The Impact of Snowfall on Crashes, Traffic Volume, and Revenue on the New York State Thruway

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ABSTRACT: Snow has numerous effects on traffic, including reduced traffic volumes, greater crash risk, and increased travel times. This research examines how snow affects crash risk, traffic volume, and toll revenue on the New York State Thruway. Daily data from January for a 10-yr period (2010–19) were analyzed for the Thruway from the Pennsylvania state line in western New York to Syracuse. Anywhere from 35% to 50% of crashes are associated with inclement weather, with smaller impacts, proportionally, in areas with greater traffic volumes. As expected, snow was almost always involved when weather was a factor. ‘‘Unsafe speed’’ was the most common cause of crashes in inclement weather with all other factors (e.g., animals, drowsiness) much less likely to play a role. The percentage of crashes resulting in an injury did not change significantly with inclement conditions when compared with crashes occurring in fair conditions, and there were too few fatal crashes to make any inferences about them. Daily snowfall rates predicted about 30% of the variation in crash numbers, with every 5.1 cm of snowfall resulting in an additional crash, except in Buffalo where 5.1 cm of snow resulted in an additional 2.6 crashes. Confirming earlier results, daily snowfall had a large impact on passenger vehicle counts whereas commercial vehicle counts were less affected. Revenue data showed a similar pattern, with passenger revenue typically decreasing by 3%–5% per 2.5 cm of snow, whereas commercial revenue decreases were 1%–4% per 2.5 cm of snow.

SIGNIFICANCE STATEMENT: While it seems obvious that snowfall increases the number of crashes, decreases traffic volume, and reduces toll revenues, research is limited to support these assumptions, especially the latter two. This study involved an analysis of such items for the New York State Thruway. We found that increasing amounts of snow did cause more crashes. While traffic counts decreased, most of the decrease was in the number of passenger vehicles; commercial vehicle traffic was much less affected. Every 2.5 cm of snow costs the New York State Thruway approximately $1300 at each toll barrier and about $331 at each exit. These findings are helpful to law enforcement, emergency responders, and highway managers.

KEYWORDS: Social Science; Snow; Economic value; Societal impacts; Transportation meteorology

1. Introduction

Inclement weather affects the number of vehicles on roadways and the manner in which people drive, as found by previous research projects (e.g., Call 2005, 2011; Roh et al. 2015). But many additional questions remain to be explored. For example, on a toll roadway, what is the economic cost of snowfall? Also, do differences in traffic volume and driving styles cause positive or negative effects with respect to the number and severity of crashes? This study examines these relationships in western and central New York State. The study region is home to approximately three million people and three of the snowiest U.S. cities (with population above 50 000): Buffalo, Rochester, and Syracuse, New York; see Fig. 1 for a map. In addition to snow from synoptic causes, this area is also subject to lake-effect snow from Lakes Ontario and Erie. For this project, crash, traffic, and revenue data from the New York State Thruway for January in the years 2010–19 was obtained. The primary findings are that snow does influence the number and causes of crashes and that each 2.5 cm of snow costs the New York State Thruway (the ‘‘Thruway’’) Authority thousands of dollars in uncollected revenue.

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2. Background and literature

Scholarship on the relationship between weather and traffic has grown considerably in the past decade. Prior research by the lead author (Call 2011) found a decrease in traffic volume within the study area during snowstorms, but most of the change was due to reductions in passenger traffic; in a similar study, Roh et al. (2015) found that commercial truck traffic in Alberta, Canada, was less affected than passenger traffic. In a study focused on lake-effected areas, Burow and Atkinson (2019) studied traffic in northeastern Ohio, downwind of Lake Erie. They found impacts of snow on traffic decreased with increasing distance from the lake. They also found that day of the week and time of day were significant variables.

Traffic speed decreases during snow events as numerous studies have shown (e.g., Kilpeläinen and Summala 2007; Strong et al. 2010), but less is known about how this may affect crash risk. Nonetheless, approximately 12% of crashes in the United States occur in connection with inclement winter weather (Ashley et al. 2015), and 8.6% of vehicle-related fatalities occur in connection with precipitation (Tobin et al. 2019). Results by state and region vary widely, but most researchers find an increased risk of a crash with injury (e.g., Eisenberg and Warner 2005; Black and Mote 2015; Mills et al. 2019). In Salt Lake County, Utah, where snowfall is much less

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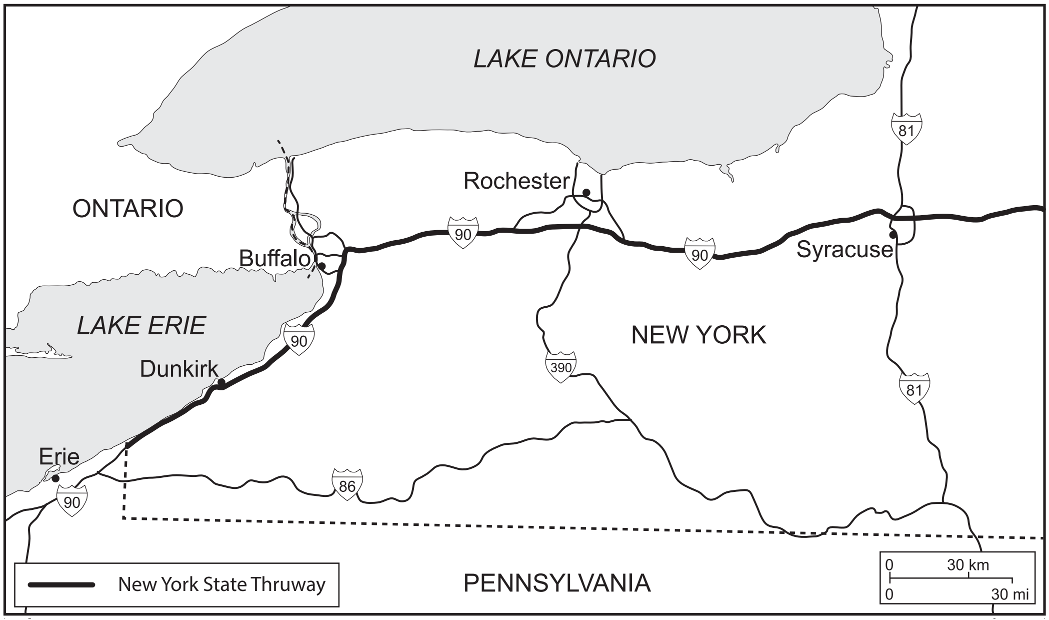


