-
8	4, 11	6, 7	-	Project 2	-	Project 2	Project 2	Yes	-
9	20, 10	16,19	Project 2	Project 2	Yes	Project 2	Project 2	Yes	Yes
10	14, 5	17, 14	-	Project 1	-	Project 1	Project 1	Yes	-

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APPENDIX

Publications resulting from this grant:

Ng, M., Lo, H. K. (2013) Regional Air Quality Conformity in Transportation Networks with Stochastic Dependencies: A Theoretical Copula-Based Model. Network and Spatial Economics 13(4), 373-397.