FIG. 1. Map of the study area.

common than in western New York, Call et al. (2019) found extremely high correlations (>90%) between monthly crash counts and snowfall amounts.

Multiple papers in recent years have examined relationships between inclement weather and crashes themselves using surface and radar observations (e.g., Call et al. 2018; Tobin et al. 2019; Tobin et al. 2021; Burow and Cantrell 2021). This particular research project is focused on crashes aggregated to daily and monthly time scales. Nonetheless, a logical follow-up project would be to apply the methods from the aforementioned studies to examine individual crashes in this dataset.

There appears to be little research on the relationship between toll revenue and weather. A comprehensive study by the National Academies of Sciences, Engineering, and Medicine lists many variables that might be considered in determining toll revenue but ignores weather entirely (National Academies of Sciences, Engineering, and Medicine 2007). Most other research involves models built to predict toll revenue for future road projects; again, weather is not considered. Lemp and Kockelman (2009) provide a good overview of research on toll revenue.

This study aims to extend previous research by seeing whether prior findings by Call (2011) about traffic counts in upstate New York are still valid and by expanding that research to examine crash risk. It also seeks to break new ground by examining how weather, specifically snowfall, affects toll revenue received by the New York State Thruway Authority.

3. Data and methods

Data on traffic counts by vehicle type, revenue, and crashes were requested from the New York State Thruway Authority for each barrier and exit from the Pennsylvania line to Syracuse. Data for three barriers and four exits were provided as well as crash data for the entire length from Pennsylvania to the east side of Syracuse. All requested data were for the month of January for the years from 2010 to 2019 inclusive. On average, January is the snowiest month of the year for the major cities in the region. Using data from January also reduces the distortions caused by the Christmas holiday season and major sporting events such as National Football League games in Buffalo.

Both a heat map and a histogram of crashes by milepost showed that crashes were heavily concentrated in the Buffalo region, with 41% occurring between mile markers 412.5 and 432.5. Additionally, since weather conditions along the Thruway were likely to vary from one end to the other, crashes were split into four groups for data analysis. An equal interval scheme was used, with each segment having a length of 89.3 km (55.5 mi) on the Thruway milepost system.

Daily temperature and snowfall data were obtained from the NCEI for first-order stations in Buffalo, Rochester, and Syracuse, all in New York, and Erie, Pennsylvania. Snowfall and temperature records for cooperative stations were also obtained when available. No cooperative station had complete records for the entire period. Including those data did not improve correlations or regression results. Various distance-weighted schemes between stations did not help either, except for the westernmost segment where the Buffalo and Erie stations are both relatively far. Thus, for three segments, a single station (Syracuse, Rochester, or Buffalo) was used; for the westernmost segment, the average of the Buffalo and Erie data was used.

Data were cleaned up and formatted to be easily readable to statistical software, and then descriptive statistics were generated. As part of the regression process, we examined correlations, normality, and results from best subsets regression to determine which variables to include and whether our data

TABLE 1. Number of crashes in each 100-km section of the New York State Thruway by reported weather condition.

Weather	Dunkirk	Buffalo	Rochester	Syracuse	Totals
Clear[a]	61	260	55	80	456
Cloudy	69	457	132	112	770
Fog/smog/smoke	0	1	0	0	1
Rain	11	56	15	11	93
Snow	210	441	126	270	1047
Other winter	21	24	11	20	76
Column totals	374	1239	339	493	2445

[a] Includes two crashes tagged as "other" in the Dunkirk region. Reports indicated fair weather.

needed to be transformed. After regression we also examined residuals, which showed no consistent pattern. The random nature of the residuals reflects the influence of nonmeteorological factors, such as a road closure due to a non-weather-related crash, on total crashes, traffic counts, and revenue.

4. Results

a. Crash statistics

For the month of January from 2010 to 2019, there were 2445 crashes on the New York State Thruway from the Pennsylvania line to the east side of Syracuse (see Table 1). Slightly fewer than one-half, or 1217, occurred under inclement weather conditions, with snow making up 86% of the weather-related crashes (1047), followed by rain (93), other winter precipitation (76), and fog (1). The reporting form only has space for one weather type. It seems likely that fog also occurred with at least some other weather-related crashes.

Regional differences in crashes are shown in Table 2. In all regions, crashes were more likely on weekdays than weekends due to higher traffic volumes. However, in Buffalo and Rochester inclement weather was much less of a factor in crashes on weekdays. This was expected in Buffalo given the high traffic volume, but somewhat surprising in Rochester given that the Thruway is farther from city limits and has 3 interchanges as opposed to 10. On weekends, the proportion of crashes due to inclement weather did not vary as much by region.

The total percentage of crashes due to inclement weather varied considerably by region but can generally be described as being about one-half of all crashes (see Table 3). Inclement weather was a factor in more than 60% of crashes in Dunkirk and Syracuse regions, and closer to 40% in Buffalo and Rochester. "Inclement weather" almost always meant snow. Snow was a factor in anywhere from 83% (Rochester) to 90% (Syracuse) of crashes during inclement weather.

The percentage of crashes with one or more injuries did not change appreciably due to weather (not shown). In Dunkirk and Buffalo, the percentage of crashes with one or more injuries increased slightly from about 12% in fair weather conditions to 16% in inclement weather, while in Rochester and Syracuse it decreased slightly, from about 13%–10%. Only four fatal crashes occurred during the study period, and only two were during inclement weather. Because the sample size was small, these were not analyzed further.

Crashes could be caused by any one of more than 40 factors. (Each crash could only have exactly one cause associated with it.) In fair weather, some common causal factors included unsafe speed, unsafe lane changes, following too closely ("tailgating") or interactions with deer or other animals. As shown in Table 4, typically around one in six crashes was associated with unsafe speed. However, in all cities, the number and percentage of crashes associated with unsafe speed rose dramatically during inclement weather to around 60% of all crashes. Driving at an unsafe speed, presumably too fast, accounts for the majority of crashes during inclement weather.

Other causes of crashes also changed with the weather. The most notable are listed in Table 5. Crashes with deer and animals decreased dramatically, especially in the more rural areas. Crashes due to driver inattention and drowsiness-related causes also showed a sharp decrease, because drivers are more alert. While crashes due to speed increased greatly, other driving errors such as tailgating and improper passing showed decreases, except in the Dunkirk region. This reflects that such crashes are relatively rare in that region during fair weather conditions. This could be due to low traffic volumes overall, or perhaps motorists tend to cluster together when the weather is snowy.

b. Predicting crashes from snowfall

Prior research in Salt Lake County showed a strong correlation ($r = 0.905$) between monthly snowfall and crashes due to inclement weather (Call et al. 2019). To see how applicable that might be in this situation, regression tests were run between snowfall and the number of crashes due to snow in each region.

The results using monthly data were mixed, with regression being successful only for the Buffalo and Syracuse segments (see Table 6). In all segments, regressions involving both

TABLE 2. Percentages of crashes on weekdays (wkdy) and weekends (wknd) and under fair vs inclement weather conditions.

Weather	Dunkirk		Buffalo		Rochester		Syracuse	
	Wkdy	Wknd	Wkdy	Wknd	Wkdy	Wknd	Wkdy	Wknd
Fair	26	9	48	10	42	13	29	10
Inclement	50	15	32	10	37	8	45	15
Total percentage	76	24	79	21	79	21	74	26

TABLE 3. Percentages of crashes due to different types of inclement weather, shown both as a percentage of those due to inclement weather (incl) and as a percentage of all crashes. Column totals may vary because of rounding.

	Dunkirk		Buffalo		Rochester		Syracuse	
Weather type	Incl	All	Incl	All	Incl	All	Incl	All
Fog/smog/smoke	0	0	0.2	0	0	0	0	0
Rain	5	3	11	5	10	4	4	2
Snow	87	56	84	36	83	37	90	55
Other winter	9	6	5	2	7	3	7	4
Total	100	65	100	42	100	45	100	61

TABLE 4. Crashes caused by unsafe speed (S), total crashes (T), and proportion of crashes (%) caused by unsafe speed by region and weather condition.

	Dunkirk			Buffalo			Rochester			Syracuse		
Weather	S	T	%	S	T	%	S	T	%	S	T	%
Fair	24	132	18	117	717	16	24	187	13	27	192	14
Incl	145	242	60	282	522	54	87	152	57	197	301	65

average temperature and monthly snowfall were attempted; however, temperature added little to no predictive value, so only snowfall was retained. The regression tests for Rochester and Dunkirk segments failed as none of the explanatory (average temperature and monthly snowfall) variables were significant. A correlation analysis quickly pinpointed the problem as a lack of correlation between the predictor and response variables. One possible explanation for the failure is the relatively small number of crashes in snowy weather for these two segments, though Syracuse did not have that many more crashes than those segments. Another possible explanation is that the snowfall data used were not representative for the segment. However, this explanation seems unlikely as significant correlations between snowfall and crashes were found when using daily snowfall data. One last explanation may be that drivers "forget" how to drive on snowy roadways after a period without any snow. Thus, months with relatively few days of snow may have higher than the expected number of crashes if those days with snow are spaced far apart. Eisenberg (2004) found a heightened risk of crash for precipitation events occurring after dry periods.

In contrast, when examining daily snowfall and daily crashes due to snow, regression was successful for all four segments. The coefficients in Syracuse, Rochester, and Dunkirk were close (see Table 7), with an average value of 0.63, further supporting this finding. This implies that for every 2.5 cm of snow in these cities an extra 0.63 crashes might occur—or, since fractional crashes are impossible, an extra crash would be expected for every 4.0 cm of snow. The coefficient in Buffalo, 1.02, implies an extra crash for just about every 2.5 cm of snow. This coefficient is 60% larger than the average coefficient for the other areas, reflecting the fact that traffic volumes, and the number of crashes, are higher there. Because of the large number of data points used to build the regression equations, the coefficients were all considered statistically significant. Additional regression with day of the week was also attempted, but this caused minimal improvement and added additional equations (one for each day of the week), a needless complication.

It is important to note that even the regression equations still only explain around 40% of the variation in the number of crashes during snow events. Since many nonmeteorological factors influence crashes (day of week, time of day, driver error, etc.) and variations in the characteristics of snow itself undoubtedly play a role (e.g., intensity) this is not surprising. Furthermore, it seems likely that a large amount of snowfall may reduce traffic volumes to such a low level that crashes become less common or even impossible. The latter case would be if the Thruway is closed due to snow, which is most likely along the Dunkirk segment because of its proximity to Lake Erie and its rural nature. Inclusion of other factors would increase the power of the equation but also complicate it and require a spatial and time analysis beyond the scope of this paper. A logical place to start would be with the data for the Buffalo segment, where greater traffic volumes cause less variation in crash counts in connection with snow.

c. *Impacts of snow on traffic volume*

Traffic count data were provided for seven interchanges on the New York State Thruway System. Three were located near Syracuse and another was near Rochester; all four of these were at intersections with other Interstate highways. The other three interchanges were for toll barriers where all traffic, including through traffic, must stop and pay a toll. One of these is at the western terminus of the Thruway, near the Pennsylvania state line, approximately 100 km southwest of Buffalo (straight-line distance) or 120 km by vehicle. The other two are in the southern and eastern suburbs of Buffalo; the Thruway between these barriers is actually free with no tolls collected. The differences between interchanges at which traffic exits the Thruway system and those where it simply pays a toll would prove notable.

Monthly snowfall amounts and traffic counts were analyzed first. For all interchanges, the regression failed and the explanatory variable—monthly snowfall totals—was insignificant. In fact, the most useful variable for predicting monthly traffic counts

TABLE 5. Proportion of crashes due to factors other than unsafe speed, organized by region and weather condition (fair or inclement).

	Dunkirk		Buffalo		Rochester		Syracuse	
Cause	Fair	Incl	Fair	Incl	Fair	Incl	Fair	Incl
Animals/deer	27%	3%	4%	0%	22%	3%	13%	1%
Tailgating	2%	7%	34%	15%	7%	5%	12%	9%
Lane issues[a]	7%	12%	20%	13%	18%	14%	18%	10%
Inattention[b]	12%	3%	4%	2%	7%	3%	15%	1%

[a] Lane issues include "improper passing" and "unsafe lane changing."
[b] Inattention includes "cell phone use," "inattention," "drowsy," "fell 13asleep," and "illness."

TABLE 6. Regression results with monthly snowfall (in.; 1 in. = 2.54 cm) as the predictor and monthly crashes as the response.

	Equation	R^2 value	P value of coef	Correlation between variables
Syracuse	15.8 + 0.382 × snowfall	31.8%	0.09	0.56
Rochester	Failed	1.18%	—	0.10
Buffalo	26.95 + 0.589 × snowfall	51.1%	0.02	0.72
Dunkirk	Failed	0.15%	—	−0.04

was calendar year, as this explained more than 80% of the variance in traffic counts. This is because the amount of traffic increased annually at all locations during the 10-yr period of the study. Monthly snowfall had minimal effect on monthly traffic amounts.

Conversely, daily snowfall had a definite effect on traffic counts. This effect was found at all interchanges but was much more pronounced at those where people can leave the Thruway entirely (those in Syracuse and Rochester). As found in previous research (Call 2011), snowfall has less of an effect on the number of vehicles with more than two axles (commercial traffic) than on automobile traffic.

Daily traffic counts were analyzed in comparison with snow. Because traffic counts vary considerably with day of the week, categorical regression, in which each day is analyzed separately, was carried out. The day of the week itself accounted for around 40% of the variation in traffic counts. Regression models based on day of the week were highly accurate for the interchanges around Rochester and Syracuse, with R-squared values between 60% and 75%, as shown in Table 8. Curiously, including calendar year did not increase the accuracy of the equations significantly. Additional regression experiments where small snowfall amounts were filtered out did increase the accuracy of the equations for the four exits slightly (see Table 8) but actually decreased the accuracy for the toll barriers. This suggests again that snowfall has a much smaller effect on the barriers. In addition, filtering out days with no or low amounts of snow reduced the power of the equations and led to more insignificant results likely due to the small sample size.

d. Impacts of snowfall on revenue

The New York State Thruway Authority provided daily revenue from passenger and commercial traffic for the seven interchanges. Initial analysis of these data showed distinctly different patterns through the week as shown in Fig. 2. Median commercial revenue on weekdays was more than double that on weekends, while passenger revenue peaked on Sunday and Friday, with lowest amounts on Tuesday and Wednesday. These patterns are different than those of traffic counts and can be thought of as a distance-weighted traffic measure, since longer trips generate more revenue.

New Year's Day showed a distinct revenue pattern independent of weekday, as shown in Fig. 3. Passenger revenue was very high, no matter what day of the week the holiday occurred on. In contrast, commercial revenue had its lowest average value, roughly one-quarter of a typical day of the month. Because these data did not fit the weekday pattern, they were not included. Data from 2 January, which is sometimes a holiday as well, also were distinct. 2 January had the highest passenger revenue of any day of the entire month, on average, and had the second lowest commercial revenue, also by a large margin. Data from 2 January were initially included, but after discovering that the regression models improved with their exclusion, they were excluded as well. Martin Luther King Day, a holiday observed on the third Monday of January, did not have a significant effect on revenue patterns.

Revenue received at different interchanges also varied significantly as shown in Fig. 4. Interchanges 34A, 36, 39, and 45 are exits where traffic leaves the Thruway system entirely with more local traffic and less commercial traffic. Interchange 45 primarily serves local traffic going to Rochester. In contrast, interchanges 50, 55, and 61 are toll barriers where all traffic, both that leaving the Thruway system and through traffic, must stop and pay a toll. These interchanges are more likely to have long-distance through traffic. Thus, revenue from commercial traffic was several times greater than that from passenger traffic. Interchange 50 stands out above all other interchanges with the greatest amounts of revenue in both categories because of high traffic volume. It is located east of Buffalo, near the Buffalo Airport, and traffic there may have entered the Thruway from as far away as Massachusetts or New York City. This traffic would pay the highest toll amounts possible on the entire Thruway system.

As a result of the variations in revenue, each interchange was analyzed separately. As before, Syracuse snow totals were used for interchanges 34A, 36, and 39; Rochester values were used for interchange 45; Buffalo values were used for interchanges 50 and 55; and an average of Buffalo and Erie values were used for interchange 61.

To assess if there was a relation at all between revenue and snowfall, several tests were performed before regression was

TABLE 7. Regression results with daily snowfall (in.) as the predictor and daily crashes as the response.

	Equation	R^2 value	P value of coef	Correlation between variables
Syracuse	0.158 + 0.75 × snowfall	39.5%	0.00	0.63
Rochester	−0.01 + 0.56 × snowfall	30.6%	0.00	0.55
Buffalo	0.47 + 1.02 × snowfall	37.5%	0.00	0.61
Dunkirk	0.08 + 0.59 × snowfall	31.6%	0.00	0.56

TABLE 8. Regression results with day of the week and daily snowfall as the predictor and traffic counts as the result.

Interchange	Closest city	R^2 value for all days (%)	R^2 value when snowfall ≥ 2.5 cm (%)	R^2 value when snowfall ≥ 5.1 cm (%)
34A	Syracuse	70.4	74.7	74.0
36	Syracuse	68.0	71.7	70.8
39	Syracuse	62.4	71.0	74.1
45	Rochester	65.0	66.7	72.4
50	Buffalo	54.6	29.8	28.6[a]
55	Buffalo	59.5	34.7	30.6[a]
61	Ripley	30.3	24.1[a]	11.9[a]

[a] At least two equations had nonsignificant coefficients because of insufficient data points for specific days of the week.

attempted. First, a correlation analysis was done to see if there was a relationship between snowfall and revenue. Initial results showed very low negative correlations (R-squared values on the order of −0.2), but when day of the week was used to separate correlations, they doubled, on average. Next, scatterplots were constructed, both with all data and with excluding days on which snowfall was less than 2.5 cm (1 in.). Scatterplots from interchange 50, the busiest one, are shown in Fig. 5. Although the slopes of the lines vary, probably due to a few large snow events, the trends are all in the expected direction: greater snowfall is associated with lower revenue.

Linear regression appeared to be the best fit for the data. Given the relatively low number of snowy days (because each day of the week was analyzed separately), other forms of regression (e.g., cubic) yielded inconsistent results. A larger dataset would be needed to determine if a different form of regression is more appropriate.

To examine how days with either very small amounts of snow (<2.5 cm) or none had an influence, all days with less than 2.5 cm were excluded and the scatterplots were remade. At this point, some days of the week simply did not have sufficient data points for a proper analysis. As will be discussed later, regression was also less productive. In summary, data from all days of the week, including those with no snow, were kept.

Following the scatterplot analysis, regression was run with snowfall as the predictor variable and revenue as the response variable. Because type of revenue, day of week, and interchange were categorical variables, two sets of seven equations were generated for each interchange, one set for passenger revenue and one set for commercial revenue. Each set equation had a different Y intercept for each day of the week, but each set used the same coefficient value for the X term. Table 9 summarizes the equations for the passenger revenue, and Table 10 summarizes them for commercial revenue.

The combination of snowfall and day of the week explained around 50% of the variation in passenger revenue at each interchange, with the equations explaining variations best at interchange 45 and least effectively at interchange 36. The

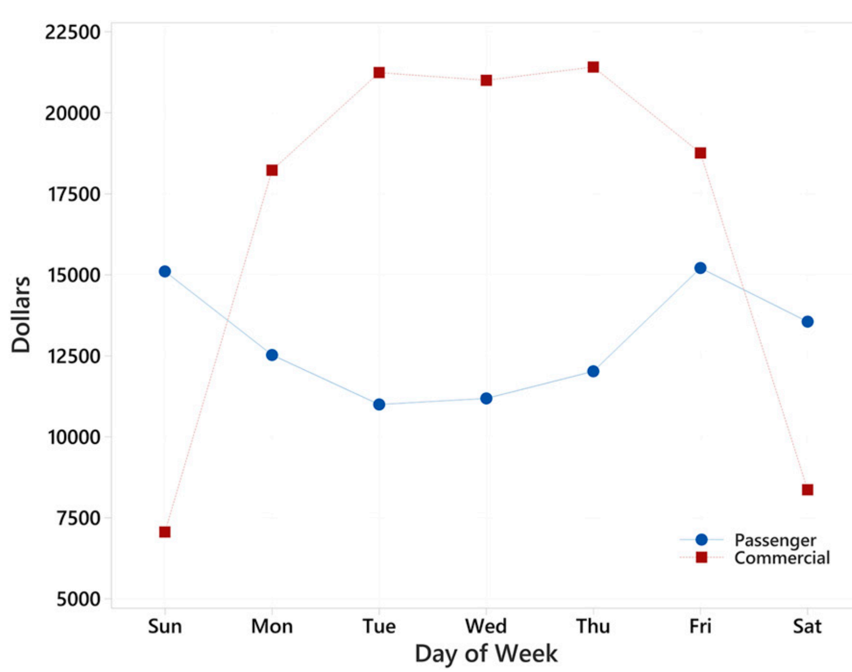


FIG. 2. Median revenue by day of the week for passenger and commercial traffic.

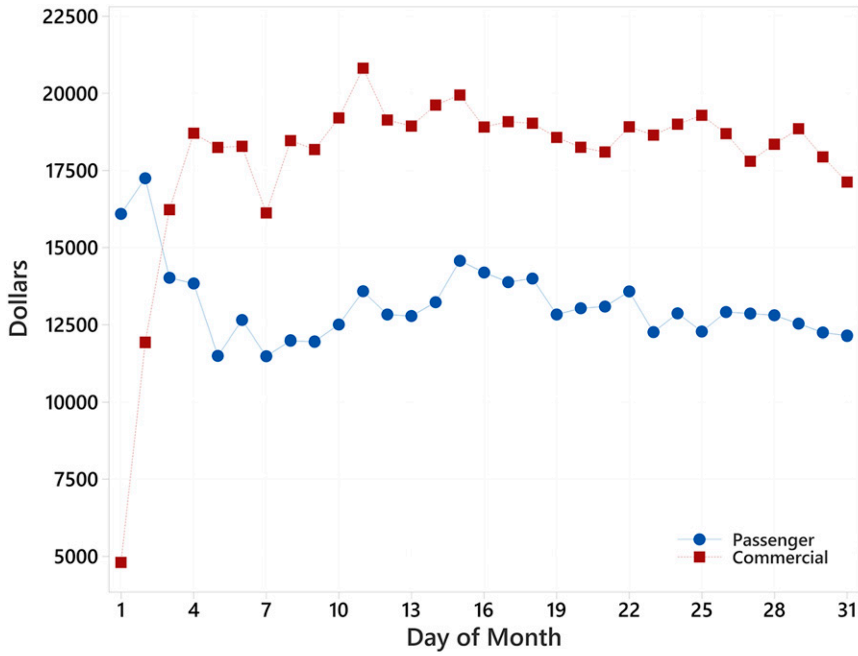


FIG. 3. Median revenue by day of month for passenger and commercial traffic.

variation in R-squared values between interchanges appears to be influenced by unknown factors; there is no pattern.

Baseline passenger revenue by day varied considerably by day of the week and by interchange. Revenue at interchange 50, the toll barrier just east of Buffalo, was approximately double to triple the other interchanges due to higher traffic counts and more long-distance traffic. As expected due to the high traffic count, the absolute decrease in passenger revenue here was the largest for any interchange: $1,405 for every 2.5 cm of snow. In comparison, at interchange 36 in Syracuse, each 2.5 cm of snow only caused a decrease in passenger revenue of $237 per day.

The percentage decrease in revenue at interchange 36 was also the smallest of all interchanges at 2.4% and was similar to the other two Syracuse interchanges. Probably because of both lower traffic volume of passenger vehicles and lower revenues (due to most traffic being local or shorter distance), the three interchanges near Syracuse had the both the smallest absolute and percentage decreases in revenue in connection with snow. However, the 4.0% decrease at Buffalo was not the largest

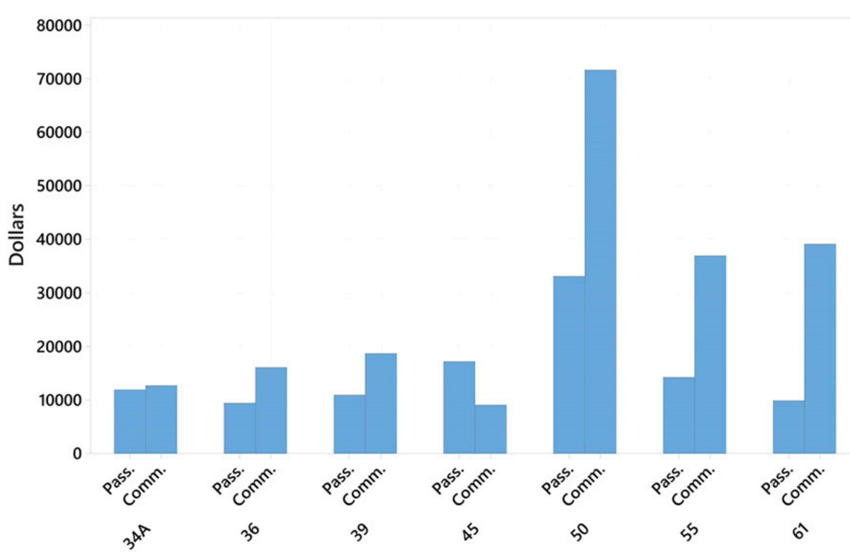
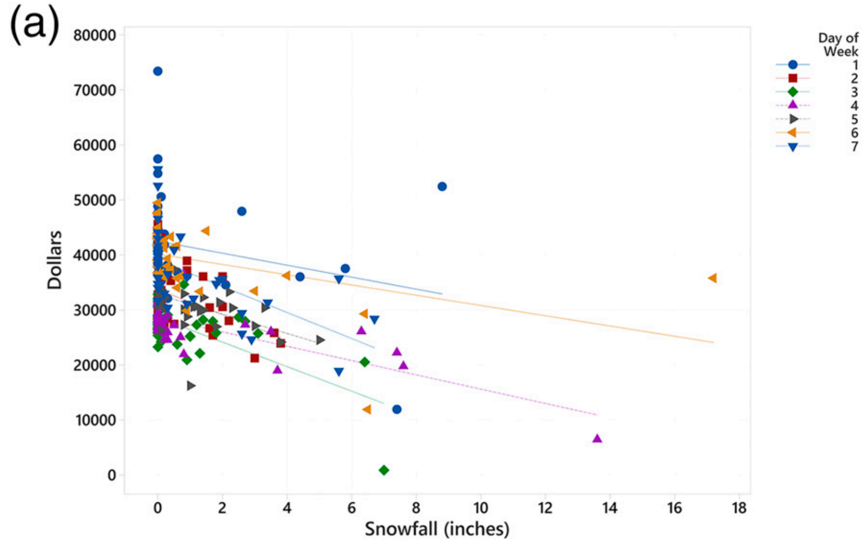


FIG. 4. Median daily revenue by interchange and vehicle classification.



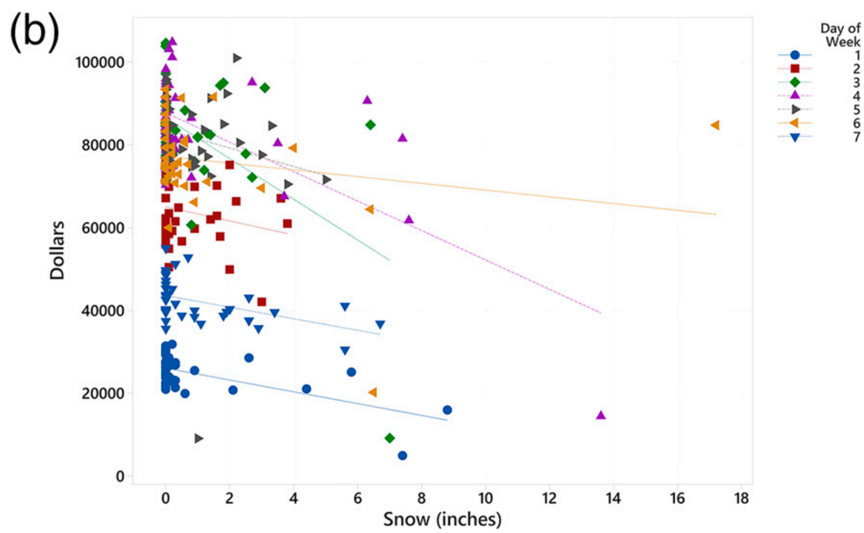


FIG. 5. Scatterplots comparing daily revenue from (a) passenger and (b) commercial vehicles with snowfall for interchange 50 (Sunday = day 1).

percentage decrease; greater percentage increases were observed at the two toll barriers west of Buffalo (interchanges 55 and 61; decreases were 4.8% and 5.5%, respectively) and at the exit near Rochester (interchange 45; decrease was 4.9%). At these interchanges, a typical decrease in revenue was around 3% per 2.5 cm of snow. Ranges in revenue decreases varied on a daily basis as well, typically within a range of ±1% from the average. At interchange 61, however, revenue variations were larger with decreases around 7% on Tuesday and Wednesday and decreases around 4.4% on Sunday and Friday.

TABLE 9. Summary information for equations relating passenger revenue and snowfall.

Interchange	Avg Y intercept	X coef	R^2 (%)	Avg percent decrease per 2.5 cm (X/Y)	Range of percentage decreases
34A	12 815	434	50.0	3.4	2.9–3.9
36	9843	237	43.1	2.4	2.0–2.8
39	11 666	354	49.2	3.0	2.6–3.7
45	18 385	904	59.5	4.9	4.2–5.8
50	34 849	1405	55.7	4.0	3.3–5.0
55	15 037	724	47.8	4.8	4.2–5.5
61	10 831	598	56.7	5.5	4.3–7.3

TABLE 10. Summary information for equations relating commercial revenue and snowfall.

Interchange	Avg Y intercept	X coef	R^2 (%)	Avg percent decrease per 2.5 cm (X/Y)	Weekday avg decrease	Weekend avg decrease
34A	10 983	128	94.6	1.2	0.9	3.1
36	14 563	189	91.7	1.3	1.1	2.6
39	16 881	270	90.3	1.6	1.3	3.6
45	7998	136	91.3	1.7	1.4	4.5
50	67 027	2159	82.1	3.2	2.7	6.5
55	36 021	1225	78.4	3.4	3.0	5.7
61	37 203	1564	81.7	4.2	3.6	7.8

It is unclear why the variation at this interchange was the largest.

A model involving snowfall and day of the week was considerably more accurate for commercial vehicles than passenger vehicles. For the commercial models, R-squared values were greater than 90% for the standard interchanges (34A, 36, 39, and 45) and around 80% for the three toll barriers (50, 55, and 61). Because commercial revenue varies much more between interchanges, the absolute declines in revenue were smallest at the local interchanges and largest at the toll barriers. However, when the changes are viewed in relative terms, a clear separation emerges that was not evident with the passenger data. Decreases at the standard interchanges averaged between 1% and 2% per 2.5 cm (1 in.) of snow and 3% and 4% for toll barriers.

For all interchanges, the overall effect of snowfall on commercial revenue on weekdays was smaller than that associated with passenger traffic. For the standard interchanges it was around 1.2% per 2.5 cm, meaning that a snowfall of 15.2 cm (6 in.) would causes less than a 10% decrease in commercial revenue and even a snowfall of 30.5 cm (1 ft) would theoretically cause decreases on the order of 11%–17%. This is vastly different than those for passenger vehicles, where a similar amount of snow would cause decrease passenger vehicle revenue by 30%–60% at the same interchanges. The differences at the toll barriers were smaller, but in all cases the decreases in passenger revenue were about 35% larger per 2.5 cm. These differences confirm Call (2011) that found that passenger vehicle counts decreases much more sharply in connection with snow than commercial vehicle counts. Unfortunately, counts by specific vehicle class were not available in this study.

For the three toll barriers, the decrease in weekday revenue associated with snowfall was roughly 2–3 times as large as that for the four interchanges. However, the magnitude of the decrease associated with snow was still about 20%–30% smaller than that associated with passenger vehicles at the same toll barriers.

Commercial vehicle traffic, which had a very strong split between weekday and weekend volume, also showed different effects from snowfall between the two. Snowfall had from double to triple the effect in decreasing revenue on weekends when compared with weekdays. Additionally, on weekends the decreases in commercial revenue for the toll barriers were greater than the decreases associated with passenger revenue. For the other interchanges they would have ranked among the larger decreases for passenger revenue.

5. Conclusions

Data on crashes, traffic counts, revenue were obtained from the New York State Thruway Authority for each January from 2010 to 2019 inclusive. Inclement weather contributed to more than one-half of all crashes, with snow being the primary cause. ''Unsafe speed'' was a contributing factor to more than one-half of crashes during inclement weather, whereas it was a factor in only about one in six crashes during fair weather. The proportion of crashes associated with an injury did not change appreciably with weather changes, and fatalities also appear to be unaffected. Daily snowfall rates predicted about 30% of the variation in crash numbers, with every 4.0 cm of snowfall resulting in an additional crash in the Dunkirk, Rochester, and Syracuse regions. In the Buffalo area, where traffic volumes were much heavier, 2.5 cm of snow resulted in an additional crash.

Confirming results from previous research, daily snowfall had a large impact on passenger traffic counts while commercial vehicle counts were less affected. Revenue data showed a similar split to traffic counts, with passenger revenue typically decreasing by 3%–5% per 2.5 cm of snow, while commercial revenue decreases were between 1% and 4% for every 2.5 cm of snow.

The findings about causes of crashes during inclement weather have some practical considerations. First, unsafe speed is often correlated with crashes during inclement weather. The effects of speed on crashes are complex because the relationship is influenced by many other factors, such as the number of vehicles on the road and driver attention (Shinar 2007). Nonetheless, the problem is most likely that drivers are unable to stop their vehicles in time because of snowy conditions. Targeted speed enforcement, electronic warning signs, and a focus on maintaining road surfaces in known problem spots are all helpful strategies. Unfortunately, if snow is falling with great intensity and visibilities are sharply reduced, these measures will have limited effectiveness. Likewise, abrupt changes in road conditions due to differences in clearing procedures or snow squalls are difficult to mitigate. Other research has found that abrupt reductions in visibility often cause chain-reaction multivehicle crashes during snowstorms (Call et al. 2018).

The relationship between monthly snowfall and crashes was poor, in contrast to what one of the authors found in Salt Lake County (Call et al. 2019). In two of the regions, no relationship existed at all. In the Buffalo and Syracuse regions, there was a stronger relationship, probably due to higher traffic volumes. It is unclear why the relationship failed. One possible explanation is that the snowfall is measured at specific point. While this value may be representative in places with relatively uniform snow amounts across a large area, it may be the case where lake-effect snow can cause large variations with a region. Nonetheless, given the relatively strong relationships between daily snowfall and crashes, traffic counts, and revenue, this seems unlikely. Another explanation is that variations in daily traffic volume and other items such as time of day are not smoothed out by looking at a longer time period unless there are a large number of vehicles. It also may be that most traffic in the Dunkirk and Rochester region was long-distance traffic and was relatively unaffected by snowfall, where commuter and other local traffic was heavier in the other two regions. This could be further evaluated by looking at revenue per individual vehicle or evaluating average trip length.

On the other hand, daily snowfall had a measurable effect on daily crashes. Furthermore, this effect was similar with three regions having nearly identical coefficients, and the fourth region have a larger coefficient due to greater traffic volume. An expansion of the dataset would be needed to attempt to evaluate how this coefficient varies with day of the week.

Snowfall has a large impact on passenger vehicle traffic, as noted by the strong relationship between day of the week, snowfall amount, and vehicle counts. Unsurprisingly, this relationship was strongest at the local exits. Long-distance through traffic, which is more common at the toll barriers, was less affected. The weakest effect was observed at the Ripley toll barrier in extreme western New York. This area has the lowest population density of any area on the Thruway; thus, almost all traffic is long-distance traffic. Snowfall has little effect on these motorists' plans.

The differences in how snowfall impacts passenger and commercial revenue probably reflect the relative freedom of drivers of passenger vehicles to postpone or cancel planned trips on the New York State Thruway when the weather is inclement. In contrast, it appears that drivers of commercial vehicles have much less flexibility to cancel or postpone weekday travel during inclement conditions. On weekends, however, commercial volume is already much lower. It appears that most commercial drivers are traveling out of their own free volition, as changes in revenue suggest that they cancel or postpone trips at a rate similar to drivers of passenger vehicles.

This study had several limitations. It only examined data from the month of January, and different results may have been obtained with December data because it is earlier in the snow season. December is also a month in which traffic volume and distance traveled are affected by several major holidays. No information was provided about vehicle type beyond passenger or commercial, and no information about distance traveled was available. Given that the patterns between different types of interchanges (e.g., barriers and exits) were consistent within groups, it seems likely that they were representative of all interchanges in western New York. It is less clear if these findings could be applied to eastern and southeastern New York, where the frequency and type of snowfall are different. There were insufficient crashes with fatalities to make any inferences about the relationship between weather and fatal crashes. Too few fatal crashes for analysis should be considered a good type of research problem to have, however.

A logical follow up study would be to examine the relationships for additional interchanges, especially those elsewhere in New York. Additionally, examining traffic counts by hour, especially in connection with hourly estimates of snowfall from radar, may yield more insights. Researchers could also examine crashes in connection with specific events and weather types, as has been done in other regions. Given the dearth of research exploring the relationship between weather and toll revenues, additional research in this area is needed.

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Data availability statement. All data used in this article are freely and publicly available. Data on crashes, traffic counts, and revenues were obtained from the New York State Thruway Authority through a Freedom of Information Law (FOIL) request. Information on snowfall, temperature, and other weather conditions was obtained from the NCEI.

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